CORE

sCience and human factOr for Resilient sociEty

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1. DOWNWARD COUNTERFACTUAL SCENARIO ANALYSIS

1.1. The importance of scenario analysis

WP4 addresses cascades that impact on societal resilience, especially the security of supply. Supporting societal resilience through security of supply is covered by Task 4.2. Cascades across events, sectors, and supply chain disruptions are covered by Task 4.3. The COVID-19 pandemic has highlighted societal vulnerabilities to supply chain disruptions, not just in health but also in the retail sector, and is prominent in Task 4.3.

The occurrence of cascade phenomena, such as during the COVID-19 coronavirus pandemic, is much less common than events that had more limited impact but might potentially have evolved to generate cascade losses. Given the intrinsic stochastic nature of the physical world, history is only one realisation of what could have happened. Such reimaginations of past events are termed downward counterfactuals, and greatly expand the domain of understanding of cascades. As an example of a downward counterfactual, the 2012 MERS coronavirus outbreak was successfully contained, but it might have had a more contagious pandemic variant capable of spreading from the Middle East through Europe (Woo et al., 2017).

Task 4.1 focuses on downward counterfactual risk analysis. This analysis is based on the counterfactual assessment of salient historical events, specifically the seven designated CORE events, and is an extension of scenario analysis. Compared with generic scenario analysis, the key innovation in downward counterfactual scenario analysis is the exploration of alternative realisations of actual historical events (Woo et al., 2017: Woo, 2019; Lin et al., 2020; Ciullo et al., 2021; Woo, 2021). Beyond WP4, this new perspective on the seven designated CORE events adds a further dimension to the understanding of the role of science and human factors in achieving societal resilience. A detailed presentation of the concepts underlying downward counterfactuals is given in section 1.2, following a general review of scenario analysis.

Scenario analysis has been a mainstay of organisational planning both for corporations and for governments, since scenario planning was pioneered in the 1960s by Royal Dutch Shell (Cornelius et al., 2005). The technique enabled the company to anticipate and better handle the disruptive oil shocks of the early 1970s, to which it could react earlier and more successfully than its competitors.

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The Shell scenarios team was run from 2006 to 2022 by Jeremy Bentham, who has warned against default human tendencies and biases. Thinking linearly, or extrapolating only from our own experience, can result in a misleading way of thinking about future possibilities.

In respect of the Russian the full scale invasion of Ukraine in February 2022, Bentham (ICAEW, 2022) recognised that this invasion was always going to be a possibility; many people overlooked this because they were looking at the world through the prism of what you see is all there is. This is a very narrow superficial perspective, open to all the pitfalls of tunnel vision. Imagine someone with tunnel vision being told that what they see is all there is. Many people perceive history in such terms: what has happened is all there was. If what you see is all there is, then what you saw is all there was. This is a deterministic fatalistic perspective, reflecting the Greek origin of the word 'disaster': a negative event linked with the stars. With any historical event, there was always much more than what we saw.

This report presents a much more elaborate expansive counterfactual prism through which to perceive history: what has happened is only one of myriad ways world events could have turned out. This counterfactual prism exhibits a kaleidoscope of alternative ways that history might be reimagined, with important lessons for societal resilience. Viewing history as fixed is a form of narrow tunnel vision, which limits imagination and foresight into the future.

The continuous need for imaginative scenario planning is exemplified by Shell's exit from its partnership with the Russian gas producer Gazprom after the Russian invasion of Ukraine on 24 February 2022. Eight years earlier, strategic foresight into the Kremlin thinking on Ukraine was provided by the American professor of international relations, John Mearsheimer (2014), whose prescient analysis was quoted by the Russian Ministry of Foreign Affairs. He anticipated the breakdown of Russian international relations with NATO after the ousting of the former Ukraine President Viktor Yanukovych in 2014. In December 2022, President Putin corroborated this world view by blaming the West for starting the conflict in Ukraine by toppling President Yanukovych.

Carl von Clausewitz, the leading authority on military strategy, who served in the Prussian army during the Napoleonic war, as well as the Imperial Russian army, wrote that perfecting the art of warfare entails knowing not only what has occurred in previous wars, but also everything that could have occurred (Clausewitz, 1832). Putin's special military operation might well have happened before; a counterfactual thought that could have informed scenario planning within NATO governments and corporations since the Russian annexation of Crimea in 2014.

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Scenario planning is a strategic planning tool for developing and thinking through possible future states and development paths (Deloitte, 2017). The aim of scenario planning is not to accurately predict the future, which of course is impossible, but rather to better understand logical paths that lead to different scenarios and to develop more comprehensive strategies. The scenario method is based on a multitude of different approaches for specific applications in corporate practice based on either a continuous or a single use of the scenario method. Most prominently, scenario planning is used to foster sense making and adaptive learning, to develop more effective decisions and strategies as well as to advance predictive capability in organisations (Chermack, 2011).

Scenario planning has been cited frequently (e.g. Virdee and Hughes, 2022) as a strategic planning tool capable to improve decision processes due to its cognitive benefits. Specifically, scenario planning has been shown to foster strategic thinking, to enhance mental models of decision makers and to reduce the negative effect of cognitive biases. A prime example is framing bias. The particular way in which a proposition is framed has a crucial effect on decision-making (Meissner and Wulf, 2012). Especially, the effect of scenario planning on cognitive biases is likely to induce significant benefits for the strategic decision making process as a whole as cognitive biases have been found to lead to severe and systematic errors that diminish decision quality.However, as pointed out by Virdee and Hughes (2022), when working with scenarios, users can face certain pitfalls. Scenarios do not provide certainty, rather they equip decisionmakers with readiness to address uncertainty. So over-reliance on scenarios is not desirable.

One specific goal of scenario planning is to achieve resilience against extreme shocks (Deloitte, 2017), especially those associated with external hazard events. It is in consideration of extreme external shocks, which may have no historical precedent, that cognitive biases may emerge in a covert latent manner and come to the fore. This is a key organisational concern of managerial complexity which is addressed here.

Scenario analysis considers a potential event, and the possible future states that may result. For each scenario, an organisation makes assumptions about its effect on different factors important to the organisation. These assumptions are then used as input variables to model the impact of each scenario on the organisation. Scenario analysis examines a spectrum of different potential situations and outcomes, typically ranging from a best-case to worst-case scenario. Organisations can then conduct scenario planning to prepare for these events and their potential impacts.

In exploring the spectrum of different situations and outcomes, there is typically quite a broad variation in personal views as to the difficulty and organisational challenge of extreme situations and possible severity of outcomes. Through its

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highly systematic and structured approach, the scenario planning process is very useful in identifying extreme eventualities, exposing and limiting potential cognitive biases, but nevertheless personal views of even the most authoritative subject experts may be subject to the following biases.

- Optimism bias: looking on the positive side of ambiguity;
- Outcome bias: ignoring the role of chance in an advantageous outcome;
- Recency bias: focusing on recent events, which come most readily to mind;
- Anchoring bias: anchoring views by particularly salient events;
- Substitution bias: Replacing a difficult risk problem with an easier one, which is less relevant.

Daniel Kahneman (2011), the Nobel Prize winning authority on cognitive bias, has stated that the confidence people have in their beliefs is not a measure of the quality of evidence, but of the coherence of the story the mind has managed to construct. Any scenario should be associated with a compelling narrative, which can be rationally constructed in a coherent and systematic manner.

In any discussion about what might happen in the future, a knowledge-based empirical starting point is information acquired what has already happened in the past. Most events, even those which are rare, have either happened before, almost happened before, or might have happened before. A prerequisite is a thorough investigation of history and past experience. For many hazards, databases have been compiled of historical events. However, even the most exhaustively compiled and rigorously checked catalogue of events for a specific hazard may contain minimal information about near-misses.

Consider passenger aviation for example. In the 21st century, this is now a mature global industry, and accidents are rare, and are each fully investigated by the aviation authorities and are well documented. However, excursions from flight plans, (which are not infrequent), are given much less attention. One of the worst cases of an aviation near-miss happened on 7 July 2017. In approaching San Francisco airport around midnight, the two Air Canada pilots mistook the taxiway for the adjacent runway, and flew the AC759 jet to just 18m above ground, before pulling up 5 seconds from crashing into four planes ready to take off. An urgent warning message came just in time from one of these endangered planes.

This might have been the worst ever civil aviation disaster, with potential disastrous consequences for the international aviation industry, and cascading impacts on the global economy in general. The taxiway at San Francisco airport had different coloured lights from the runway, which should have warned the

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pilots to change course on their airport approach - except for their cognitive dissonance in not complying with data incompatible with their prior perception.

In the context of scenario planning, for any proposed scenario, the following three key questions need to be posed.

[1] Has the event happened before? For some scenario analysts with limited practical experience, or limited reading knowledge of the grey unpublished literature, the full history of previous events may be unfamiliar.

Beyond this factual information on precedents, the following related counterfactual questions might be asked.

[2] Was there a similar, related, previous near-miss event, or perhaps several?

[3] Might this event have happened before?

These searching counterfactual questions are not routinely asked or investigated in scenario analysis; reflecting a combination of the optimism, outcome, recency, anchoring and substitution cognitive biases identified above. Indeed, even the use of the term 'counterfactual' may be unfamiliar. In most European languages, the word for 'history' is the same as the word for 'story'. Thus, in Icelandic, a saga might be a legend or an actual historical event.

The lack of a specific counterfactual vocabulary for general application to risk analysis and risk management has been observed by Woo (2019), who has developed natural hazard applications to seismology (Woo and Mignan, 2018), volcanology (Aspinall and Woo, 2019), as well as compound climate events (Woo, 2021). An application to the European Union Solidarity Fund has been given by Ciullo et al. (2021), and referenced also by Kunimitsu et al. (2023).

In addition, applications have been developed for man-made risks such as terrorism (Woo, 2022), cyber risk (Coburn et al., 2019), and pandemic risk (Woo, 2021). The prescience of this methodology for resilience planning is illustrated by a 2015 MERS coronavirus counterfactual (Woo and Johnson, 2023), which was conceived years before the COVID-19 pandemic emerged.

1.2 Downward Counterfactuals

A counterfactual is a thought about the past. A *downward counterfactual* is a thought about the past, where things turned for the worse (Roese, 1994). Most counterfactual thoughts which people have are upward; how things might have

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been better. For an Olympic athlete, a silver medallist might ponder what might have been done to have won the gold medal. It is relatively uncommon for people to have downward counterfactual thoughts, but an Olympic bronze medallist might ponder what might have happened with no podium finish.

The downward counterfactual vocabulary originated in the domain of cognitive psychology, and has been used primarily in the psychological literature. Daniel Kahneman, a leading cognitive psychologist, has been a notable contributor to this literature (Kahneman and Miller, 1986). Recognising the inevitable intrusion of cognitive bias into risk assessment, the downward counterfactual vocabulary is also relevant in a risk context. Few counterfactual thoughts are downward – how things might have been worse.

As a term taken from the social sciences, the downward counterfactual is an enlightening concept for the CORE project, contributing to making society more disaster-resilient. A standard definition of disaster resilience (UNISDR, 2005) is as follows: The capacity of a system, community or society, potentially exposed to hazards to adapt, by resisting or changing in order to reach and maintain an acceptable level of functioning and structure. Limitations in the narrow way that people think about historical events can be detrimental to resilience. Exploration of how things might have turned for the worse is an uncommon endeavour, even for highly experienced risk professionals. It does take time, resources and effort. Yet such a deliberate exercise in disaster discovery is valuable for avoiding surprise by the unexpected or unanticipated.

At the time of the great global financial crash, a former financial markets trader, Nicholas Taleb (2007), published his highly influential book, 'The Black Swan'. Taleb was sceptical about human efforts at foreseeing unprecedented disasters, citing as prime illustrations the then recent 9/11/2001 terrorist attacks, and the 2004 Indian Ocean tsunami, which killed a quarter of a million people. The quest for ways of tracking Black Swans remained a formidable challenge for risk analysts. But a decade after Taleb's book publication, a systematic method for tracking Black Swans was developed. Woo et al. (2017) managed to demonstrate that Black Swans, elusive as they may be, might have appeared on the risk horizon through the following general thought experiment, which is universal to all hazards:

(1) Start with a historical system state leading to a significant initial loss L;
(2) Construct an alternative system state S[1] that would have led to a higher loss L + d(1), where d(1) is a loss increment;
(3) For increasing integer values of K, construct an alternative system state S[k], that would have led to a still higher loss L + d(K). As K increases, the alternative system state increases in loss outcome, so providing an explicit simple algorithm for exploring increasingly worse outcomes.

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(4) After the final step k = F, no further worse alternative system states can be plausibly constructed, and no loss generated beyond L + d(F).

For the salient test case of the 9/11/2001 terrorist attack on the World Trade Center, New York, the downward counterfactual thought process is as follows. The starting point is Halloween 1999, less than two years before 9/11. On that day, Gameel El Batouti, the pilot of EgyptAir Flight 990 from JFK New York to Cairo, crashed his passenger plane into the Atlantic Ocean, killing everyone on board. The loss, large and tragic as it was, would have been greater if he had crashed his plane close to the Atlantic shore, where people on small boats might also have been killed or injured by debris. The loss would have been worse still if the pilot had crashed his plane into a suburb of New York, such as Queens, where local residents might have become casualties. Finally, the loss would have been catastrophically greater, if the pilot had turned his plane around and flown it into a Manhattan skyscraper.

This downward counterfactual sequence leading to a deliberate aircraft impact on a Manhattan skyscraper might seem to be rather implausible. Yet, someone who heard of the ditching of the EgyptAir flight into the Atlantic Ocean actually had this specific counterfactual thought. His name was none other than Osama bin Laden, the leader of the Al Qaeda terrorist organisation. Information about his seminal counterfactual thought came directly from his personal aide-de-camp.

Of course, the Al Qaeda destruction of the World Trade Center on 9/11 had enormous long-lasting implications for the global economy and international geopolitics. The security consequences cascaded across business sectors, causing major supply chain challenges. Analyzing the various alternatives that firms utilised to create resilience in the aftermath of 9/11, Rice and Caniato (2013) observed there are two principal methods to create resilience in the supply network. One entails achieving resilience through flexibility, and the other entails achieving resilience through redundancy. Each has different cost and service characteristics that are important considerations when designing for resilience. Counterfactual analysis of significant historical events can illuminate alternative pathways towards achieving resilience.

Lesser events than 9/11 can also impose severe shocks on the global transportation network. A more recent such event is the stranding of the Ever Given container ship in the Suez Canal in March 2021. The Ever Given container ship was on its way to Rotterdam, from its starting point in Yantian, China. This is a hugely valuable trade route: $40 billion is the annual amount of goods that flow between these ports. Severe trade disruption can leave many organisations and their insurers exposed to business interruption risks.

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1.3 Example: the Suez Canal Blockage of March 2021

There have been several incidents at the Suez Canal over the years, attributable to the large dimensions of container ships. The Suez Canal's length is about 193.3 kilometres with a depth of 28 metres, and its widest point located at the Great Bitter Lake is only 133 metres wide. The Suez Canal Authority (SCA) has set out limitations on a vessel's width and depth, however, there have been no restrictions on the length of vessel, which can be far larger than the narrow Canal width. Instead, vessels over 400 metres long must have permission from the SCA before navigating the Canal. Fitting within the limits is the Ever Given, a very large container ship, 400 m long and 59 m wide, with a container capacity of 20,124 twenty-foot containers (TEU).

At around 7:40am on 23 March 2021, the Ever Given was enroute from Malaysia to the Netherlands. The winds on that day were strong, reaching 40 knots. While the Ever Given was crossing the southern end of the canal, the force of the strong wind caused the head of the vessel to deviate, leading it off course and getting stuck on the southern canal.

Initially, efforts were made to refloat the vessel using tugs, with an excavator being used to remove sediments from beneath the bow of the Ever Given. On 28 March, it was announced that more than 20,000 tons of sediments and mud had been removed successfully, loosening the vessel's bow within the bank of the Canal. Crucially, the engineer had taken advantage of high tide to make the Ever Given refloat. On 29 March 2021, the Ever Given was finally freed. Engineers took advantage of the high tide plus the pulling power of 14 tugboats to refloat the Ever Given eventually. The Ever Given blockage cost $400 million/hour, or about $10 billion/day according to Lloyd's list estimates.

To examine the cause of the Incident, the Ever Given travelled north to the Greater Bitter Lake for further investigation. Soon afterwards, the maritime traffic resumed and 450 ships gradually and successfully passed through the canal. Meanwhile, approximately 400 ships were still awaiting to pass through the Canal in the Red Sea, Mediterranean Sea and the Great Bitter Lakes.

One of the first questions to be asked about the serious Ever Given blockage incident is whether a similar event had happened before. Indeed it had - in 2017. Less than two months after it was launched, a vessel of similar size, the Orient Overseas Container Line vessel *OOCL Japan,* ran aground in the Suez Canal. Steering gear malfunctioned, the rudder went hard over, and caused the container ship to ground at around noon local time on 18 October 2017. The vessel experienced mechanical problems and because of that, the ship went off course and was grounded in the sands. The ship turned perpendicular to the shipping

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fairway before running aground. A fleet of tugs were deployed by Egyptian authorities and were able to refloat the ship from the sandy embankment within just a few hours of the grounding. The vessel suffered damage below the waterline to a tank, which required underwater repairs. The Maersk Mimi, which was following the container ship, was able fortunately to stop in time.

The loss consequences of a grounding lasting just a few hours were quite modest. However, had the vocabulary existed at the time, the question could have been raised: What are the downward counterfactuals? Resilience depends on being able to address the demands of near-miss disaster situations that turned for the worse. Exploration of downward counterfactuals following the OOCL Japan grounding would have increased risk awareness and preparedness for the subsequent Ever Given grounding. In the case of the Ever Given grounding, three specific notable downward counterfactuals should be considered:

- It was lucky that the blockage occurred at the end of March, because of the high Spring tide, associated with the full moon. With adverse timing, experts had predicted that the task of refloating the Ever Given might take weeks.
- The Ever Given had cut in front of the Maersk MV Denver in entering the Suez Canal. The ship behind almost hit the MV Denver. Any kind of collision would have compounded the engineering challenge of refloating the Ever Given.
- It was fortunate that the grounding occurred in March, which is not a busy time for maritime trade. By contrast, business disruption would have been much greater if it had happened in October, when European stores stock up for the important Christmas season.

With any multiple combination of these downward counterfactuals, the cascade of supply chain impacts of the Ever Given grounding would have been far more substantial and prolonged than the disruption of the global supply chain that actually materialised. Downward counterfactuals have the virtue of being rooted in actual historical events, and thus achieve an intrinsic credibility status that may be lacking in many arbitrary hypothetical scenarios.

A suite of extreme Suez Canal closure scenarios can always be proposed. For example, for any lengthy blockage of duration D days, a corresponding scenario can be hypothesised. However, it is insufficient for a scenario merely to be constructed; every such scenario needs a convincing and compelling narrative. For a highly unusual and extreme scenario, a narrative rooted in past experience may be essential for it to be accepted as plausible, rather than merely fanciful. Prior to its actual occurrence, the near-miss aircraft collision disaster on the taxiway at San Francisco airport on 7 July 2017, would hardly have passed the plausibility test. For a worst-case Suez Canal closure scenario, it is salutary to be

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reminded of the eight year closure in 1967 after the war between Israel and Egypt. But for this historical precedent, the notion that the Suez Canal might be closed for years would seem extremely implausible.

With regard to political ramifications, the Ever Given blockage has raised significant logistical hurdles to global infrastructure development, such as envisaged in the ambitious Chinese 'One Belt One Road' initiative. In this globalised world, many items are completed with components from multiple different countries. The delay caused by a Suez Canal blockage would affect manufacturing industry in multiple important ways. Since the delay would affect on-time delivery of components, potentially it might cause a serious component shortage. Although Ever Given was freed after only a few days, the cascading domino effect of the Suez Canal blockage is enormous, and its consequences would last for several years (Lee and Wong, 2021).

Good fortune may be mistaken for good judgement. Downward counterfactual thinking is an antidote to wishful thinking. The Suez Canal blockage would have lasted much longer had the Ever Given accident occurred further in the month from the high astronomical tide, and the supply chain failures would have been far more extensive had the accident occurred closer to the busy end-of-year holiday season. An obvious immediate lesson is that the Suez Canal needed to be expanded to accommodate the size of vessels. This lesson was acted upon by the Suez Canal Authority soon after the Ever Given accident. Another lesson from the Ever Given accident is that extra care and vigilance are needed in traversing the Suez Canal when there are strong winds. Important safety lessons can be learned not just from what happened, but also from what might have happened.

2. COUNTERFACTUAL ANALYSIS FOR SEVEN DESIGNATED SCENARIOS

Each of the seven designated historical disaster scenarios studied in WP2 constitutes a research laboratory for studying the key issues addressed within the CORE project. These historical scenarios span the entire world with COVID-19, and individual parts of Israel, Italy, UK, France, India and Japan. The size of the underlying hazard event, and the scale and footprint area of the overall loss, vary from one scenario to another, so diversifying the type of event considered. This is

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an illustrative exercise for these specific seven scenarios, which constitute a central thread linking the CORE work packages. Downward counterfactual analysis provides an innovative perspective on these designated scenarios. However, the downward counterfactual concept is universal, and is generally applicable.

As pointed out by Linkov et al. (2022), resilience can be viewed intrinsically as a risk-agnostic characteristic of a system. Whatever the hazard exposure, a system should have a high measure of resilience, such as a degree of redundancy. The archetype of a resilient system is a transport network with sufficient nodal links such that even if some links are broken (whatever the cause), a route still exists between any two nodes.

Even highly resilient systems may be vulnerable to extreme events such as associated with systemic risk. The use of downward counterfactuals provides an exploratory tool for identifying plausible extreme scenarios that might not otherwise have been considered. Among these plausible extreme scenarios are multi-risk scenarios, combining geohazards with human factors. These are considered in depth in report D4.5. By identifying downward counterfactual scenarios which expose gaps in resilience, risk awareness is raised, leading to opportunities for closing these resilience gaps.

WP4 focuses on three types of cascade that impact on security of supply and societal resilience: cascading events; cascading impact of disaster risk reduction decisions across sectors, and cascades through supply chain disruptions. The largest of the historical disaster scenarios, i.e. Japanese tsunami and COVID-19 pandemic, generate significant cascading phenomena. For the lesser historical events, loss impacts are smaller in scale and geographically more localised. However notable cascading phenomena can be generated from consideration of downward counterfactuals. This applies to the larger scenarios as well.

For each of the seven designated historical disaster scenarios studied in WP2, a methodical downward counterfactual search has been conducted to identify plausible pathways leading to greater human and economic losses as well as extensive societal disruption. These pathways define sequences of potential supply chain failures and cascading effects of the three different types, some of which may not have been previously appreciated as threats to societal resilience. Downward counterfactuals for the seven designated events are summarised as follows.

Wildfire: Fortunately, there were no casualties in the Jerusalem Hills forest fire of 15-19 August 2021, but 2,000 residents had to evacuate (Horovitz, 2021). However, the control of a wildfire in a very dry hilly pine forest is a highly precarious challenge, subject to vagaries of the weather. Counterfactually, there might

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have been a heatwave, as well as adverse winds thwarting efforts at limiting the fire spread, which might well have exceeded the control capacity of firefighters. The fire outbreaks might have been further exacerbated by acts of terrorist arson, such as historically have emanated from Gaza.

Earthquake: Preceded by several months of tremors, a large M 6.3 earthquake occurred in L'Aquila on 6 April 2009 (Jordan, 2013). Counterfactually, there might have been less prior regional seismic activity, and a larger earthquake main shock, with magnitude closer to the maximum regional seismological value. Both the number of casualties and extent of physical damage would have been higher. The supply shortage of skilled artisans for the reconstruction of old buildings would have created a narrow bottleneck in the recovery process (Alexander et al., 2013). This would have been delayed further by water supply restrictions from pipe failures.

Terrorist attack: The improvised explosive device detonated by Salman Abedi on 22 May 2017 was designed to maximise human injuries. Counterfactually, it might have been contaminated with some radiological material, making this a dirty bomb (Radiological Dispersion Device) scenario. The terrorist's mother was a nuclear scientist, so Salman would have been familiar with the basic elements of radiation science Salman Abedi may have learned about dirty bombs in Syria, from another English ISIS follower, Hamayan Tariq (Porter, 2018) . Because the Manchester Arena adjoins Victoria station, a major transport hub in Manchester, any release of radiological material would have been dispersed into the station, and potentially onto trains, which could have been vectors of low level radiological contamination in Manchester.

Industrial accident: Following closure due to COVID-19, a rise in temperature in a styrene tank at the LG Polymers plant in Venkatapuram, India, led to a leak of toxic styrene gas, which vented through a safety valve system on 7 May 2021 (Gargava, 2020). Counterfactually, had the safety valve system failed, the tank might have exploded under the pressure buildup, leading to a much bigger catastrophe with numerous casualties and long term health impacts in the area around the plant. The cascade of repercussions include a supply shortage of some polystyrene products.

Flash flood: The Aude region of France suffered extreme rainfall and subsequent flooding in October 2018, driven partly by the remnants of Hurricane Leslie (Perez, 2018). Counterfactually, yet more intense and persistent record rainfall, driven by a stronger Hurricane Leslie, might have triggered bridge and dam failures in the Aude region. The heightened demand for emergency flood rescue services might have led to a bottleneck in the supply of trained firefighters, and an increase in flood casualties.

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Tsunami: A great earthquake M9 offshore northeast Japan on 11 March 2011 generated a tsunami that far exceeded the design level of the tsunami defences for the Fukushima Dai'ichi nuclear power plant. (Dauer et al., 2011). Plant explosions led to a release of radioactivity. Counterfactually, a change in wind direction blowing the radioactivity towards Tokyo, rather than seawards, might have exposed a highly populated onland region to significant levels of radioactivity. A further downward counterfactual is that half of the reactor units might not have been offline for maintenance and would have suffered explosions doubling the release of radioactivity.

COVID-19: The multiple waves and variants of the coronavirus SARS-CoV-2 pandemic have emerged over several years from December 2019. Even though less lethal than SARS, a high level of COVID-19 asymptomatic transmission has thwarted efforts at controlling contagion through contact tracing and quarantine. Fortunately, the rollout of effective COVID-19 vaccines in 2021 has greatly helped to mitigate pandemic risk. But, counterfactually, such vaccines might not have been available to contain the pandemic. Indeed, BioNTech would not have been authorised commercially to develop an mRNA vaccine, had the pandemic emerged just two years earlier (Miller et al., 2022).

Vaccine development has been advancing steadily over the past two decades. Had the coronavirus pandemic struck two years earlier, there would have been a significant delay time before COVID-19 vaccine testing, production, and rollout. Lack of timely successful vaccine development would have greatly increased the global spread of the coronavirus pandemic, resulting in much higher numbers of hospitalisations and fatalities, as well as more lockdown disruption. With the alpha variant being much more transmissible than the original SARS-CoV-2, the demand on healthcare services would have been extremely high in winter 2020-2021, and there would have been major life-threatening supply bottlenecks in personal protective equipment, ventilators, as well as ICU staff in Spring 2021.

2.1 Israel Wildfire: 15 – 19 August 2021

The average August daily high temperature in Jerusalem is 29^{0}C, with 42^{0}C degrees being the highest recorded temperature. The daily temperature averages at a comfortable 23^{0}C. There was a heatwave in the first week of August 2021, with the daily temperature averaging in the range: 29^{0}C to 31^{0}C. In the following two weeks of August 2021, the daily temperature averages were in the normal range.

Overall, according to the Israel Meteorological Service, August 2021 was considerably warmer than average, and in comparison, with past years, it is

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ranked as fourth on record. After the first week, the weather became regular for summertime. In the latter part of the month, the weather was warmer than usual.

This moderate weather setting for mid-August 2021 contrasts with the extreme heatwave that occurred in Israel in May 2019, when there were more than a thousand fires over the Lag B'Omer Jewish bonfire holiday. On 23 May 2019, temperatures reached 43^0 to 45^0 C in many areas. The heatwave continued on 24 May 2019, becoming more intense in the Jordan Valley, the Dead Sea area, and the northern Arava with highs of 45^0 to 48^0 C.

Sunday, 15 August 2021, was an average hot summer day; dry but with strong winds. Increased concern over nature preservation has led to the substantial accumulation of biomass in Israel. Two welcome wet winters in 2018-2019 and 2019-2020 greatly increased forest vegetation. However, the dry and warm spring and summer 2021, with high night temperatures, resulted in extreme dryness of this vegetation. Buffer zones around communities would offer protection against forest fires. A good example is the protection for the Yad Vashem Holocaust memorial museum on Mount Herzl in Jerusalem. After the Mount Carmel fire disaster in 2010, which killed 44, a firefighting law in 2012 mandated the construction of buffer zones, but budgetary constraints have limited implementation.

At 3.03 pm on 15 August, 2021, the first report of fire came from a resident of Beit Meir, a small village in the pine forests west of Jerusalem. Pine forest fires are notoriously hard to control because hot pine cones travel large distances in the heat of a fire. A massive fire broke out near Beit Meir, a religious Moshav community nine miles west of Jerusalem, just off the Jerusalem-Tel Aviv highway.

Ten communities were evacuated, with thousands of residents in the Judean Hills ordered to leave their homes as a precaution. A fire storm was observed in Ramat Raziel, one of the communities, and houses were actually on fire in the evacuation process. Several people were treated for smoke inhalation. A plume of black smoke covered Jerusalem, and residents were advised to limit outdoor activity because of high pollution levels.

The Defence Minister and IDF Chief of Staff ordered the immediate deployment of firefighters, airborne rescue forces, including Search & Rescue Unit 669, and other Home Front Command fire services. A dozen firefighting planes and helicopters were deployed to support sixty to seventy teams of firefighters as they battled the blaze. It is recognised that there is a dire need to increase the squadron of firefighting aircraft. A meeting of the Israeli government security cabinet was interrupted due to the severity of the flames spreading through the forested Jerusalem Hills.

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It took some 1,500 firefighters working for three days to put out the fires, which may have been intentionally lit in several places. Israel is exposed to terrorist arson, particularly the Gaza border communities which are under assault from incendiary balloons and kites.

The outcome of the fire was that around 3,200 acres of forest burned – but this was less than the 5,000 acres initially feared by the Israel fire department. This was fortunate, because the Israel National Fire and Rescue Services were stretched to the limit. There were no fatalities, but the outcome might have been very different. The Eitanim psychiatric hospital was evacuated in time and escaped serious damage by accident. Thanks to the foresight of the hospital director, a firebreak had been cleared around the complex, giving rescuers time for evacuation. On 16 August, the second day of the fire, the Public Security Minister raised the issue of a nationwide Israel firebreak plan with the Prime Minister. There needs to be a substantial thinning of forests around residential communities.

2.1.1 Downward Counterfactual: Heatwave and Adverse winds

Forest fires in hilly areas are very difficult to control, because a firestorm can generate dynamically its own local weather. To a large extent, the feasibility of human control depends crucially on nature, specifically the key meteorological variables of temperature and wind strength and direction. Counterfactually, the heatwave in the first week of August 2021, might have happened two weeks later, when temperatures were normal for August. On Monday night, 16 August 2021, flames were moving eastward, posing a threat to communities in west Jerusalem. With sustained strong winds directed towards west Jerusalem, firefighting would have been an even greater struggle and potentially posed an urban threat.

As the fires spread rapidly in the Jerusalem Hills, a logistical bottleneck would form in both the supply of professional firefighters, and also associated firefighting airplane support. As it was, Israel turned to Greece and Cyprus for firefighting planes, having assisted Greece with its historic heatwave-driven forest fires in early August.

The following cascade of downward counterfactual consequences may then ensue:

- Destruction of village buildings in evacuated regions;
- The wildfire spread in the Jerusalem Hills may trigger a national crisis;
- The ensuing chaos may be exploited by terrorists in Gaza as an opportunity for arson and other acts of wanton destruction to make

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matters worse. Helium balloons and kites carrying containers of burning fuel from Gaza have caused hundreds of fires in Israel, burning thousands of hectares of forest and farmland;
- Israeli state retaliatory air strikes against military compounds, rocket launch sites and other terrorist targets in Gaza may escalate into another major military confrontation, breaking the ceasefire in May 2021.

In respect of disaster risk reduction decision-making in an era of climate change, a national programme of firebreak barrier forest development needs to be implemented. Furthermore, the national emergency services (fire, ambulance, police, military etc.) need to be well coordinated to ensure maximal delivery, at speed, of fire risk mitigation capability. With the historic Jerusalem Hills being the epicentre of the forest conflagration, tourism, hotel and leisure sectors of the Israeli economy would be significantly impacted.

2.2 The l'Aquila earthquake: April 2009

A moderate magnitude 6.3 earthquake struck l'Aquila city and province in central Italy at 3.32 in the morning (CET), on 6 April 2009. There were 308 deaths and 1,500 injuries of which 202 were serious (Alexander and Magni, 2013). About 100,000 buildings were severely damaged, including the regional hospital, and 67,000 were left homeless.

Before the M6.3 mainshock, there had been a prolonged sequence of foreshocks which caused alarm, and induced some people to leave their homes, or sleep on a couch near an exit. There was a gender imbalance: women were more fatalistic, and more likely to seek refuge at home as a place of safety. A limited degree of public seismic risk awareness mitigated the nocturnal casualty toll.

2.2.1 Downward Counterfactuals: Later Timing and Larger Earthquake

Counterfactually, a death toll several times greater might have resulted if the mainshock had occurred eight hours later, when the city centre, which was seriously damaged, would have been thronged with visitors (Alexander, 2010). This scenario would have been worse during the summer tourist season.

A further downward counterfactual is that the magnitude of the mainshock might have been greater. Paleoseismic investigations (Cinti et al., 2011) indicate the possibility of the occurrence of larger surface faulting earthquakes in the past (M>6.5) producing longer surface rupture and larger displacement. Such a greater event would have generated stronger and longer ground motion,

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resulting in more severely damaged buildings. The cost of the damage from the L'Aquila earthquake was estimated to be 16 billion Euros. If a maximal earthquake event had struck, the damage would have been substantially greater.

Allowing for inherent stochasticity in the casualty outcome, with 100,000 buildings severely damaged, it is plausible to envisage alternative realisations of the L'Aquila earthquake, which might have claimed as many as a thousand lives. Based on the actuality mortality statistics, the great majority (93%) would have been Italian by birth, with 65% being from L'Aquila province itself.

The political, societal and judicial fallout from the 6 April 2009 L'Aquila earthquake was widespread and far-reaching. If there had been as many as a thousand fatalities, there would have been a greater cascade of consequences, which might well have affected construction supply chains.

In the aftermath of the L'Aquila earthquake, a major source of employment was the construction and demolition industry, which attracted workers from all around. The challenge of construction bottlenecks due to a shortage of labour and building materials has been handled through reconstruction programs such as CASE (Complessi Antiseismici Sostenibili ed Ecocompatibile) and the smaller scale MAP (Moduli Abitaviti Provisori). However, one year after the earthquake, 5,000 remained in hotels, 15,000 in provisional housing, and 27,000 in rented accommodation (Contreras et al., 2014).

The lack of home disaster insurance, such as exists widely in a number of other European countries, places a heavy burden of responsibility on the Italian state to manage the recovery process in a fair, timely and efficient manner. In contrast with commercial insurers, who can settle claims promptly, government bureaucracy is inherently cumbersome and slows down the pace of development. Furthermore, citizens who have suffered loss are not customers in a business sense. The commercial concept of good customer service, and the obligation for efficient claims settlement, which are hallmarks of insurance companies, run counter to the primary civil service obligation to tax payers to scrutinise diligently all government expenditure.

After seven or eight years, the result in L'Aquila was a mixture of restored occupied and non-occupied buildings; buildings undergoing restoration; buildings buttressed but abandoned; buildings left to decay and collapse; and empty building plots (Alexander, 2019).

It is possible for centralised authoritarian states to coerce the national construction industry to speed reconstruction, even after massive devastation; this happened in China after the M8 May 2008 Wenchuan earthquake. But this is not possible in a democracy, where the voices of individual citizens in disaster

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areas must be heard. But even in Italy, the consent of homeowners or inhabitants was not gained in some demolition and shoring-up work (Imperiale and Vanclay, 2021).

2.2.2 Supply chain failure: Bottleneck in Skilled Artisans

With the designated downward counterfactual scenario, where the larger earthquake was more damaging over a wider geographical footprint, the ambition of building back better would be so very much harder to achieve. The additional damage caused by the larger earthquake would require more resources to rectify. More financial aid might be forthcoming from donors like EU, as well as disaster charities and NGOs. More construction materials can be trucked in from afar. But the primary logistical problem lies with finding additional reliable and trustworthy contractors.

Specialist construction skills are needed to protect Italian cultural heritage, and deal with substantial damage to historic buildings and old homes in a culturally sensitive manner, respectful of the occupants. Where buildings are partially damaged, insensitive shoring-up operations can cause additional excessive damage (Imperiale and Vanclay, 2021). The limited availability of experienced skilled artisans creates a constricted labour bottleneck, which can lead to a cascade of subsequent reconstruction problems. These are listed as follows:

- Scarcity of skilled artisans leads to demand price inflation and overcharging for labour;
- Excessive charging for labour leads to some work being done by unscrupulous contractors;
- The surging profits attainable in the distorted construction market of unbalanced supply and demand may attract organised crime;
- Infiltration by such contractors undermines the integrity of the reconstruction process;
- Inferior standards of rushed reconstruction increases building seismic vulnerability;
- Instead of building back better, some buildings may be built back worse.

Maintenance of critical infrastructure needs to be prioritised in the aftermath of a large earthquake. An important water pipe within the Gran Sasso Aqueduct failed in the L'Aquila earthquake because of the coseismic rupture of the Paganica Fault that crossed the pipe (Dolce and Bucco, 2015). For the downward counterfactual scenario, a more extensive rupture geometry might cause further water pipe breaks, impacting the broader integrity of the regional water supply system. It is essential for the resilience of the essential water supply system that an adequate number of pipeline technicians and engineers are trained and

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prepared to tackle a multiple pipe break situation, such as might arise under the downward counterfactual scenario.

In respect of disaster risk reduction decision-making, foresight is required to anticipate cascading impacts of infrastructure failure. Water supply breakdown and inadequate shelter for the homeless may have detrimental physical and psychological population health consequences, which aggravate the healthcare needs of those injured in the earthquake. However, even with a larger magnitude earthquake, the epicentre is too distant from Rome or any other large Italian city for the national economic impact to be significant.

2.3 The Manchester Terrorist Attack: May 2017

The largest city of northern England, Manchester, features significantly in the annals of UK terrorism. On 15 June 1996, the Irish Republican Army (IRA) detonated a 1,500 kg lorry bomb in the principal shopping centre. From this same Arndale shopping centre, Salman Abedi, a 22 year-old Mancunian of Libyan parentage, bought a rucksack on Friday, 19 May 2017. Shreds of this rucksack were found in the foyer of the Manchester Arena concert venue on the following Monday night, 22 May 2017. The rucksack had contained an improvised explosive device, assembled by Abedi in his Manchester apartment, and packed tightly with nails and bolts. The bomb detonation and shrapnel blast obliterated the terrorist, killed 22 others, and injured more than a hundred others. Most of the casualties were young fans of the American superstar singer Ariana Grande, who was performing on that night.

The foyer of the Manchester Arena adjoins the Manchester Victoria station, a key transport hub in the city, with both rail and tram links. Salman Abedi might have detonated his bomb within the station, or on a train, or in a store; instead, he chose the Manchester Arena concert venue. Terrorism is the language of being noticed. With the superstar, Ariana Grande, at this venue, it was the optimal terrorist target: a suicide bomber can only die once. The bomb explosion created carnage, but caused limited damage in the foyer. There was some structural damage to the Manchester Victoria station, which was closed for eight days for repairs, and the police investigation. The adjoining concert venue was closed until September, with scheduled concerts being cancelled or relocated to venues elsewhere.

2.3.1 Downward Counterfactual: Dirty Bomb Attack

Counterfactually, the outcome of the terrorist attack might have been far more disruptive. The British Security Service (MI5, 2007) has noted a potential UK dirty

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bomb plot. It is not necessary to have detailed scientific knowledge to construct such a bomb. As it happened, Salman Abedi's mother was a nuclear scientist, so the terrorist would have had the basic scientific knowledge to construct a Radiological Dispersal Device (RDD or dirty bomb). He was close to his mother, and called her shortly before his terrorist attack. Salman Abedi may have learned about dirty bombs when he was in Syria.

His brother, Hashem, who was subsequently convicted as an accomplice, could have assisted with procurement. He helped buy, stockpile and transport the components of his brother's bomb. The very real possibility of Jihadi access to radiological material was demonstrated by Ali Harbi Ali, who assassinated a UK member of parliament on 15 October 2021. Ali Harbi Ali, who also came from an African refugee family, had trained as a technician in the radiography department at a major London hospital, and would have been familiar with the hospital nuclear waste system. The plausibility of a dirty bomb attack is reflected in the seriousness with which the Manchester Fire Brigade treated a dirty bomb warning call on the night of 22 May, which could have been a supplementary factor in their much delayed response.

Although there has not, as yet, been a UK dirty bomb attack, there were fears that the 29 June 2007 Tiger Tiger nightclub propane car bomb attack in central London might have included a radiological element. One of the terrorists, Bilal Abdullah, was a hospital doctor in Glasgow, and might have had some access to radiological material. Fortunately, the car bomb did not detonate. Counterfactually, a detonation would have created a fireball engulfing the London night club, and hundreds in the nightclub might have perished, or suffered severe burns. Concern about radiological poisoning was front of mind for the Metropolitan police, because on 1 November 2006, the highly toxic Polonium-210 was used to poison Alexander Litvinenko, a former FSB agent, in a central London hotel. Counterfactually, there might have been a substantial number of collateral poisonings, and government crisis meetings were held to address this contingency.

A radiological dispersal device is recognised as a weapon of mass disruption, fear and panic, rather than a weapon of mass destruction, which a nuclear bomb would be. If Salman Abedi had included some radiological material with his improvised explosive device, this material would have been dispersed not just within the open Manchester Arena foyer, but also within the adjoining Manchester Victoria station, and also on some trains and trams passing through the station. In the early stage of a radiological emergency, extending from hours to days, the public should be evacuated or sheltered-in-place (Eraker, 2004). The intermediate stage of a radiological emergency would begin after the level of contamination and radiation exposure have been reliably measured. This could

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take some weeks. Late-phase cleanup would begin with the initiation of recovery actions designed to reduce radiation contamination to acceptable levels, and would terminate when such efforts are completed. This could take months.

The improvised explosive device detonated on 22 May 2017 closed the Manchester Arena concert venue for four months, and closed Manchester Victoria station for a week. This station closure led to the cancellation of some northern rail services, rerouting of others, and the use of replacement buses.

A dirty bomb attack could close the adjoining Manchester Victoria station not just for a number of days, but potentially for several months, depending on the residual degree of radioactive contamination. Important transport links affected would be to the northwestern towns of Liverpool, Blackpool, Wigan and Southport. Manchester Victoria is a major interchange for the Metrolink light rail system, which would be severely disrupted. This major transport hub closure would exacerbate mass public phobia about even minor levels of radiation, and could thus lead to a cascade of disruption in and around Manchester, England's second city:

- Partial lockdown of North Manchester, around Victoria station;
- Decontamination of local public venues, and key buildings;
- Cancellation of some major public events;
- Business interruption in areas of residual low level contamination;
- Decline in tourism, hotel leisure and service sectors across the northwest of England and beyond;
- Reduction in passenger flow at Manchester airport;
- Reduction in investments in the city, property price drop, company and individual bancruptcy;
- Reduction of exports from the UK, as buyers are worried to purchase radioactive products.

In respect of disaster risk reduction decision-making, evacuation and relocation decisions taken by households and businesses will have important knock-on consequences across the regional economy, and beyond at a national level. Depending on the amount of radiological material dispersed in a dirty bomb, there could be significant supply chain disruption.

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2.4 Styrene Gas Leak at LG Polymers Plant in Venkatapuram, India: May 2020

The LG polymers facility is situated at RR Venkatapuram Village of Visakhapatnam district, a densely populated area in Andhra Pradesh, India. When the plant was established in 1961, the site was on the outskirts of populated areas. This predates the Bhopal toxic gas leak disaster of December 1984, which reformed the siting of hazardous facilities in India. Prior to the Bhopal disaster, there had been multiple early warnings of leaks, which downward counterfactual analysis might have highlighted as highly dangerous and alarming.

Spread over 213 acres, LG polymers was involved in manufacturing polystyrene, (both general and high impact), expanded polystyrene (EPS), and engineered plastics. The South Korean subsidiary LG Chemicals took over the plant in 1997 and renamed it LG Polymers Ltd. As an example of the business development of production, EPS capacity doubled in the decade from 2004 to 2014.

LG Chemicals had little experience in monitoring and maintaining full tanks of styrene that were idled for long periods of time without operation (Gargava, 2020). Due to COVID-19, the plant was shut down on 24 March 2020. Preparations for a restart were made on 4 May 2020, with proposed resumption on 7 May. As a consequence of the shutdown, there was some polymerisation at ambient temperature of styrene to polystyrene. This is an exothermic process, leading to an increase in temperature. This further increased the rate of reaction, increasing the pressure further.

In the early hours of 7 May 2020, CCTV video captured the release of styrene gas from the top of the M6 tank through the flame arrestor vent and dip hatch vent. The M6 tank had 1830 tons of storage. The leaked tank was old and only had provision to measure the temperature at the bottom, where refrigeration is provided. Warning temperature sensors at the middle and top of the tank were missing.

At around 3.15am, the entire facility was engulfed in dense styrene vapours. The temperature in the M6 tank had been stable until 3am on 7 May, after which it started to rise exponentially. The peak temperature was 153.7^0 C., which is above the 145^0 C boiling point of styrene. The consequent rise in pressure resulted in uncontrolled release from the vents. Tank insulation prevented the heat generated from being dissipated to the atmosphere, which would have slowed the rise in pressure.

The released vapours spread beyond the factory boundary towards the west side due to the wind direction, and affected the residents of five nearby districts:

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Venkatapuram, Venkatadri Nagar, Nandamuri Nagar, Pydimamba colony, Kamparapalem, and BC and SC colony. Also impacted were Tailors Colony, Babuji Nagar, and Ajanta Park Colony. From an examination of damaged trees, the gas plume moved at a height of up to 20 feet from the ground towards the nearby settlements. Fumes were dispersed over 3km, and hundreds of people were hospitalised with breathing difficulties and nausea. A high exposure can lead to coma and irregular heartbeat. Some people exposed to the fumes were found lying on the ground, unconscious and semi-conscious. As a result of the self-polymerisation runaway reaction, 12 people and 22 animals died, and around 1000 of 3000 who were affected were hospitalised (Sivaraman et al., 2021). Soil contamination rendered unsafe the consumption of agriculture products for at least a year. A local evacuation zone was established around the site, with radius of about 3km to 4km.

The closure of the plant was a loss to the India polystyrene market, and caused unemployment in Venkatapuram village, some residents of which suffered from breathing difficulties and other symptoms associated with styrene gas exposure. Any relocation would be to a place outside residential areas. Initial government financial aid of Rs10,000 (€120) was made to each of 15,000 residents of five villages. The National Green Tribunal directed the LG polymers management to make Rs 50 crore (€6 million) initial deposit towards victim compensation (Pavan, 2020). The state government paid Rs 1 crore (€120,000) to the next of kin of those killed; Rs 1 million (€12,000) to those treated in hospital on ventilator support; and Rs25,000 (€300) to those who had less acute medical treatment (Devalla and Potnuru, 2021). This level of compensation is far less than would have been awarded if the plant owner had been American rather than South Korean.

2.4.1 Downward Counterfactual: Tank Rupture and Boiling Liquid Expanding Vapour Explosion

The styrene gas leak at the LG polymers plant in May 2020 led to a serious crisis. Thoughts turned to risk mitigation, and how the crisis might have been less severe. Yet, the crisis could have been very much worse. As the temperature rises, styrene starts vaporising, and pressure increases. The safety valve system enabled the styrene vapour to be vented into the atmosphere.

Counterfactually, the venting of the M6 might have failed. This specific failure scenario was considered in the official report on the styrene gas leak (Gargava, 2020), recognising that the build-up of pressure might have caused a catastrophic rupture of the tank, escalating to a catastrophic Boiling Liquid Expanding Vapour Explosion (BLEVE). Even with a moderate release of M6 tank

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contents, the massive fireball and explosion would have completely wrecked the plant, and caused widespread regional casualties and damage over many kilometres radius. Furthermore, styrene metabolites are genotoxic and can cause carcinogenic health effects. So the population living in a large area of many sq.km. around the plant would need to be screened regularly for cancer risk.

Beyond the regional impact, a catastrophic BLEVE event would generate a cascade of subsequent production issues and economic disruptions:

- Severe chemical pollution and high cleanup costs;
- Long term carcinogenic health effects;
- Major regional business disruption, and economic loss;
- Local shortfall of 80,000 tons per year of polystyrene from the LG Polymers plant, which might impact the local Indian market;
- Potential global impact on polystyrene production due to public safety fears and international regulatory safety checks and crackdowns on inadequate plant operational safety.
- Reduced polystyrene production could lead to supply chain disruption for products such as: beverage cups, packaging, high impact car parts etc..

Reusable plastic packaging for food can have environmental benefits over cardboard (Verghese et al., 2013). Expanded polystyrene (EPS) is 98% air, and is one of the lightest packaging materials. It has a lower carbon footprint than many other packaging materials, and is hygienic and safe. Thus a polystyrene supply chain bottleneck could adversely impact fresh food transportation, and increase food wastage.

A catastrophic BLEVE is a downward counterfactual that might have been realised if there had been a safety valve system failure in the M6 tank. Such a BLEVE would be highly destructive as well as dangerous to thousands living in the area around the site. Beyond the death and destruction wrought by a BLEVE, there would be significant local business disruption to polystyrene production, with consequent cascade supply chain impacts on other businesses using essential polystyrene products.

In respect of disaster risk reduction decision-making, preparedness for a catastrophic BLEVE is fraught with difficulty over the scale of the major response required to safeguard the local population as much as possible. Factors influencing decisions are the availability of means and infrastructure concerning fire fighting, transportation, communication, health care, shelters and personal protective equipment. Other organisational measures include the level of training of the population. This is a sensitive environmental safety issue, because of the understandable community apprehension associated with such training.

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Regardless of the combination of protective actions to be implemented in the area of concern, the challenge is inherently complex: multiple criteria must be considered related to the health consequences for the population and socioeconomic factors (Georgiadou et al., 2010). A reasonable estimate of the subsequent supply chain disruption can be found as a function of the optimally selected criteria.

2.5 Aude Flash Flood, France: October 2018

In southeastern France, the Mediterranean coast is regularly affected by heavy precipitation events. On 14-15 October 2018, in the Aude department, a quasi-stationary mesoscale convective system produced up to about 300mm of rain in 11 hours. According to Météo France, three months rain fell in just a few hours. The rain was produced by remnants of Hurricane Leslie, which had made landfall in Portugal on 13 October as a Category 1 Hurricane.

Viewed at a synoptic scale, the former Hurricane Leslie was involved in the formation of a Mediterranean surface low that channelled unstable air towards the coast. The location of the exceptional precipitation over the Aude department was the result of convection focusing west of the quasi-stationary cold front, and downwind of the Albera Massif and the Corbières Massif (Caumont et al., 2018).

Heavy precipitation events are common in coastal regions bordering the Mediterranean, and regularly cause flash floods with tragic consequences, as the catchment areas are small and therefore react very quickly to very heavy rainfall. The most extreme events may be due to the stationary nature of the precipitation or its long duration. In mid-October 2018, the Aude river rose to a height of 7 metres, the highest since 1891.

In the Aude region, 39% of residents live in flood-prone areas. Carcassone received 160mm to 180mm of rainfall within five hours, and the water level in the city rose 8 metres during that period. At least 14 people died because of the flash flood, mainly in the town of Villegailhenc, Aude, where a small bridge collapsed and was under water. An elderly nun was swept to her death when rising waters destroyed a nunnery in the village of Villardonnel, north of Carcassone. Injuries numbered 75.

Flash floods, which came overnight while many were sleeping, amplified the loss of life, and hampered the emergency response. The floods swamped a number of towns and villages around Carcassone, leaving a trail of overturned cars, damaged roads and collapsed houses. Police were stationed on bridges, only allowing emergency vehicles to cross. Schools were closed, and people were

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instructed to stay at home. One of the properties flooded was a brand new multi-million Euro hospital that had been built in a flood zone. The financial cost of damage in the Aude region was estimated at €230 million.

In the town of Trèbes, 7km east of Carcasssone, the river level rose eight metres in five hours. The resilience of local citizens to deal with the flooding was strained because it was only seven months after the tragic terrorist murder of selfless police hero Arnaud Beltrame in a Trèbes supermarket, which was a highly traumatic event for the town's people. Although there is no hazard connection between a terrorist attack and heavy rainfall, an effective disaster recovery process is dependent on the strength of community morale, which is a multi-risk function. Two shocks in quick succession is a daunting psychological challenge for any local community to withstand.

2.5.1 Downward Counterfactual: More Intense Rainfall

The storm was triggered by the collision of warm and humid air from the Mediterranean with colder air around the Massif Central. This weather pattern occurs just a few times per year, but there are indications, according to Météo France, that the frequency and severity are increasing. This suggests the downward counterfactual that the rainfall might have been even more intense and prolonged, with the influence of a stronger Hurricane Leslie. An increase in extreme precipitation events is expected for northwestern Mediterranean watersheds under climate change (Colmet-Daage et al., 2018).

In the area of Pezens, the population of around 1,800 were evacuated due to fears that a nearby dam could burst. Upstream of Pezens are several dams, such as Cenne-Monestiés, in the commune of Saissac. By luck, the sluice gates of one of the local dams had been opened the previous day for maintenance work (Perez, 2018). As a consequence, Le Fresquel river catchment was almost dry. Counterfactually, more intense and prolonged rainfall might have triggered a dam failure. Without the good fortune associated with the timely scheduling of maintenance work, the regional flooding might have been much worse than it turned out.

On 14-15 October, helicopters and 700 firefighters helped with the rescue operations, particularly in the floodplain of the Aude River. Another key component of the disaster response effort was the maintenance of the regional drinking water supply. Veolia (2018) supplies 40% of the 227,000 population of the Aude Department with water. During the flood, a hundred staff were mobilised to maintain a continuous and potable water supply. In the worst affected area around Carcasonne, the Barthes drinking water production plant, which was

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partially flooded, was brought back on line. The plant at Cuxac-Cabardès treats 10,000 cu.m. of water per day for 50,000 inhabitants.

Under the downward counterfactual scenario, a cascade of problems impacting population health and safety might have unfolded:

- A large number of inaccessible roads, some blocked by bridge failure, would have prevented emergency teams from reaching trapped people in good time.
- There might have been a dam breach, if maintenance work had not been carried out.
- Shortage of helicopters would have left some people stranded precariously on roofs, without assurance of prompt escape.
- Lack of an adequate supply of firefighters trained in flood rescue would have put in danger many lives in flooded towns, such as Carcassone with a population of 45,000.
- The Veolia plant at Cuxac-Cabardès might have been seriously flooded, and not brought back on line; compromising the purity of the regional drinking water supply.
- Attention to the rescue operations postponed a French government reshuffle, prompted by the resignation of the interior minister, Gerard Collomb, several weeks earlier. A much worse flood outcome might have had a broader political impact, if there was some attribution of blame over the degree of unpreparedness or mismanagement of the flood disaster.

Flood resilience and disaster preparedness requires that critical infrastructure such as bridges and dams are maintained to the required functional level. The availability of rescue helicopters should be reviewed for adequacy in meeting the demand of occasional extreme events. To increase disaster preparedness, there should be additional training of firefighters in emergency flood rescue.

In respect of disaster risk reduction decision-making, planning for potential dam and bridge failures requires coordination across multiple sectors of the regional economy. The better the planning, the greater will be the community resilience.

2.6 The Japanese Earthquake and Tsunami : March 2011

At 2.46pm on Friday, 11 March 2011, a great magnitude 9.0 earthquake occurred offshore northern Japan, with an epicentre 130 km east of Sendai on the east coast of Honshu. The ground motion automatically triggered shutdowns of several nuclear power facilities along the northeast coast of Honshu. Although each of these nuclear facilities experienced some damage, shutdown procedures

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were able to achieve and maintain a safe, cold shutdown condition in all plants – except for those at Fukushima Dai'ichi.

Fukushima Dai'ichi units 1, 2 and 3 were operating at the time of the earthquake and consequent tsunami. Units 4, 5 and 6 had previously been taken offline for inspection and planned maintenance. The plants had been modified in 2002 with a seawall designed to withstand a tsunami with a height of 5.7m. But this was less than half the unprecedented wave height of 14 to 15m of the tsunami which arrived within an hour of the earthquake. The prime reason for this disparity was that the maximum magnitude had been significantly underestimated by Japanese seismologists on the basis of the age of the subduction zone to be 8.2, which is far less than 9.0.

The massive flooding that ensued disabled critical equipment, including all six external power supply sources and on-site backup power emergency diesel generators. The power loss resulted in loss of coolant to each of the reactors 1, 2 and 3, and associated spent-fuel pools. As the facility experienced a significant loss of cooling capabilities, the pressures within the primary containment vessels rose beyond design limits, and plant operators started primary containment venting to prevent extensive damage to the reactor, and a possible large-scale environmental release of radioactive material.

In the afternoon of 12 March, a hydrogen explosion occurred at the top of the unit 1 building, severely damaging the roof and walls of the top floor. On 14 March, unit 3 also experienced a large hydrogen explosion, damaging the upper portion of the building. On 15 March, unit 2 experienced an explosion. These three hydrogen explosions not only released a significant amount of radioactivity into the environment, but also impeded emergency work and attempts to provide active cooling. Counterfactually, there might have been additional hydrogen explosions at the other reactors 4, 5 and 6, had they not been offline. As it was, on 17 March, one electrical generator at unit 6 was restored to operation, and external power was returned to units 5 and 6. The facility was unable to maintain adequate cooling of the spent-fuel pools in units 1 to 4. Overheating of the unit 4 pool led to a hydrogen explosion which caused significant damage to the upper floors of the reactor building, and the release of additional radioactivity.

The prevailing wind in Japan blows from the west, and would have carried most of the radioactivity east over the Pacific Ocean. However, as shown in Figure 1, there was significant deposition to the northwest, and an additional pathway to the southwest. To control public exposure, an evacuation zone of 20km was established, with a shelter-in-place zone of 30km. Early protective actions taken by Japanese authorities mitigated the public risk from radioactive iodine and caesium.

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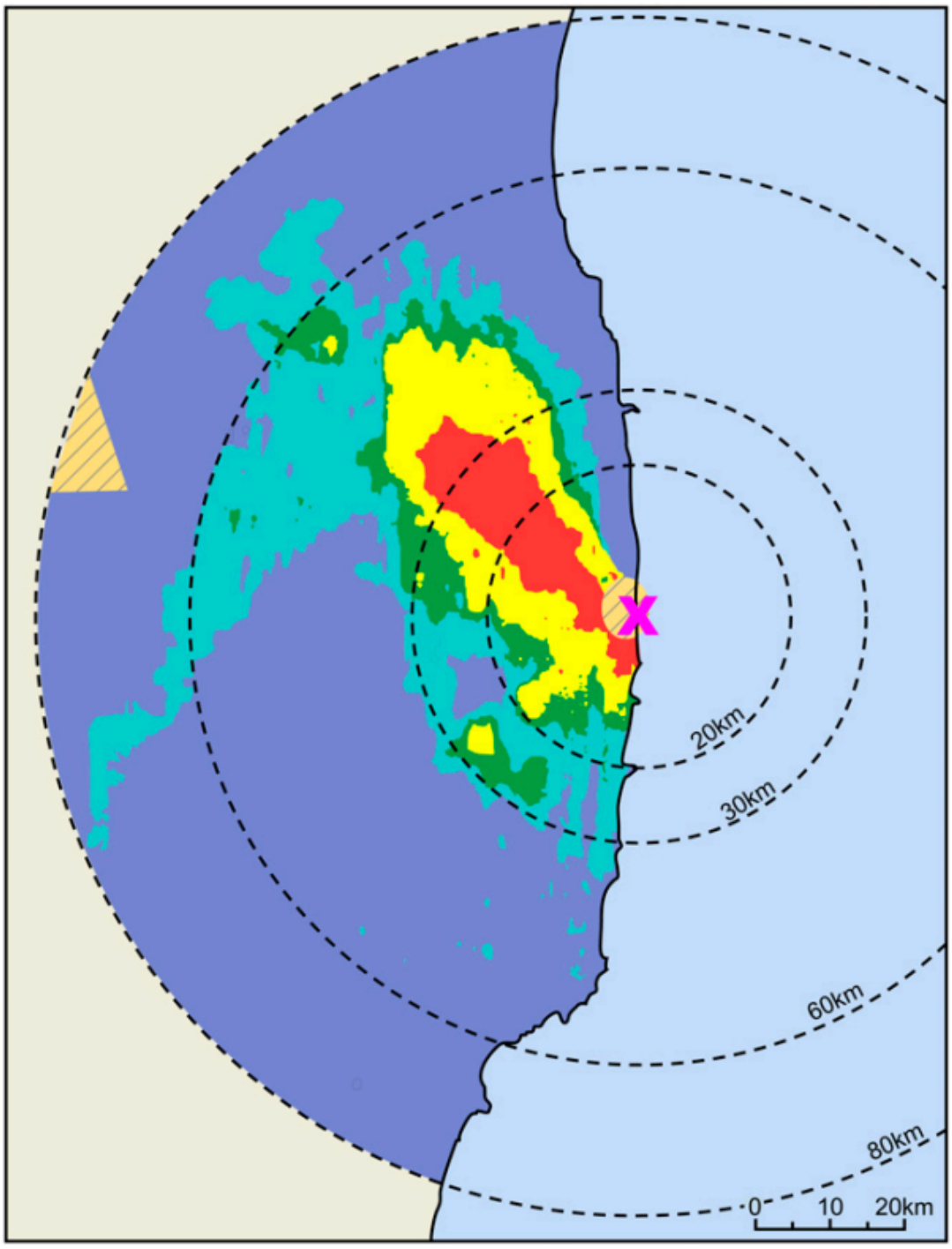

Figure 1 - Geographic distribution of radioactive caesium fission products after the Fukushima Daiichi nuclear accident, based on aerial monitoring. In MBq/m2: Zone red 3-30; yellow 1-3; green 0.6-1; light blue-green 0.3-0.6; darker blue <0.3 (From Dauer et al. (2011))

Despite their huge impact on coastal areas, the M9 earthquake and tsunami impacts were largely regional. Industrial production for the whole of Japan declined by 15% in April 2011, but was back to its pre-earthquake growth rate a

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year later (Carvalho et al., 2021). Even though infrastructure across northeast Japan was severely affected by the M9 earthquake and tsunami, pre-earthquake levels of activity were largely restored in a few weeks, with the obvious exception of electricity supply because of nuclear plant outages.

Figure 2 - Time evolution of nuclear fallout from the Fukushima Dai'ichi nuclear accident.

2.6.1 Downward Counterfactuals: Units 4-6 Online and Wind Direction Towards Tokyo

With all industrial facilities, there are occasional periods of maintenance, which are generally kept as short as possible to minimise loss of production. It was fortunate that units 4, 5 and 6 were offline at the time of the earthquake and tsunami. Counterfactually, had they been operational, there would have been pressure build-up and hydrogen explosions, (as with units 1, 2 and 3), which might have doubled the release of radioactivity.

A further downward counterfactual is the wind direction. As shown in Figure 2, the wind direction was favourable in blowing radioactive material out into the Pacific Ocean. But had the winds been less favourable directed, the consequences could have been more serious than Chernobyl (Butler, 2013). In particular, had the winds been directed southwards towards Tokyo, the consequences would have been very different. Even if the radiological fallout in the Tokyo metropolitan area were well below the threshold dosage for personal injury, widespread fear might take hold and cause panic among citizens, leading to significant self-evacuation and substantial prolonged economic disruption.

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The bitter memory of the fallout from Hiroshima in 1945 is deeply imprinted in the Japanese psyche.

In the event of a radiological accident threatening Tokyo, the decision-making process of civil authorities, as well as households and corporations, would involve a complex cascade of mitigating defensive actions, which would impact the entire Japanese national economy, and disrupt the more fragile supply chains. One of the key decisions is whether foreign visitors are advised by their national governments to leave Tokyo. The UK government sought the advice of scientific experts on this contingency in March 2011 (Grimes et al., 2014). In Japan itself, consideration was given to the need for evacuation of Tokyo, if the situation worsened, (Japan Atomic Energy Commission, 2011).

2.7 COVID-19 Pandemic

Before the emergence of SARS in 2003, there were two coronaviruses known to infect humans, both of which were mild, causing cold-like symptoms. Coronaviruses were known to infect animals as well. The switching of virus hosts from animals to humans has been driven by the opportunities provided by the human consumption of bushmeat, live animal markets and environmental degradation. SARS emerged in 2003 via civet cats from bat populations in China. MERS emerged in 2012 from camel herds in Saudi Arabia. Neither of these coronaviruses led to a pandemic, although they both had high mortality rates. However, for both SARS and MERS, a counterfactual analysis would have warned of a coronavirus pandemic, and highlighted the need for global preparedness to increase resilience. One possible counterfactual MERS pandemic scenario, which was constructed after the MERS outbreak in South Korea, has been outlined by Woo and Johnson (2023).

With the opportunities for coronavirus host-switching increasing with size of human population and meat consumption in Southeast Asia, it was unsurprising that SARS-CoV-2 emerged from China, at the end of 2019, giving rise to the disease known as COVID-19. Although the case fatality rate was much lower than the 10% of SARS, which emerged in 2003, those infected with SARS were not contagious if they had no symptoms of illness. In contrast, those infected with SARS-CoV-2 can infect others, even if completely asymptomatic – which about one-third have been. The large amount of asymptomatic transmission has rendered COVID-19 disease control very much harder than SARS, for which diligent contact tracing was highly effective, even though the coronavirus was much more deadly.

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In some countries, e.g. New Zealand, South Korea, Taiwan etc., mass coronavirus testing, diligent contact tracing, and publicly compliant quarantine regulations, were able to contain the spread of COVID-19 without the enforcement of draconian social distancing measures, such as sustained school and business closures. However, for most countries, the spread of the coronavirus could not be contained except at the high social and economic cost of multiple lockdowns. These lockdowns were necessary to prevent hospital resources, notably intensive care facilities, from being unable to cope with the admission of more very sick patients.

For these countries, relief from a cycle of lockdowns was provided eventually by the progressive rollout of effective vaccines. These were developed much more rapidly than hitherto in pharmaceutical history. At the outset of the pandemic, the prospect of an effective vaccine progressing through rigorous drug trials within several years was generally considered to be exceedingly remote.

2.7.1 Downward Counterfactual: COVID-19 Emerges Two Years Earlier

Of the COVID-19 vaccines under development, a number were not particularly effective. In particular, the vaccine development programmes of the big pharmaceutical companies GSK, Merck and Sanofi have not turned out successful. Fortunately, some have been. The two most remarkably successful and effective vaccines have been those based on the radical new mRNA technology, developed by Pfizer-BioNTech and Moderna. The key innovation is that mRNA contains the code for cells to produce the spike protein that the coronavirus SARS-CoV-2 uses to enter cells. It has taken decades of research for mRNA technology to be ready for mass vaccination (Dolgin, 2021). One of the crucial steps was to modify mRNA so as make it non-inflammatory. The mRNA modification technology was subsequently licensed to BioNTech and Moderna. Counterfactually, most likely, none of the research programmes would have been able to achieve the very high degree of success necessary to make a major difference to the outcome of the pandemic.

According to Ugur Sahin, CEO of BioNTech, if the coronavirus outbreak had happened just two years earlier, BioNTech's board would not have considered the idea of building a vaccine (Miller et al., 2022). BioNTech's prime focus and corporate commitment was on cancer rather than infectious disease. Furthermore, it was only in July 2018 that Moderna opened its large manufacturing plant in Norwood, Mass., which has since been expanded to boost its COVID-19 vaccine production (Dolgin 2019). With many hazards, there is a substantial degree of chance in event occurrence, and just a change in the date when a hazard event strikes can be a notable downward counterfactual. The emergence of SARS-CoV-2 from an animal spillover in China might well have

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happened at least several years earlier. The fact that the animal pathway to the emergence of SARS-CoV-2 is still unclear, even after three years, is a measure of the significant uncertainty over timing.

As it happened, from the start of COVID-19 vaccination roll-out to 25 November 2021, as many as 470,000 lives had been saved among those aged 60 and over across the WHO European region. Through early adoption of a commercial risk-weighted vaccine procurement strategy, UK was ahead internationally in rolling out vaccines in early 2021. Because of the early UK national procurement and adoption of vaccines, this counterfactual analysis focuses on UK experience.

On 14 September 2021, ahead of the Autumn pandemic wave, when there were already 134,000 UK deaths and 8 million confirmed cases, England's Deputy Chief Medical Officer asserted that vaccines had already saved 112,000 lives in UK and averted 24 million cases of COVID-19. This counterfactual assessment of lives saved and cases averted is important for public health management to ensure optimal use of resources. The vaccines have been highly effective at lowering hospitalisation and death rates. However, they have not been so effective at preventing infection or the spread of contagion. Nevertheless, many millions of cases have been averted through the vaccine rollout.

Not only have many millions of cases been averted, but a major healthcare supply chain crisis was averted as well. With the emergence of the much more transmissible alpha variant in December 2020, there were 4000 new UK patient admissions daily at the start of 2021, according to UK official government statistics. This was a time of general UK lockdown, with maximum social distancing, including work at home instructions. If the demand for hospital admission had increased substantially, in the absence of vaccination, some sick patients would have been denied the urgent hospital care needed, and the death count would have risen sharply.

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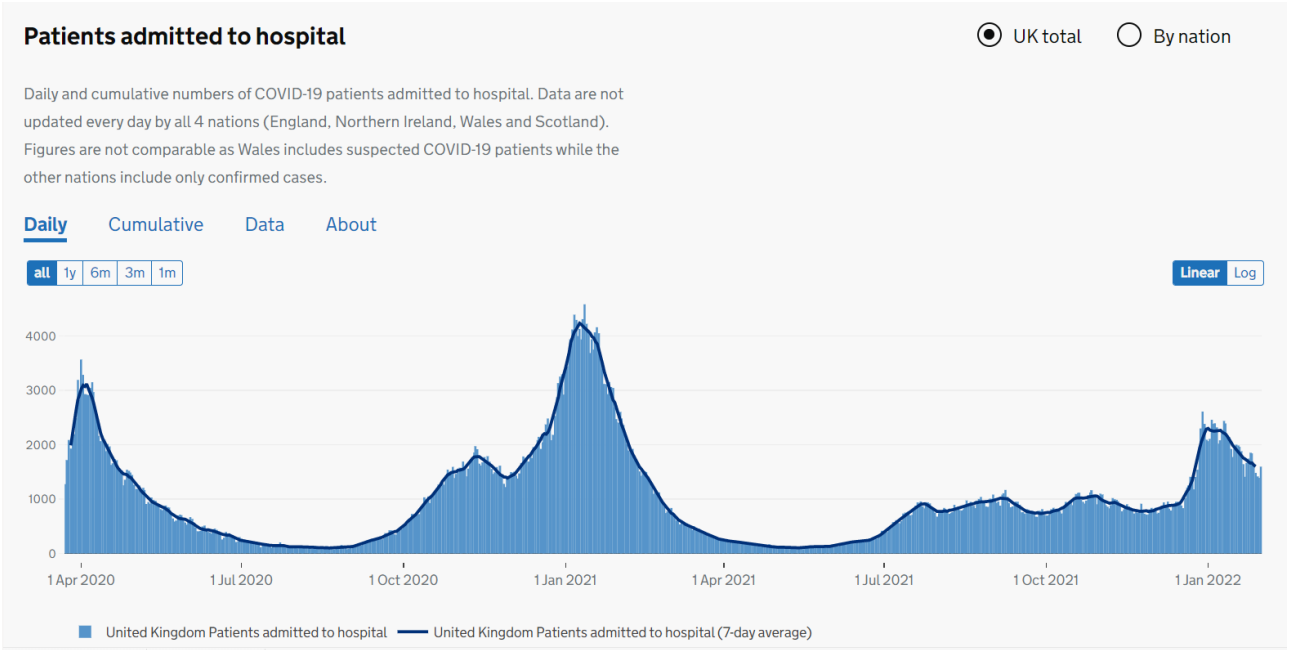

Figure 3 - Graph of patients admitted to hospital daily in UK during the pandemic (Our World in Data).

As can be seen in Figure 3, there was a large spike in daily UK hospitalizations in January 2021. The previous month, on 8 December 2020, the first Pfizer-BioNTech jab was given in UK; the start of a population rollout. Counterfactually, in the absence of any vaccine available then, and with the alpha variant being about a half more transmissible than the original coronavirus, the demand on healthcare services would have been much worse than in the first wave; as in the 1918 influenza pandemic.

This could have led to healthcare supply chain bottlenecks, such as over personal protective equipment, and absenteeism among COVID-infected medical staff. The economic impact would have been enormous because of the drastic need to curb the exponentially rising infection rate, through closing down public transport and all venues of public assembly, including factories and offices. This dire situation of mass business shutdown would have caused sustained supply chain disruption, way beyond what has developed with the variants of COVID-19 in the three years 2020 to 2022.

As a guide to the supply chain chaos without the highly effective mRNA vaccines, consider China, where the local vaccines are only 2/3 as effective as the mRNA vaccines. Following the relaxation of the zero-COVID policy in China on 7 December 2022, COVID-19 spread rapidly. At least Pfizer's Paxlovid antiviral pills have been approved in China to help mitigate the prevalence of severe illness.

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With sickness rates exceeding 50%, many factories and logistics companies started their New Year holiday early. Some factories had to slow production for lack of components and truck drivers to make deliveries. With supply chain and industrial operations requiring a combination of physical labour and technological talent, the distinctions between blue and white collar staff are diminishing. Accordingly, it is harder to find skilled people to replace sick staff at short notice.

2.8 Multi-Hazard Combinations

WP4.5 specifically addresses multi-hazard risk issues. An obvious source of downward counterfactuals is the compounding of one hazard event with another hazard event. Supply chains need to be resilient against compound events. This is challenging, because compound events can have nonlinearly increasing loss consequences: the loss from combined events A and B can be much larger than just A + B. The finite resources available to deal with several events would limit emergency response to mitigate losses. More worrying, tipping points may be reached which can result in exponentially higher losses.

Exploration of downward counterfactuals of historical events is an insightful exercise in lateral thinking about emerging compound disasters. Psychologists who have studied human response to events observe that most counterfactual thoughts about the past are upward, i.e. how things might have been better. However, resilience against surprising compound events is gained by contemplating downward counterfactuals – how things might have been worse. A round-table exercise has been suggested (Woo, 2019) to elicit downward counterfactuals that might be surprising otherwise. Human error is one human factor that can compound the loss of a hazard event to a significant degree. Malicious action, such as vandalism or terrorism, is another.

Preparatory to the WP4.5 work package section, some multi-hazard downward counterfactuals are considered here.

- Sunday, 15 August 2021, was an average hot summer day in the Jerusalem Hills; dry but with strong winds. The wildfire would have been more intense had there been a heatwave, as there had been in May 2019, when there was major Israel wildfire loss. Given the finite resources available for firefighting, a substantial increase in the intensity of the wildfire might have threatened the capability of firefighters to prevent the fire from spreading to urban areas. Arson is another human factor exacerbating fire loss.

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- The L'Aquila, Italy, earthquake was preceded by a protracted sequence of regional tremors, which had an impact on the population seismic risk perception. Another sequence of seismic energy release, involving a larger main shock, might have been more detrimental to population safety, and resulted in much more building and infrastructure damage. The challenge of reconstruction would have resulted in substantial delays in building back better, thus straining societal resilience.

- The Manchester Arena terrorist attack on 22 May 2017 was preceded by a terrorist attack on Parliament at Westminster, London, on 22 March 2017, and was followed by a terrorist attack on London Bridge on 3 June 2017. All the attacks were inspired by ISIS. It is known that Salman Abedi's younger brother Hashem was an accomplice to his suicide bombing. Counterfactually, he might have accompanied his brother as a second suicide bomber, which would have greatly exacerbated the casualty loss. Fear of multiple terrorists in the Manchester Arena was one of the causes of the delayed response of the emergency services. Following the Paris terrorist attacks of 13 November 2015, special counter-terrorism focus was on marauding armed terrorists.

- The accident at the LG polymers plant in India followed reopening after the COVID-19 shutdown. Had the coronavirus shutdown been even more prolonged, as might well have happened given the severity of the pandemic in India, it is possible that more than one styrene tank might have developed the overheating problem that forced the M6 tank gas venting. This would not only have increased the volume of gas leakage, it would have increased the chance of a BLEVE through pressure valve failure.

- The flash flood in the Aude region in France was induced by heavy rainfall induced by Hurricane Leslie. Intensification of Hurricane Leslie would have increased the rainfall further, and elevated the possibility of dam failure. Any such failure would have resulted in a massive increase in the loss consequences.

- The Japan tsunami followed a great M9 earthquake. The combination of earthquake and tsunami is one of the most significant and well-established geological multi-hazards. For the first time, a tsunami subsequently caused a nuclear accident, when the sea wall was overtopped at the Fukushima Dai'ichi nuclear power plant. This is the archetypal example of how

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compound events, i.e. earthquake and tsunami, can trigger a massive catastrophe – a major nuclear accident.

The restrictions required for containing the spread of COVID-19 hampered efforts to respond to natural disasters during the pandemic period 2020-2021. Emergency fire and ambulance services were limited by COVID-19 in their ability to respond promptly. Crucially, intensive care units were at their maximum capacity, so would have struggled to cope with trauma injuries from another major hazard event. In respect of repairing damage from natural hazards, lockdowns prevented timely action to fix roofs, so exacerbating loss from water intrusion into buildings.

3. SECURITY OF SUPPLY

It is important to identify and analyse the pathways of potential cascading effects that impact the security of supply and societal resilience. This is addressed in Task 4.3, but it also aligns with the objectives outlined in Task 4.1, emphasizing the need to map causes of detrimental impacts and establish connections between events, sectors, and supply chain disruptions. This mapping is based on a methodology of exploring downward counterfactuals of historical events.

Through being founded on actual historical events, this approach avoids the speculation associated with more abstract scenario conjecture. However, being scenario-based, it is possible to identify explicit connections between events, sectors and supply chain disruptions. By exploring alternative realisations of historical events, it is possible to discover plausible modes of supply chain disruptions that might have threatened security of supply.

Societal resilience in any country is enhanced through security of supply. Under most business circumstances, security of supply is taken for granted as being the natural outcome of a well-managed free market economy, where extra product demand is met by extra product supply. However, supply bottlenecks can arise if key suppliers are impacted by rare extreme events. This is exemplified in 2022 in USA by Abbott Nutrition, which was forced to shut down its Michigan baby formula plant by FDA because of bacterial infection. The shut-down duration was about four months, and caused a US nationwide shortage in baby formula. A shortage of a basic product like baby formula might be anticipated in an authoritarian state with centralised planning and market control, but not in the United States with its free market economy. However, at the national and EU level there are state organisations that are looking at security of supply of critical products, with countries such as Finland and Sweden leading in this area.

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However, the adoption of efficiency maximisation policies can lead to shortages. Short-term efficiency maximisation may be achieved through just-in-time management, which minimises resource redundancy and duplication. But resilience is gained through just-in-case management, where additional resources are allocated, in advance with foresight, to deal with a hypothetical rare extreme risk. There are additional inventory costs, as well as opportunity costs in tying up capital in inventory. Spoilage of inventory can lead to excessive wastage.

Downward counterfactual analysis supports just-in-case management by identifying circumstances where the availability of additional inventory would be desirable in case of an extreme event, which may have no historical precedent. Such events may otherwise be known as Black Swans (Taleb, 2007). The insights gained from downward counterfactual analysis do depend on the availability of a reasonably substantial historical event catalogue. With the passage of time, event catalogues are progressively expanding with the occurrence of events, so facilitating downward counterfactual analysis.

For public services like healthcare and energy supply, where resilience is paramount, the just-in-case strategy can lead to better protection against downside risk. Thus, the provision of surplus hospital capacity in case of a health emergency, such as a pandemic or terrorist attack, would be prudent, as would the stockpiling of antivirals and personal protective equipment, even if they may not have a long shelf-life.

Another critical government decision is over security of supply of energy. This issue has been highlighted in 2022 with the electricity supply shortages and price rises following the Russian invasion of Ukraine on 24 February 2022. Resilience against such an extreme event requires diversification of energy supply. Achieving resilience can be politically unpopular at the time of decision-making. Thus, the decision by Prime Minister Blair in 2006 to proceed with the development of new UK nuclear power plants, when this was politically very unpopular in the British Labour Party and within environmental groups, was influenced by the need for energy security resilience against Russian hostility towards Ukraine. Counterfactually, without this unpopular initiative, UK would have been highly dependent on Russian gas in 2022.

3.1 Prepositioning and Training

The prepositioning of resources and training of crisis personnel are factors which can make an important contribution to crisis resilience. In considering the amount of resources to be prepositioned, or the number of personnel to be trained, a basic benchmark is provided by past events. Assessing prepositioning

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requirements is easier if there has been a recent major event. In circumstances where the largest historical catalogued event is far from being extreme, a downward counterfactual version of it can be taken as a basis for prepositioning and training. Table top exercises exploring downward counterfactuals can be undertaken for training purposes.

The 2009 influenza pandemic was highly contagious but mild; the lethality rate was comparable with seasonal flu. The UK government stockpiling of the antiviral Tamiflu was criticised in the media as wasteful, and generous to the pharmaceutical company Roche. However, this prepositioning of medical resources would have been justified by downward counterfactual analysis.

Except for the catastrophic earthquake/tsunami in Japan in 2011, and the global COVID-19 catastrophe, downward counterfactual versions of the other designated scenarios inform prepositioning and training requirements.

In reimagining the past, one of the most obvious downward counterfactuals is a shift in geographical footprint of the historical event towards a larger metropolitan region. As and when a hazard event strikes an area of comparatively low population, this may be considered as a near-miss, and counterfactual thought should be given to an alternative strike at an adjacent metropolitan area of high population.

On a national level, prepositioning and training may be established to meet the potential demands of a strike on a principal metropolitan region. For specific high-cost resources that are deployed seldomly, the pooling of resources between neighbouring countries is an efficient way of dealing with a spike in demand. Mutual assistance agreements between countries is a cost-effective form of prepositioning, which might be supplemented by some cross-border training exercises.

Jerusalem wildfire

In the case of the Jerusalem wildfire, around 3,200 acres of forest burned – but this was less than the 5,000 acres initially feared by the Israel fire department. This was fortunate, because the Israel National Fire and Rescue Services were stretched to the limit. There were no fatalities, but the outcome might have been very different. A dozen fire fighting planes and helicopters were deployed to support sixty to seventy teams of firefighters as they battled the blaze. It is recognised that there is a dire need to increase the squadron of firefighting aircraft. The scale of the increase in firefighting capability should recognise the following downward counterfactual. The heatwave in the first week of August 2021, might have happened two weeks later, when temperatures were normal for August. On Monday night, 16 August 2021, flames were moving eastward,

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posing a threat to communities in west Jerusalem. With sustained strong winds directed towards west Jerusalem, firefighting would have been an even greater struggle and potentially posed an urban threat.

The fire safety of Jerusalem warrants the prepositioning and training of adequate firefighting resources to meet the challenge of such a counterfactual scenario, which is of Israeli national significance. Just as Israel has provided air support for fighting Greek and Cypriot wildfires, so Israel was assisted by Greek and Cypriot firefighting services in dealing with the August 2021 Jerusalem wildfire. Prepositioning and training for a future major wildfire in Israel includes the collaborative contribution from neighbours also exposed to wildfire risk. In the previous month, July 2021, the worst wildfire in the Cypriot record was contained with assistance from Greece, Israel, Italy and UK.

L'Aquila earthquake

Traumatic as the L'Aquila earthquake was for the local population and the civic authorities, it might have been worse. A possible downward counterfactual scenario considers a larger earthquake, with a more extensive rupture geometry causing further water pipe breaks, and impacting the broader integrity of the regional water supply system. It is essential for the resilience of the water supply system that an adequate number of pipeline technicians and engineers are trained and prepared to tackle a multiple pipe break situation, such as might arise under the downward counterfactual scenario. Foresight is required to anticipate cascading impacts of infrastructure failure. Water supply breakdown and inadequate shelter for the homeless may have detrimental physical and psychological population health consequences, which aggravate the healthcare needs of those injured in the earthquake. Another post-event concern is the supply of skilled builders to repair damaged historic buildings. An increase in the training of skilled artisans and builders would boost the disaster resilience of the region, in speeding up the reconstruction process.

With a population of about 70,000, L'Aquila is a comparatively small town. National Italian earthquake resilience is measured by the potential societal impact of a large urban earthquake, where the population affected might be an order of magnitude larger. Coordinated prepositioning for a large national earthquake disaster should have corresponding resilience benefits for all seismic regions in Italy.

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Manchester bombing

An individual operative, Salman Abedi, with a backpack bomb at the Manchester Arena caused the worst casualty toll for a terrorist attack in Northwest England (Saunders, 2021). But it might have been worse. Salman Abedi's mother was a nuclear scientist, and he might have had the capability and resources to develop a radiological dispersal device, known as a dirty bomb.

Although there has not, as yet, been a UK dirty bomb attack, there were fears that the 29 June 2007 Tiger Tiger nightclub propane car bomb attack in central London might have included a radiological element. A radiological dispersal device is recognised as a weapon of mass disruption, fear and panic, rather than a weapon of mass destruction, which a nuclear bomb would be. If Salman Abedi had included some radiological material with his improvised explosive device on 22 May 2017, this material would have been dispersed not just within the open Manchester Arena foyer, but but also within the adjoining Manchester Victoria station, and also on some trains and trams passing through the station.

The capability to deliver rapid medical treatment for those receiving a significant dose of radiation would improve societal resilience against a dirty bomb attack. The elimination of radionuclides out of the body can be enhanced by the administration of decorporation agents, lowering the radiological dose absorbed. Therapeutic efficacy decreases if treatment initiation is delayed after incorporation and in most cases there is a time slot of hours to several days to achieve optimal results, depending on the radionuclide. Therefore, it seems medically prudent to start treatment already if radionuclide incorporation is only suspected until a substantial intake is excluded by measurement.

In the case of a large number of victims who are potentially internally contaminated, as can be expected after a dirty bomb attack, this urgent approach strategy requires a large number of antidote daily doses that must be available in stock. The Manchester bombing downward counterfactual provides a cogent argument for such prepositioning for an extreme terrorist attack. This prepositioning would be nationwide, irrespective of the UK urban location of any dirty bomb attack. Given the propensity for terrorist targeting to focus on major cities with name recognition, these should be prioritised for prepositioning of medical supplies.

The rationale for prepositioning radionuclide decorporation agents has been enhanced in 2022 by the hostile political environment with Russia, which deployed a radiological poison in London in November 2006 to kill Alexander Litvinenko, who had recently become a UK citizen. As with the later Novichok attack in Salisbury in March 2018, there was complete Kremlin denial of responsibility, which might have resulted in many collateral UK casualties. Such

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deception is reflected in the false flag accusation of Ukrainian development of dirty bombs.

The international crisis following the Russian invasion of Ukraine on 24 February 2022 is the most acute since the Cuban missile crisis of 1962, when the chance of a nuclear disaster was estimated by President Kennedy as high as between one-half and one-third. The threat level is well below this crisis level, but London has been explicitly threatened because of UK military support for the defence of Ukraine. The nuclear threat level is significant enough to justify prepositioning of radionuclide decorporation agents. Following President Putin's threats to use nuclear weapons in Ukraine, fears of reprisals have led to panic sales of potassium iodide tablets in Russian pharmacies.

Venkatapuram BLEVE event

The styrene gas leak from the LG plant in Venkatapuram in May 2020 was a severe regional industrial accident. However, the consequences might have been far worse and global in extent. Counterfactually, there might have been a Boiling Liquid Expanding Vapour Explosion. Beyond just the regional impact, a catastrophic BLEVE event would generate a cascade of subsequent production issues and economic disruptions. A catastrophic BLEVE is a downward counterfactual that might have been realised if there had been a safety valve system failure in the M6 tank. Such a BLEVE would be highly destructive as well as dangerous to thousands living in the area around the site. Beyond the death and destruction wrought by a BLEVE, there would be significant business disruption to polystyrene production, with consequent cascade supply chain impacts on other businesses using essential polystyrene products. Preparedness for a catastrophic BLEVE is fraught with difficulty over the scale of the major response required to safeguard the local population as much as possible. Factors influencing prepositioning decisions are the availability of means and infrastructure concerning fire fighting, transportation, communication, health care, shelters and personal protective equipment. Other organisational measures include the level of training of the population. This is a sensitive environmental safety issue, because of the understandable community apprehension associated with such training.

On an international level, the loss of the LG plant at Venkatapuram might possibly have impacted the supply of styrene products, which are used in many industries, notably the automobile industry. Following the styrene leak in May 2020, corporations around the world using styrene products would have been prudent to check their styrene supplier, and preposition alternative suppliers for the downward counterfactual where LG could not meet its supplier commitments.

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Aude flood

The Aude flood was a notable regional flood event. The consequences would have been worse if there had been a dam failure. Flood resilience and disaster preparedness require that critical infrastructure such as bridges and dams are maintained to the required functional level. A serious downward counterfactual for many major flood events is dam failure, which might have catastrophic consequences for the downstream population. Dam failures are rare; but further training of reservoir and dam engineers is warranted.

The availability of rescue helicopters should be reviewed for adequacy in meeting the demand of occasional extreme events. To increase disaster preparedness, there should be additional training of firefighters in emergency flood rescue. The prepositioning of a larger squadron of rescue helicopters would minimise the prospect of casualties in the event of a larger flood than occurred in October 2018. This would require additional resources for training helicopter pilots. Lessons such as this can be learned from every significant regional event. The Aude region is only one of many flood-prone regions of France. Accordingly, flood protection in the Aude region needs to be viewed more broadly within the national context of flood protection in France, and especially in the Paris-Ile de France region.

A 2018 OECD report on this region remarked that a better risk knowledge and a more widespread risk culture are increasingly evident. While remarkable efforts have been made to reinforce critical network resilience, flood risks are not always taken into account in French urban management and development policies. Regarding structural risk prevention measures, OECD emphasised the need to maintain protection and storage infrastructures even while investment choices for new infrastructure projects are slow in materialising. Since the effects of all these prevention measures will only be felt in the long term, OECD stressed the importance of improving crisis management capacities and resources, and accelerating procedures for ensuring business and public service continuity.

Japan earthquake and tsunami

The great Japanese earthquake and tsunami was a rare extreme event that exposed some serious supply chain failures, and demonstrated the need to consider just-in-case strategies as alternatives to just-in-time management. A classic case study is the production complex for xirallic metallic paint at the Merck plant at Onahama, Fukushima prefecture, which was shut down on 11 March 2011. This was the only plant in the world manufacturing xirallic. Repair work began on 4 April 2011. Six weeks later, in early June 2011, the xirallic plant was reopened, and full capacity was restored at the end of June 2011. But there was a serious production delay on car models with metallic paint using xirallic.

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Prepositioning for this bottleneck has involved Merck constructing another xirallic plant in Darmstadt, Germany. The Fukushima warehouse storing xirallic was inaccessible after the earthquake and tsunami. Prepositioning additional quantities of xirallic would contribute to increasing resilience against supply chain failure.

Elsewhere in the auto industry, Toyota, Suzuki and Nissan ceased production completely. Even Mazda, located far to the south near Hiroshima, closed down, unable to keep its plants running without critical parts sourced from suppliers closer to the damage zone. Bottlenecks were created by the earthquake impact on Renesas plants making automotive micro-controllers. Renesas plant locations are shown in Figure 4 below, with the sites of damage highlighted in orange. A key lesson from the poor experience of Renesas is that the standardisation of components across plants facilitates the continuity of production, when some plants are damaged and out of production. Such standardisation is a facet of just-in-case prepositioning in advance of an extreme external hazard.

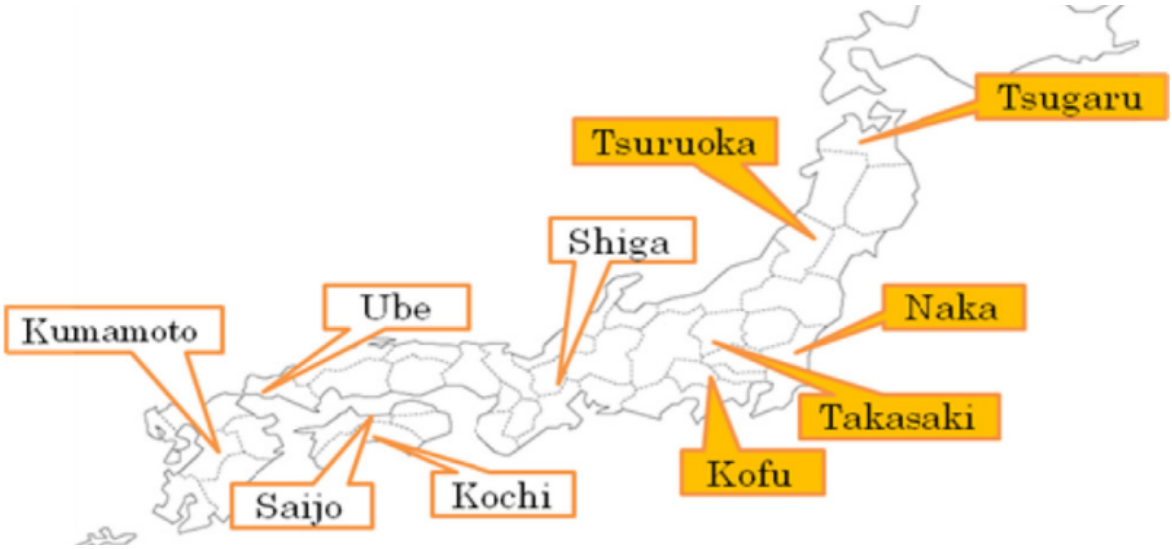

Figure 4 - Renesas plants in Japan. Damaged plants are indicated in orange callout boxes.

Aerospace industries were also impacted by the Japanese earthquake and tsunami. Boeing retained collaboration with Japanese suppliers. Five Japanese companies, including Mitsubishi, produced structural parts comprising 21% of the 777, and 35% of the 787. For corporations with a global supply chain, resilience requires a detailed understanding of supplier risk, and the availability of alternative sources of supply if needed.

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As an illustration of the supply chain challenges faced by Japanese companies which themselves actually suffered minimal damage to their own plants, the operations of Kenki construction were halted after two weeks due to incapacitated suppliers. Integrated circuit components were in short supply, and there was an electricity power shortage. It took an actual disaster to reveal the vulnerability of semiconductor supply chains on the northeast coast of Japan. Prepositioning must be risk-informed of the identification of supply chain vulnerabilities.

COVID-19

The coronavirus pandemic exposed numerous supply chain failures, which have taken a heavy toll in human lives, and must be avoided for the next pandemic. Since the great influenza pandemic of 1918, the subsequent flu pandemics of 1957, 1968 and 2009 have been comparatively moderate in scale, and the SARS and MERS coronaviruses were controlled quite rapidly. Downward counterfactual thinking about these near-misses might have encouraged more prepositioning and further training for healthcare workers, so mitigating losses from COVID-19. At the time of the 1957 and 1968 pandemics, intensive care treatment for severe cases of influenza was limited, so there was no imperative to introduce lockdowns to reduce pressure on hospitals. Reimagining these flu pandemics would have raised awareness of potential pandemic economic disruption.

An important step towards enhancing future global resilience was the July 2021 G7 Carbis Bay, Cornwall, declaration. This has recognised the value of having a rapid response framework for pandemic tools ready to deploy in the event of a pandemic. Prepositioning for COVID-19 was inadequate in every country, although those countries, such as South Korea and Taiwan, which had previous pandemic experience of SARS and MERS fared much better in industrial scale testing. The training of medical staff to deal with a major pandemic crisis was also inadequate for purpose.

The G7 will explore potential future solutions for a sustainable network of international health organisations, with the WHO coordinating, poised to kick-start global collaboration, such as advance commitment facilities for vaccines, therapeutics and diagnostics, when faced with another pandemic. The G7 will also support and strengthen rapid response networks and mechanisms, where needed, such as the Global Outbreak Alert and Response Network (GOARN). The G7 will explore the establishment of regional hubs for manufacturing vaccines, therapeutics, diagnostics and personal protective equipment to strengthen resilience in the face of the next pandemic threat.

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The prospect of a vaccine being available for deployment within 100 days of the emergence of a pandemic influenza virus has come closer with the publication (Arevalo et al., 2022) of significant progress in the development of a universal flu vaccine. The mRNA of all 20 known influenza types were put into a single vaccine. Each strain has been delivered in a 2.5 microgram dose. All together a vaccine shot includes a 50 microgram dose of mRNA. This is about the standard dose for existing quadrivalent flu vaccines, accommodating just four flu types. Further along the research horizon is the prospect of a universal coronavirus vaccine.

Tested as effective on mice and ferrets, human trials of the universal flu vaccine are still awaited. However, with an approximate 4% annual chance of emergence of a pandemic flu vaccine, there is a high chance, in excess of 80%, that there will be a universal flu vaccine before the next flu pandemic arises. With COVID-19 casting a long shadow over the global economy for years to come, another major pandemic shock in the near future would cause widespread economic hardship. Already, there have been several near-miss avian influenza pandemics this century, H5N1 in 2005 and H7N9 in 2013. Counterfactual analysis of these emerging infectious disease outbreaks underlines the importance of rapid development of a universal flu vaccine.

3.2 Framework Contracts and Supplier Management

A framework is an agreement with suppliers to establish terms governing contracts that may be awarded during the life of an agreement. It is a general term for agreements setting out terms and conditions for making specific purchases. Framework contracts are useful for establishing an understanding of what is expected of suppliers. Framework contracts can be used when the contracting authority needs to develop a strategic relationship with the supply chain over a long period. There are efficiency gains to be made in a strategic relationship involving high budget expenditure.

However, as shown in Figure 5 below, strategic partnering framework contracts are associated with higher risk than term contracts. One factor in the higher risk of strategic partnering compared with project partnering is the possibility of an extreme event occurring haphazardly in the future which can disrupt the supply chain. Both the Japan earthquake and COVID-19 illustrate the pitfalls of strategic partnering when a major disaster strikes. Beyond these two designated case studies, downward counterfactual analysis provides insight into the potential for supply chain disruption detrimental to strategic partnering. For any strategic partnership, scenarios need to be identified that would result in substantial business interruption. Failure to do this adequately can lead to the kind of business dislocation witnessed with COVID-19.

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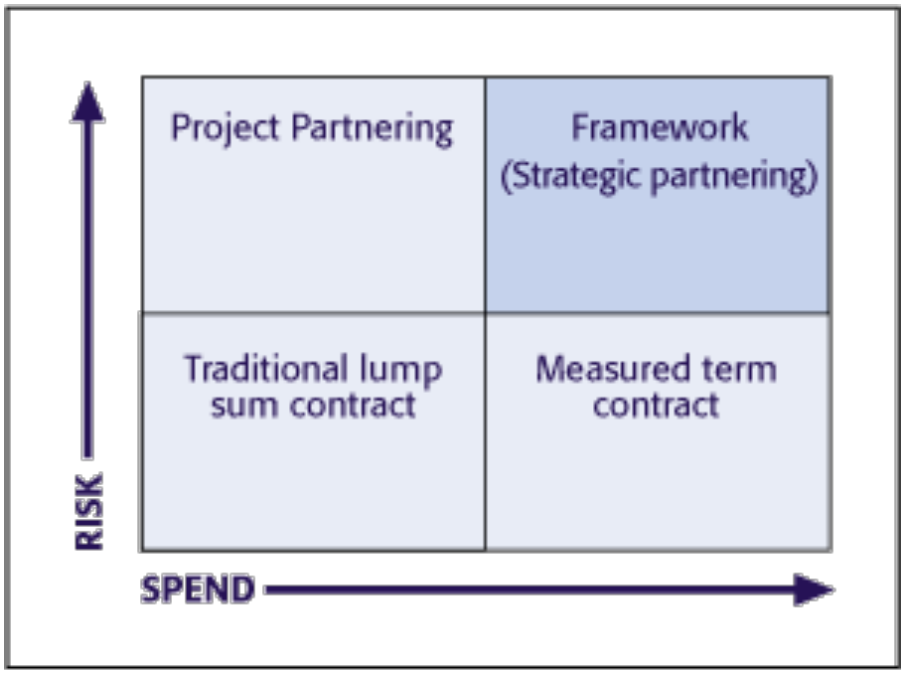

Figure 5 - Risk and spend matrix associated with contracts.

One of the largest global strategic partnerships has been between Apple and Foxconn for the manufacture of half of the world's iPhones. Following an outbreak of COVID-19 in mid-October 2022, the Foxconn plant in Zhengzhou, known as iPhone city, went into lockdown, with 200,000 workers inside. Panic and worker exodus hit Apple's supply chains ahead of the busy holiday season. A letter from the Foxconn founder to the Chinese authorities warned of the disruption to global supply chains, and the national zero-COVID policy was relaxed on 7 December 2022.

New Zealand enforced a zero-COVID policy until it had to be abandoned due to the spread of the highly contagious omicron variant. In its place, an effective mass vaccination policy was introduced, with the Pfizer-BioNTech vaccine being preferred. This is more effective than the Chinese COVID-19 vaccines. The huge uncertainty over the effectiveness of vaccines under development has highlighted the importance of risk-weighted contracts for vaccine supply.

An instructive example of contracts for specific projects, and effective supplier management during a time of crisis, is the UK procurement of COVID-19 vaccines in 2020. This was done outside the usual National Health Service bureaucracy by Kate Bingham, who was an experienced biotech expert astute in commercial contracts with pharmaceutical companies. A Harvard MBA, she led a specialist team to negotiate the security of vaccine supply on behalf of the UK government. Crucially, these contracts were negotiated at significant risk when there was

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absolutely no guarantee that any vaccine would be proven safe and effective. Accordingly, risk was diversified through a carefully selected portfolio of vaccines under development. Such entrepreneurial supplier management requires either the hiring of capable private sector finance professionals, like Kate Bingham, and/or the training of less experienced government officials.

Compared with the undoubted success of UK vaccine procurement, personal protective equipment for frontline medical staff, and PCR mass testing capability were both notable UK procurement failures. In both cases, there was a tight bottleneck in the supply available by foreign manufacturers for export to UK, which added to the UK healthcare burden. In some instances, UK National Health Service units were bidding against each other for urgently needed PPE. In April 2020, an initiative was developed to buy from UK PPE manufacturers. Beyond PPE, prepositioning for a future pandemic crisis has involved developing a UK network of testing laboratories.

3.3 Conclusions

The global crises in healthcare and energy establish security of supply as a high priority for both government and commercial organisations. Scenario analysis is a valuable tool in assessing security of supply. Seven designated historical scenarios for the CORE project span a broad range of natural and man-made hazards. Yet what was seen in these scenarios is not all there was. Through exploring downward counterfactuals of these designated scenarios, new insights can be gained and lessons learned for societal resilience.

Consideration of downward counterfactuals adds weight to the just-in-case strategy over the just-in-time approach to make society more resilient against external shocks. It is increasingly recognised that the biggest internal roadblock to a more effective supply chain is the use of supply chain metrics that are too focused on efficiency at the expense of flexibility. Just-in-time management drives efficiency at the expense of diversification.

A question that policy-makers and decision-makers may rightly ask is over evidence that the exploration of downward counterfactuals would make a significant difference as a strategic foresight tool. Looking back in time, what if downward counterfactuals had been used? Such evidence is amply provided just within the past decade. Suppose that the exploration of downward counterfactuals had been adopted as a strategic foresight tool in Europe in 2014.

In February and March 2014, Russia invaded and subsequently annexed Ukraine. A downward counterfactual risk analysis at that time would have identified

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further Russian encroachment into Ukrainian territory as a potential threat. Indeed, Mearsheimer (2014) did warn of the Kremlin's red line over the political status of Ukraine. His article in the respected and influential U.S. Foreign Affairs journal captured the intent of Kremlin policy and was even referenced by the Russian Ministry of Foreign Affairs. Inability to understand the political thinking of an adversary is a form of political autism. Agreement amongst members of our own side can lead to Groupthink.

Of course, nobody can predict any specific decision that President Putin might have made. But this is unnecessary. All risk management decisions are made under uncertainty. Whatever the aggressive intentions of President Putin, this 2014 counterfactual analysis would have advised against excessive European reliance on Russian gas, and promoted more diversification of European energy supply. With the Russian annexation of Ukraine coming only three years after the Fukushima nuclear accident, with subsequent downscaling of reliance on nuclear power, a revision of European energy policy in 2014 would have been prudent. As of March 2011, a quarter of Germany's electricity came from nuclear power. Even a partial brake on the closure of German nuclear plants would have enhanced energy supply resilience.

One year later, a serious outbreak of Middle East Respiratory Syndrome (MERS) developed in Seoul, with the return of a South Korean businessman from the Gulf. Fortunately, the reproduction number of this emerging coronavirus did not quite attain the threshold for pandemic spread. 2015 was also the year of the mass migration of Syrian refugees to Germany and other parts of Europe. Throughout history, pandemics and plagues have been driven by massive population movements. The plague of Justinian and the Black Death are prime examples (Piret and Bolvin, 2021). Other examples are described by Schama (2023). (The combination of an emerging coronavirus pandemic with the Syrian War would have been a highly dangerous multi-hazard scenario. Using a meteorological metaphor, this would have been a perfect storm.

A downward counterfactual scenario named MERS+, developed by Woo et al. (2017), considered a more contagious variant of MERS emerging in 2015, and spreading through Europe and around the world, driven by the large flux of more than a million Syrian refugees. At the time, according to the chief medical officer, there was some UK groupthink that dangerous emerging infectious diseases would be restricted to developing countries. Attention to this downward counterfactual in 2017 would have motivated and expedited preparedness measures such as the development of a coronavirus vaccine, which was slowed due to lack of funding, as well as research into antiviral coronavirus treatments. Along with a reassessment of the status of intensive care facilities, upgrading of testing laboratories and stockpiling of personal protective equipment, European

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preparedness for an emerging coronavirus like COVID-19 might have been substantially enhanced.

Looking towards the future, the downward counterfactual analyses of seven designated scenarios have collectively identified the following key avenues to explore to promote European resilience against extreme events:

- Increased resources for responding rapidly to fighting wildfires
- Review of the seismic vulnerability of water supply and other lifelines
- Review of the seismic design of critical industrial installations
- More frequent engineering checks on dam safety
- Warehousing of materials for dealing with radiological contamination, and health impacts
- Increased preparedness for a leak of toxic gas, and a large chemical explosion
- Commitment to the 2021 G7 Carbis Bay Declaration on pandemic preparedness

Out of all the possible scenarios to populate a societal risk matrix, downward counterfactuals are especially relevant because they correspond to scenarios linked with actual historical events. Kahneman and Varey (1990) argue that events that could have happened are cognitively distinct from events that almost happened and are likely to be processed differently. Specifically, they argue that whereas events that almost happened can trigger counterfactual thinking, which should induce learning, near-misses that could have happened may not trigger this learning.

Research shows that those with counterfactual mindsets use more analytical decision-making processes, and can be motivated to learn from past events (Dillon et al., 2008). If people consciously note that they were quite close to a failure outcome and that they personally could have acted to avoid it, people may learn to alter future behaviour.

However, all near-misses do not necessarily evoke counterfactual thought, and not all counterfactual thoughts yield learning. People can be primed with counterfactuals to think more critically of near-miss events (Roese, 1994) and counterfactual priming should promote more risk-averse decisions. In the context of near-misses, managers and decision-makers might engage more in downward counterfactual thinking about near-misses, and so enhance societal resilience.

As a salutary lesson in strategic foresight for decision-makers, both the Russian annexation of Crimea in 2014, and the Seoul MERS outbreak in 2015 might well

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have led to disastrous military and coronavirus outcomes of the kind that eventually developed in 2022 and 2019.

Whenever a significant hazard event occurs, such as these two, the following question can be raised: what are the downward counterfactuals? This is not a question that is customary in the wake of a significant hazard event, but it should be. More commonly, questions are raised over what mitigating action might have lowered the risk of event occurrence. But by asking unusual questions, surprising discoveries can be made. The development of a methodology to uncover surprising events is a key objective of Task 4.1. Another searching question is the following. Why didn't this happen before? Most disasters have either happened before; nearly happened before; or might have happened before. This is true of the coronavirus pandemic, which might have evolved as a variant of SARS in 2003, or as a variant of the Middle East Respiratory Syndrome (MERS) in 2012.

In testimony to the COVID-19 UK government public inquiry in June 2023, the former Prime Minister, David Cameron (2023), admitted to UK groupthink in that there was UK government planning for only one type of pandemic, namely an influenza pandemic. Yet, two years before COVID-19 emerged, the counterfactual risk analysis report of Woo et al. (2017) had warned of a coronavirus pandemic.

This key lesson concludes this report into downward counterfactual analysis by demonstrating the practical applicability of this methodology at the highest level of civic authority public concern. It fulfills the objective of Task 4.1 in providing a discourse on this methodology, and demonstrating its practical societal value.

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