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Definitions and taxonomy for High Impact Low Probability (HILP) and outlier events

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A B S T R A C T

High Impact Low Probability events (HILPs), often referred to as outliers, are becoming more important in disaster management because they are linked to complex risks and tipping points in interconnected systems. Recent events, such as the cascading effects of the coronavirus pandemic, rising uncertainties from global geopolitical instability, and successive and concurrent extremes driven by climate change, underscore the limitations of relying solely on severe but plausible scenarios for risk practitioners and policymakers. Despite the critical need to integrate HILPs into risk assessment models and emergency preparedness, the field is fragmented, with inconsistent definitions and methodologies.

We present a perspective developed under the HORIZON AGILE project (AGnostic risk management for high Impact Low probability Events), which introduces two comprehensive definitions of HILPs and a taxonomy designed to enhance risk assessment, resilience analysis, and crisis management. We provide a validated scientific definition for the academic community and an operational definition tailored for practitioners and stakeholders. Additionally, our taxonomy offers a structured framework to address outlier events that often fall below traditional risk thresholds, ensuring that low-probability, high-impact scenarios with cascading and concurrent dynamics are effectively integrated into risk registers, legislation, and standards development.

This study shows how this approach improves methods like stress testing and scenario modelling, especially for the loss of critical services. This empowers policymakers, practitioners, and stakeholders to include more scenarios in their strategies, enhancing resilience and preparedness.

1. Introduction

Disaster risk reduction has recently entered 'uncharted territory' with more uncertainties, complexity, and sudden changes in operations. Evolving hazard patterns, such as those influenced by climate change, combine with new system vulnerabilities, triggering cascading scenarios [1]. The interaction between multiple risks, including successive and concurrent events, and the changing

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interdependencies in critical infrastructure networks, complicates the assessment and prediction of how impacts propagate [2,3]. On the one hand, extreme scenarios may be more frequent than previously assumed, necessitating a new understanding of their drivers and possible expectations [4]. For example, this is the case natural hazards triggering critical infrastructure and supply chain disruptions, such the eruption of Eyjafjallajökull eruption (2010) and the consequent effects on air transport, or the recombination of environmental stressors such as the Wildfire in Hawaii (2023).

On the other hand, Perrow's concept of "normal accidents" explains that tightly coupled, complex systems—such as chemical plants or nuclear power stations—are inherently prone to failures from unanticipated interactions between criticalities, including failures in regulation, ignored warnings, and human errors [5]. In other words, even systems with robust safety mechanisms can trigger unpredictable cascading failures [5], as exemplified by the Exxon Valdez oil spill in the Gulf of Mexico (1989),the meltdown of the Fukushima Daiichi Nuclear Power Station in Japan (2011), or more recent events such as the Suez canal blockage (2021). As Lee et al. [6] highlight, incorporating the costs of externalities and reviewing risk-assessment practices to address worst-case scenarios should be a priority, requiring coordinated efforts between governments, industries, and the scientific community.

Policymakers increasingly recognise the need to prepare for complex scenarios, acknowledging that predicting all the details of specific threats, the extent of disruption, or the likelihood of a scenario is often nearly impossible [7,8]. Recent work has highlighted that hazard-specific resilience approaches are increasingly inadequate, as they rely on predefined scenarios that fail to capture the complexity of cascading failures, emergent threats, and environmental interdependencies—prompting a shift toward risk-agnostic strategies that prioritise adaptability across a broader range of disruptions [33]. Freddi et al. [9] argue that innovative frameworks are critical for addressing cascading impacts of multiple hazards by accounting for temporal variability and region-specific interdependencies between physical damage and functional loss. Strengthening infrastructure resilience depends on effective decision-making policies, communication strategies, and consistent regulatory implementation. Such complexities highlight the urgent need for a paradigm shift in disaster management, focusing on understanding the behaviour of tightly coupled systems in terms of resilience and capacity, irrespective of the specific hazard [7,10,31].

Reflecting this shift, systems thinking is gaining relevance across sectors, incorporating the "new normal" into training and operations. In 2017, the United Nations published the "Words into Action Guidelines: National Disaster Risk Assessment" [32] to support the implementation of the Sendai Framework. This document explains how to develop national risk registers, highlighting the need to consider frequent, low-impact events and occasional, high-impact events, along with potential cascading and simultaneous events from the same cause. The banking sector is adopting an approach that more widely includes these aspects, with recent frameworks requiring institutions to maintain critical operations under the assumption of inevitable disruptions [11]. For example, the Bank of England (2021) now mandates the identification of important business services and the determination of their tolerances in "severe but plausible scenarios". However, implementing this approach presents challenges, including developing and integrating new stress-testing tools to assess single points of failure in organisations and networks [12,13]. This methodology can be broadly applied to critical networks and organisations to help countries understand infrastructure vulnerabilities and system interdependencies [14]. A significant limitation remains the lack of clear theoretical and operational boundaries to guide for operators, critical infrastructure providers, and stakeholders involved in crisis response. An ambiguous area is the definition of borderline scenarios, especially High-Impact, Low-Probability (HILP) events or "outliers," often associated with extremes and described using terms like Dragon Kings. For example, Lee et al. [6] distinguish three types of HILPs based on the level of preparedness: those that are 'known and prepared for,' 'known but unprepared for,' and 'Black Swans,' noting that some risks are mitigated through preventative measures, while others are neglected due to perceived futility or low likelihood. This underscores the need for structured approaches that systematically address cascading impacts and vulnerabilities across systems. An important component of the process could be associated with the development of harmonised taxonomies and benchmarking criteria to overcome challenges in identifying, selecting, and combining vulnerability models with varying characteristics and reliability [15]. Frameworks like those for flood fragility can provide consistency and comparability in risk assessments, helping to understand interdependencies and support effective decision-making[15,16]. Similarly, there is a clear need to align assessments of operational capacity, organisational resilience, and disaster risk reduction, supported by clear metrics to strengthen practical implementation [17].

This perspective paper aims to address this gap by proposing a validated definition developed within the HORIZON AGILE project (AGnostic risk management for high Impact Low probability Events), a consortium of 15 international partners, mainly practitioners. We present key findings from the project's first deliverable and its validation process, making the topic is accessible to academics, practitioners, and stakeholders.

Definitions are crucial for providing a clear framework to identify and categorise events like High-Impact Low-Probability (HILP) event. They help practitioners and policymakers by providing guidelines and boundary conditions that can be used to enhance mitigation measures, such as early warning systems, improving emergency response planning, and informing legislation. Constructing precise definitions and glossaries is crucial for organisations to effectively address procedural or operational gaps and evolve organisational visions, determining thresholds for key performance indicators and the broader allocation of resources. Complementary to this, taxonomy supports the classification process. In our work, we aim to provide a tool to understand whether an event is a HILP or not, supporting the construction of scenarios and tabletop exercises, new training, and stress testing tools with specific criteria for compliance in sectors such as finance or critical infrastructure resilience.

First, we outline the approach used to establish foundational elements common across existing definitions, scenario examples, and reference thresholds. These elements can complement qualitative definitions, for example, by identifying when infrastructure or systems fall below an acceptable level of functionality. Next, we propose a validated definition for HILPs tailored for academic and conceptual use, alongside a shorter, complementary definition for operational use by practitioners suggested during the validation process (see "approach"). Finally, we identify a complementary taxonomy that could support the creation of datasets, legislation, and

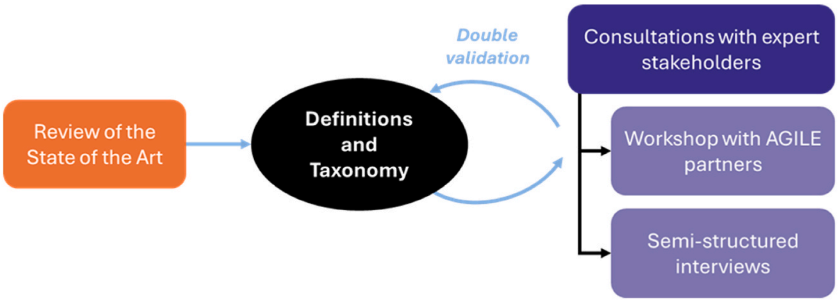

Fig. 1. Approach to the development of the definition and taxonomy.

scenario-building, providing a robust foundation for improving resilience and preparedness.

2. Methodological approach

Our methodology followed three complementary steps (Fig. 1):

1) **Literature Review:** We conducted a narrative review of the state of the art [18] to establish a baseline definition of HILP. This review aimed to identify common themes associated with HILPs and outlier events, ensuring replicability across case studies, scenarios, and applications. We explored existing definitions to understand the distinguishing elements of HILPs, ensuring consistent inclusion of case studies. Previous examples of HILPs were evaluated against common patterns to align with our proposed taxonomy. During this phase, we considered both quantitative thresholds, such as fatalities, and qualitative aspects of risk and vulnerability. Challenges in setting risk thresholds, which could trigger action, were also considered, recognising the influence of personal or organisational concerns, risk perception, and media impact. Therefore, we developed a complementary taxonomy to distinguish between HILPs and other events.
2) **Validation Process:** After establishing a baseline definition and taxonomy, we validated them to ensure replicability across disciplines and among practitioners. We employed a qualitative approach, including a focus group and semi-structured interviews [19]. These interviews were part of broader research on theory building, to be presented in a forthcoming paper. Both methods adhered strictly to UCL's ethical procedures and data-sharing protocols (project ID: 23120801). The initial validation occurred during an online workshop with the AGILE consortium in January 2024, where project partners provided input on key terms and the taxonomy, leading to a working definition. Subsequently, we conducted semi-structured interviews with 38 senior-level practitioners from the public and private sectors, all with over 12 years of experience and holding positions such as "Director" or "Head of …". The working definition was agreed upon and validated by the respondents, with no substantial disagreements. Changes to the original definition placed greater emphasis on context and proportionality, reflecting interviewees' views on the importance of context and risk appetite. For example, the phrase "events that must be considered proportionally to the specific context in which they occur" was added. Interviewees also confirmed the removal of impact thresholds, such as >1000 casualties, due to their context-specific nature. Additionally, the definition was revised to highlight limited resources as a barrier to HILP management, noting that HILPs may not meet the threshold for adequate mitigation action due to resource constraints or risk appetite. Finally, the section on lateral thinking was expanded to include interviewees' comments on various methodologies and the limitations of 'lessons learned'. This includes the adoption of methodologies such as lateral thinking, counterfactual analysis, adaptation pathways, precautionary principle, and scenario stress testing to address uncertainties and enhance resilience. The most significant change was the development of an operational definition: several respondents, especially from the private sector, noted that the working definition was too scientific for their operational environments. They suggested a complementary definition that would be more applicable to their work and suitable for executive-level presentation. Consequently, we developed a draft operational definition, which was cross-checked with those who indicated this need, according to feasibility (See limitations). Finally, some comments from a minority of respondents, which could be significant but do not affect the bulk of the definition, are reported in the next section

2.1. Limitations

The semi-structured interviews highlighted the importance of having the complementary thresholds and parameters of reference in the taxonomy. Additionally, some respondents noted the need to contextualise the definition's usage, as perceptions and the validity of elements like 'shock' or 'surprise' can be culturally or organisationally influence. Finally, we tried to maintain consistency in validating the operational definition by getting feedback from participants who suggested the need for it, but this was limited by their time availability.

Table 1
Existing patterns across definitions available in official documentation.

Low Probability	High Impact
Events or occurrences that cannot easily be anticipated, arise randomly and unexpectedly Source: Tender, HORIZON-CL3-2022-DRS-01, EU Commission, www.ec.europa.eu	*Immediate effects and significant impacts* Source: Tender, HORIZON-CL3-2022-DRS-01, EU Commission, ec.europa.eu
Outcomes/events whose probability of occurrence is low or not well known as in the context of deep uncertainty IPCC (2018), Glossary. www.ipcc.ch/sr15	*Potential impacts on society and ecosystems could be high especially when large consequences are involved* IPCC (2018), Glossary. www.ipcc.ch/sr15
Low likelihood of occurrence IPCC (2021), Climate Change 2021: The Physical Science Basis. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, In press, https://doi.org/10.1017/9781009157896.	*Would cause large potential impacts on societies or ecosystems* IPCC (2021), Climate Change 2021: The Physical Science Basis. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, In press, https://doi.org/10.1017/9781009157896.
Events that if they were to occur … Source: Australian Energy Market Operator Limited 2019 Risk Assessment https://aemo.com.au	*… they would have a very high impact leading to loss of load (USE)* Source: Australian Energy Market Operator Limited 2019 Risk Assessment https://aemo.com.au
Rare events too unlikely to occur to be relevant … Extremely low probability events that do not normally meet the threshold for action according to risk assessment models utilised in private industry Source: CISA (2011). National Infrastructure Advisory Council. Previously Proposed Study Topics (Still Outstanding) https://www.cisa.gov. Note: CISA elaborates this further in 2023 considering specifically Electromagnetic Pulse and Geomagnetic Disturbance.	*The occurrence of such events would … Have systemic consequences … Would pose immediate and simultaneous challenges to national and local decision-makers, Sector-Specific Agencies, private sector critical infrastructure owner-operators, and emergency managers at all levels of government* Source: CISA (2011). National Infrastructure Advisory Council. Previously Proposed Study Topics (Still Outstanding) https://www.cisa.gov

3. Common patterns in definitions and recurrent HILPs scenarios

The current approach to High Impact Low Probability Events is fragmented, characterised by many definitions that often differ from one another. In the AGILE project, we explored existing definitions, including those in European Commission calls and sector-specific definitions, such as from the Australian Energy Market, to identify common patterns distinguishing “low probability” and “high impact.” A summary of the essential elements found in official documentation is presented in Table 1. However, it should be noted that our comprehensive review also considered sector-specific literature, such as Sperstad et al. [20].

Overall, the definitions share a common emphasis on surprise, uncertainty, unpredictability, and catastrophic impacts, with associations with compound, cascading, and interacting risks [1]. A key challenge in dealing with HILPs is that a known risk may materialise in a new context where vulnerability has shifted, **due to differences between geological and human timescales, or may be linked to a sudden shift with no precursors, like technological innovation.** Planning for HILPs often involves scenarios with no or limited precursors (e.g., electromagnetic pulses) or precursors that have not yet directly affected human civilization (e.g., meteorites). The complexity of societal and organisational impacts further suggests focusing on the critical loss of services [10,13].

Following definitions from the European Commission and Cybersecurity and Infrastructure Security Agency (CISA), an important aspect of HILPs is that they often fall below traditional risk assessment thresholds due to their low likelihood and high mitigation costs. In other words, when applying a traditional risk management approach, the many uncertainties surrounding HILPs may prevent them from reaching the ’cut-off’ point where the event’s impact and likelihood justify the cost of preventative action (Bussière and Fratzscher, 2008). This creates an operational challenge in distinguishing between the "worst-case scenario" and the "reasonable worst-case scenario" (RWCS). RWCS represents the worst plausible risk, excluding highly unlikely variations (HM Government, 2023). The United Kingdom [30] employed this approach in preparing for a “no-deal Brexit,” highlighting HILPs as a critical factor in setting operational thresholds. Similar approaches are applied across Europe. For example, in Italy, Civil Protection plans for a sub-Plinian eruption based on the 1631 event, rather than a Plinian eruption with a 1 % probability, such as the historic eruption of 79 AD [21].

3.1. Example scenarios

Our project review identified more than 30 examples of High Impact Low Probability (HILP) events reported in the literature, ensuring that common patterns and themes were established as a baseline for the subsequent work of the AGILE project. Recurring examples of HILPs in the literature include complex events such as the 2011 Earthquake, Tsunami, and Fukushima Meltdown; the 2002 floods in Prague; and the Coronavirus pandemic. Systemic failures, such as the Northern Rock Bank crisis, and events characterised by high uncertainty, like the Eyjafjallajökull Eruption and the resulting disruption of air transport, were also noted. Additionally, accidents in highly reliable infrastructure, such as the Deepwater Horizon Chemical spill, Chernobyl nuclear disaster, and the 2021 Suez Canal blockage, were included. Natural hazards with potential future tipping points, like the 1953 flooding in the Netherlands and recent wildfires in Hawaii, were considered. Historical events that could reoccur due to geophysical cycles, such as meteorite impacts (e.g., the 1908 Tunguska Event) and caldera explosions or volcanic eruptions (e.g., Vesuvius, Campi Flegrei, Tambora, and Krakatau), were also included.

It is important to note that some events presented as HILPs, or associated with terms like Black Swan, are subject to debate regarding their classification as HILPs. For example, the coronavirus pandemic (COVID-19) required extensive discussion. While the

Table 2
Examples of HILPs events.

Event	Description
Lisbon earthquake and tsunami, Portugal, 1755	An earthquake, estimated at a magnitude of 8.5–9.0, generated a tsunami that caused widespread destruction and triggered a firestorm. The disaster killed tens of thousands of people and destroyed eighty-five percent of Lisbon's buildings. The effects were felt as far away as the Caribbean and South America.
Carrington event, 1859	A massive solar storm was detected on Earth, generating one of the largest recorded magnetic storms. This storm led to strong auroras and induced currents in telegraph lines, causing system failures and fires in some locations. Such an event could disrupt critical infrastructure if it happened today.
Mount Tambora eruption, Indonesia, 1815	The eruption was one of the most powerful in recorded history, caused the collapse of the volcano's summit and produced pyroclastic flows resulting in thousands of deaths. It also ejected massive amounts of volcanic ash into the atmosphere which led to global cooling known as "the year without summer." This resulted in widespread crop failures, food shortages, and economic hardship.
North Sea Floods, Netherlands, 1953	A severe storm combined with a spring tide, catching the Dutch citizens unaware and resulting in extremely high-water levels. Many dikes failed and a subsequent high tide worsened the flooding. The flood killed 1,836 people, and damaged buildings, agricultural land, and infrastructure, orienting long term policies.
Chernobyl Nuclear Disaster, Ukraine, 1986	A reactor meltdown released radioactive material into the atmosphere, leading to impacts on life, health and environment. Thousands of people were evacuated, with the creation of an exclusion zone that is still valid. The incident highlighted severe flaws in design and safety protocols, affecting global nuclear policies and public perception of nuclear energy.
Floods in Europe and Prague, Czech Republic, 2002	Heavy rainfall expected once in a century, caused major rivers to flood across Central Europe with widespread damages. In Prague, a chlorine gas cloud was released from a chemical plant and there was widespread contamination from inundated wastewater plants. The lessons of the event were integrated in the first European Floods Directive.
Northern Rock crisis, United Kingdom, 2007	The crisis was due to multiple factors: Norther Rock's transition from a mutual building society to a bank, its heavy reliance on securitisation and short-term market funding. and exposure to high impact, low probability risk. The global financial turbulence triggered by the Us subprime mortgage crisis exposed the bank's vulnerabilities
Eyjafjallajökull eruption and disruption of air transport, 2010	The eruption happened in specific weather conditions, generating an ash cloud that affected an area with heavy concentration of air transportation routes. Although its direct impacts were limited, the ash cloud disrupted civil aviation for almost a week, with cascading effects on society and economy.
Great East Japan Earthquake, tsunami, and nuclear meltdown, Japan, 2011	This case shows the interaction between natural and technological hazards. The primary event (earthquake) generated a chain of cascading effects, with the ensuing tsunami killing thousands and triggering the Fukushima Daichi nuclear meltdown. The disaster disrupted global supply chains, contaminated agricultural products, and infrastructure.
Coronavirus pandemic (COVID-19). cascading effects and loss of critical services, 2020–2022	The cascading effects triggered by the pandemic were highly unpredictable and disrupted supply chains, reduced workforce availability, and strained healthcare systems. Cascading, compounding and concurrent dynamics were visible across the world, for example during the Texan blackout in 2021 happened during cold weather and a pandemic peak.
Suez Canal blockage, Egypt,2021	The mega container ship Ever Given blocked the Suez Canal in March 2021 for an accident triggered by strong winds, halting 12 % of global trade and impacting billions worth of goods. The blockage caused a significant backlog, with 450 ships affected, and disrupted global supply chains.
Wildfires in Maui Hawaii, 2023	A series of wildfires erupted in multiple locations across Maui, Hawaii. Fuelled by dry vegetation and powerful descending winds, the fires spiralled out of control causing life losses and infrastructure failures and making it the deadliest U.S. wildfire in over a century. The event was exacerbated by communications breakdowns and inadequate alert systems.

pandemic had a catastrophic impact, the probability of a flu-like pandemic was debated. Before COVID-19, a pandemic was considered a high-probability event and was included in some risk registers (e.g., UK Cabinet Office, 2017). Consequently, we concluded that the distinguishing feature of the COVID-19 scenario lies in the cascading effects and the implications of these dynamics. Compared to precursors like the 1918 influenza pandemic, the COVID-19 case clearly illustrates how changes in societal vulnerability and operational contexts, influenced by technology and culture, significantly shaped the event's development, leading to variations and recombination of cascading effects. Similarly, this conceptual aspect can be associated with technological breakthroughs that change suddenly the relationship between vulnerability and hazards. Table 2 provides examples of events that can be used as references when considering HILPs, offering a range from different historical periods and types.

Table 3
Indicative summary of the quantifications of “low probability “and “high risk” in the risk register considered.

Low Probability	
UK Risk Register[22,30]	Percentages are split into five bands, from 1 (low) to 5 (high), non-linear, over five years (2 years for malicious threats). Remote chance is associated with a range between 0 and 5 %,divide in three categories were 1 is < 0.2 %; 2 is 0.2–1 %; 3; 1–5 % (HM Government, 2023)
Dutch National Risk Assessment [23]	There are Five likelihood categories, from very likely to very unlikely, over five years. Very unlikely is reported as less than 0.05 %, unlikely is from 0.05 to 5 %
Finnish Risk Register [25]*)*	There is no attempt made to assess the likelihood of any of the scenarios occurring,
Swedish National Risk Assessment[24]	Test ‘annual likelihood’ of given scenario, from very likely to very unlikely, with annual likelihood (but the version available could be outdated. Low likelihood is comprised between ≥0,0002 on an annualised basis (≥ once in 5000 year); 0,0001 on an annualised basis (once in 1000 year); and <0,002 on annual basis (< once in 500 years). Very low is between ≥0 and <0,0002 on an annualised basis (< once in 5000 years.
High Impact	
UK Risk Register [22,30]	Impact scale from 1 (low) to 5 (high), non-linear, focusing on domestic impacts across seven dimensions. For example, impact 5 is: fatalities> 1000; casualties; >2000; economic cost Tens of Billions (HM Government, 2023). In another version, impact scale from A to E, from low to high, non-linear, where E is: economic impacts: more than £10Billions; fatalities in the UK: more than 1000; evacuation and shelter: 100 thousand people evacuated over 3 days; public perception: extreme, widespread, prolonged impact; environmental damage or contamination: city (is)or region for more than 5 years; essential services: lack of health and care affecting 40 % of the population for 30 day; International relations: significant damage to UK relationship with key allies (HM Government, 2020).
Dutch National Risk Assessment)[23]	Impact is measured against six national security interests and classified on a 1 to 5 scale from limited to catastrophic. For example, catastrophic is associated with example criteria such >10000 fatalities, and structural violation of the functioning of institutions, freedoms right and core values.
Finnish risk register [25]	*Impact is assessed against seven ‘vital functions of society’, with four levels of impact* from no Impact to severely compromising impact. where severely compromised impact it is intended as extremely significant and compromising impact on the maintenance of strategic tasks, with the need of major measures deviating from the norm.
Swedish National Risk Assessment [24]	Scale from minimal to very significant, where very significant is associated with impact ≥50 dead and or >100 severely injured; >SEK 1 billion; very serious political and social impact

4. Existing thresholds in risk registers

In 2017, the United Nations issued the "Words into Action Guidelines: National Disaster Risk Assessment" to support the implementation of the Sendai Framework. This document reviewed the development of national risk registers and highlighted the need to address both frequent, low-impact (extensive) events and occasional, high-impact (intensive) events in the risk identification process, including potential cascading events linked to the same cause (e.g., El Niño and La Niña). Public-facing risk registers, despite their limited methodological transparency, offer valuable insights into a country’s risks over a typical five-year period. These registers typically use a two-dimensional matrix to classify risks by ’impact’ and ’likelihood’. We reviewed publicly accessible versions of national risk registers across Europe, mostly limited by availability in English:

1. The United Kingdom’s National Risk Register (UK NRR, [22]) is the public version of the government’s National Security Risk Assessment (NSRA). The UK NRR evaluates risks based on their likelihood (the percentage chance of the worst-case scenario occurring within the assessment period) and impact.
2. The Dutch National Risk Assessment aims to provide ‘an overview of the main risks attributed to different disasters, crises, and threats with potentially disrupting effects on society’ [23]. The current publicly available version was published in 2019. Similarly to the UK NRR, the Dutch National Risk Assessment analyses risks through the perspectives of impact and likelihood.
3. Sweden published its first national risk assessment in 2012, aiming ‘to create a common understanding of serious risks in Sweden and future consensus on proposed measures and resource priorities’ [24]. Like the UK, it employed the dimensions of likelihood and impact. However, recent publications have shifted focus to specific risks, such as cybersecurity.
4. The 2023 revision of Finland’s National Risk Assessment aims ‘to anticipate relatively sudden incidents potentially targeted at Finland that require activities deviating from the norm by authorities or even necessitate assistance from other countries or international organisations’ [25]. Notably, Finland’s risk register moves away from likelihood assessment, instead focusing on the impact on critical services, aligning with our methodology and theory.

The values in the reporting, as well as their approaches, have been considered in the development of the definition and taxonomy for benchmarking to criteria that could be familiar to decision-makers. Table 3 provides an indicative summary of the quantifications reported in the risk registers that we considered to outline their similarities and key differences. It must be noted that this is a simplification, and for the full assessment criteria, please refer to the original sources. As expected, the literature on risk registers publicly available does not provide common thresholds for the probability and impact of HILPs. However, it suggests a range of effects and impacts that can be considered as examples when defining quantitative and qualitative thresholds in the complementary taxonomy sections, both in terms of impact and probability.

As a reference, we propose limiting quantitative considerations to a general threshold, such as a perceived remote chance of <2.5 % over five years in the context considered for the analysis. This figure is derived as a compromise based on available estimates and

Table 4
Taxonomy for distinguishing HILPs: Low probability.

Low Probability	
Complexity and the role of uncertainty	
○	Existence of **concurrent, compound, interacting or interconnected dynamics** (See Pescaroli and Alexander 2018). For example, linked risks have separate impacts that are connected to the same causal event. For instance, in the summer of 2010, an atmospheric blocking pattern over Russia gave rise to conditions of severe drought and subsequent forest fires in Russia, while simultaneously contributing to extreme rainfall that resulted in unprecedented floods in Pakistan (Government office for science 2011).
Examples: • In the summer of 2010, a persistent atmospheric blocking pattern over western Russia led to extreme drought and devastating wildfires, causing thousands of deaths and major air quality issues. This same climatic anomaly simultaneously contributed to intense monsoonal rainfall in Pakistan, resulting in catastrophic floods that displaced over 20 million people.	
○	Dynamics such as a **sudden onset, creeping crises, or crossing thresholds/ tipping point**s, reflected in high uncertainty in predicting, recording, or forecasting soft signals. For example, wildfires in Hawaii 2023, the Northern Rock Crisis in 2007, cascading effects of coronavirus pandemic.
Examples: • The 2023 Hawaii wildfires escalated rapidly, fuelled by dry conditions, invasive grasses, and strong winds from distant hurricane Dora. These factors weren't initially fully recognised as a high-risk combination and the sudden onset overwhelmed local response systems. • Preceding the 2007 Northern Rock Crisis in the UK, Northern Rock's exposure to liquidity risk wasn't seen as an immediate threat but was initially a creeping financial issue. However, once market confidence eroded, a bank run followed. It signalled a broader tipping point in the global financial system that was largely missed due to weak early indicators. • While initial reports of the COVID-19 virus emerged in late 2019, the global impacts were underestimated. The crisis evolved from a localised outbreak into a complex, multi-sectoral disaster, with cascading effects on health systems, economies, education, and social structures. These cascading impacts demonstrate how creeping crises can suddenly accelerate past response thresholds.	
○	Failure of **tightly coupled systems** (with highly interdependent components) that are designed and engineered to be highly reliable and the joint failure is considered a remote possibility (e.g. nuclear accidents, such as 1986 Chernobyl, or Suez Canal blockage 2021).
Examples: • The 1986 Chernobyl nuclear disaster saw safety mechanisms, human error, and design flaws interact catastrophically in a tightly-coupled system. The nuclear plant, engineered for reliability, failed in a way that was considered extremely unlikely, with cascading technical and environmental consequences that extended across borders.	
Recombination of known and unknown patterns	
○	The **recombination of relatively common** (high/medium frequency) hazards that together result in an uncommon **scenario** in the operational context that is considered. For example, this is the case of rare winds and weather conditions that interact together with a volcanic eruption influencing exposure, such as the 2010 eruption in Iceland took place during weather conditions that moved the ash cloud in the direction of major infrastructure nodes.
Examples: • The 2010 Eyjafjallajökull eruption in Iceland involved a relatively moderate volcanic event, but this coincided with specific weather patterns. Prevailing winds carried the ash cloud directly over densely trafficked European airspace, leading to an unprecedented shutdown of aviation across Europe. While volcanic eruptions and strong winds are individually well-understood, their recombination created a scenario that was largely unanticipated and disrupted travel, trade, and logistics on a global scale.	
○	The **recombination of physical and social dynamics that are not directly associated with each other**, or not commonly associated with each other in the operational context of reference (e.g. supply chain emergency triggered by the combination of an ongoing event or emergency and miscommunication). This can be influenced by the negative feedback loop influencing disaster risk, such as mismanagement. For example, this is the case of cascading effects of coronavirus pandemic.
Examples: • During the COVID-19 pandemic, the public health emergency rapidly evolved into a global supply chain crisis. The recombination of a biological threat with complex economic and logistical systems, typically not managed together in operational contexts, exposed deep vulnerabilities. Lockdowns, miscommunication, and inconsistent international coordination created feedback loops that amplified shortages in critical goods, from medical supplies to semiconductors.	

Role of History

○ HILPs can be associated with hazards that can be recorded in historical series but have **low recurrence/ long return period/low likelihood**. Any value assigned to the likelihood of an event occurring should be considered within the context of the assessment window, availability and reliability of precursor data, quality of modelling tools, and geographic constraints. As a reference, given the assessment windows used in publicly available National Risk Registers, HILPs can be considered events that occur with a remote chance, unlikely but somewhat conceivable. For example, as general reference derived from the documentation, this can be considered in the range between 0.001% and 2.5% within the next five years. This number has to be considered as indicative and has to be contextualised in the political and cultural reality analysed, as it will be influenced by factors such as risk tolerances, risk appetites, experience and more in general by the social amplification of risk. Judgement should be used to translate this likelihood across different assessment windows, considering the underlying assumptions behind any probability estimation.

Examples:

- The 1707 Hōei Earthquake and Mt. Fuji eruption in Japan is a compelling case study of a HILP event. A magnitude ~8.6 earthquake hit Hōei, Japan, in 1707, causing widespread destruction. This was followed weeks later by the last eruption of Mt. Fuji, covering nearby regions in ash. Despite these events being well-recorded in historical data, no eruption has occurred since, and the return period for such a dual event is extremely long and uncertain.
- The 1953 North Sea Flood, which impacted the Netherlands, the UK, and parts of Belgium, occurred after a powerful storm surge coincided with a high spring tide. The flood breached dikes and flooded vast areas, resulting in over 1,800 deaths in the Netherlands alone. The event is estimated to have had a return period of around 1 in 250 to 1 in 400 years..

○ Alternatively, there could be **limited knowledge of known precursors**, that could have traces in geology, geomorphology but could have been well documented (e.g. Meteorite impacts such as the Tungska Event, and dinosaur extinctions). This lack of well-known precursors can be also associated with the new recombination of known climate extremes, such as the wildfires in Hawaii in 2023, or technology that have been never used before (Electromagnetic Pulses).

Examples:

- The 1908 Tunguska Event in Siberia, likely caused by an airburst from a meteorite, flattened over 2,000 square kilometres of forest but left no crater, making it a geological anomaly with limited well-documented precursors.
- Emerging threats like Electromagnetic Pulses (EMPs) represent a high-impact threat with limited historical precedent and no well-documented precursors in operational experience. While theoretical effects on electrical and digital infrastructure are understood, no large-scale EMP has ever occurred in the modern technological era, leaving major uncertainty around real-world consequences.

○ In society, these events are reflected in a **loss of memory/knowledge/awareness** (total or partial) of the previous event (e.g. Tsunamis), and more in general with considerations of disaster memory. For example, it can be the case that events have a history of recurrence in a certain area but there is no longer the possibility to hear first-hand stories from survivors of the previous events, such as in case of the 1896 tsunami in Japan compared to the 2011 event in the same areas. This can also be true for events with similar or comparable impacts, even if the events themselves differ (e.g. widespread education disruption).

Examples:

- The 1896 Meiji-Sanriku tsunami devastated northeastern Japan, killing over 22,000 people. However, by the time that the 2011 Great East Japan Earthquake and tsunami struck the same region, loss of intergenerational disaster memory meant many communities perceived the risk as minimal. In the aftermath of the 1986 event, some communities erected tsunami stones, warning future generations not to build homes below certain elevations. This offered a way to pass warnings down between generations.

○ Finally, **precursors that are embedded in societal memory or history** (E.g. Eruption of the Vesuvius, Carrington event, 1755 Lisbon tsunami and earthquake). Such events and their associated impact on societal memory can be potentially used for scenario building, but there is evidence of significant changes in geomorphological or socio-technological structures since the event (e.g. changes to the built environment or technological breakthroughs). In this sense, this dynamic vulnerability can orient the probability of the hazard creating new trigger events that otherwise would be not on the spectrum (e.g. Karakatoa Eruption 1883).

Examples:

- The destruction of Pompeii and Herculaneum by the Vesuvius eruption in 79 is etched into cultural memory as a symbol of volcanic catastrophe. While it informs modern evacuation planning in the Naples region, today's vastly higher population density and urban development around Vesuvius create a radically different risk landscape.
- Remembered as a spectacular natural phenomenon that disrupted telegraphs at the time, the 1859 Carrington Event was a massive geomagnetic storm. The exponential growth of digital and satellite-dependent infrastructure means that a similar event today could cripple power grids, GPS, communications, and financial systems.

Table 5
Taxonomy for distinguishing HILPs: High Impact.

High Impact	
Quantitative measures	
○	Following risk registers and sectoral guidelines, universal quantitative thresholds are challenging, as it is assumed that they need to be contextualised in each operational reality. As a general reference, they could range from serious to catastrophic impact. This could imply casualties above a specified threshold, economic disruptions over a certain gross domestic product (for example, the UK's 2023 Risk Register (HM Government, 2023) lists >1000 fatalities, >2000 causalities, and 'Tens of Billions' of pounds of economic loss as examples in the highest impact category), or large or sustained disruptions to critical services (e.g. energy usage/availability). Different countries or regions will have different thresholds based on individual contexts that need to be considered in this assessment and are determined by local risk tolerance and risk appetite, which will influence the final values and thresholds. For example, this the case for the quantification of the cascading effects of coronavirus.
Examples: • A 1908 earthquake hit the cities Messina and Reggio di Calabria, as well as dozens of nearby coastal towns. Casualties numbers are uncertain but are estimated to be between 60,000 and 100,000 people, which are the highest figures of any earthquake ever to hit Europe. The earthquake destroyed many buildings, including historic sites such as Messina's Norman cathedral, and interrupted all routes of communication - roads, railways, tramways, telegraphs and telephones. • The role of quantitative measures in estimating impact is also underscored by the quantification of the cascading effects of Covid-19. Efforts have been made to quantify the impacts of these cascading effects on physical and mental health, educational outcomes, economic losses, employment, property prices etc.	
Contextual impacts	
○	A certain degree of **irreversibility** with regard to losses, both tangible and intangible, including the possible "surprise" for the "unprecedented" anomalous impact compared to the context of reference. This may be in terms of lives, economy, other physical damages to the environment, referring also to unique ecological, cultural heritage, icon sites (E.g. impact of the 1966 flooding on the Uffizi, 2002 flooding in Prague and the impact on cultural heritage).
Examples: • The 1966 flooding of the Arno river in Florence had a lasting cultural impact, with millions of documents, literary works, and paintings damaged or destroyed across a range of institutions including the National Central Library and the Uffizi Gallery. • Summer floods in 2002 similarly damaged significant cultural sites. Prague's historic pneumatic post system, which began operations in 1889, was rendered inoperable by the floods and, as of 2025, remains closed.	
○	**A substantial, compromising, or disproportionate** effect on a closed or isolated system (e.g. local community losing the main bridge of supply), including ecological and environmental systems (e.g. loss of a forest due to a storm 1987). This could be the case for a small island state, or an isolated community (e.g. Wildfires in Hawaii in 2023, Karakatoa Eruption 1883).
Examples: • The 2023 wildfires in Maui, Hawaii, caused massive damage to the town of Lahaina, cutting off a major cultural and economic hub for the island. The disaster had a disproportionate impact on a relatively isolated population with an economy heavily reliant on tourism. The fires also displaced thousands in a region with limited alternative support infrastructure. • An 1883 eruption destroyed over two-thirds of the island of Krakatoa, triggering massive tsunamis and killing around 36,000 people across the surrounding region. Entire local communities were wiped out, and the eruption significantly altered regional climate patterns.	
○	**High uncertainty** in the dimensions of impact, that is hard to quantify due to lack of information, data, or due to the changing nature of vulnerability, affecting decision making and possibly resulting in a slower response to the challenges of prioritising response and recovery efforts (E.g. cascading effects of coronavirus)
Examples: • The cascading impacts of the COVID-19 pandemic were associated with a high degree of uncertainty, particularly in the first few months of the pandemic. Initially, there was major uncertainty regarding transmission rates, long-term health impacts (e.g. Long Covid), and secondary effects (mental health, education loss, global supply chains). These unknowns delayed coordinated responses, disrupted prioritisation of resources, and affected recovery planning. • The 2010 Deepwater Horizon oil spill, also known as the BP oil spill, in the Gulf of Mexico was one of the largest environmental disasters in history. Long-term ecological and health effects (e.g. to marine life, fisheries, local populations) were difficult to quantify. Limited baseline data on the ecosystem compounded the uncertainty.	

System dynamics

○ High impact could be associated with **substantial loss of critical services and critical functions** (e.g. sectoral disruption of functions due to cyber-attack, or cascading effects of power failures). In other words. There is an evident link between critical service disruptions, such as a lifeline disrupted, and the progress of systemic risk.

Examples:

- The 1859 Carrington Event was a powerful geomagnetic storm which disrupted telegraph systems globally. If a similar solar storm occurred today, it could cause massive outages across interconnected critical systems – including power grids, satellite-based communications, aviation, GPS, banking, and emergency services.
- The WannaCry Cyberattack in 2017 was a ransomware cyberattack spread across over 150 countries, severely impacting public and private sector operations. The UK's National Health Service (NHS) was one of the hardest hit, with thousands of appointments cancelled, non-emergency cases turned away from hospitals, and ambulance services disrupted.

○ Complex social, ecological, technological, or political dependencies can escalate the severity of the outcome of an initial event, triggering widespread or escalating **cascading effects** (e.g. widespread power failure, triggered by natural, accidental, or man-made events).

Examples:

- In the February of 2021, a severe storm struck Texas and lead to an unprecedented failure of the state's largely isolated power grid (ERCOT). While the immediate cause was extreme weather, the crisis escalated due to complex dependencies between energy, water, healthcare, and governance systems. Power outages led to extensive cascading effects. Water treatment plants lost power, leading to water shortages and widespread boil-water advisories. Hospitals faced operational challenges, with some forced to evacuate patients. Spills and pollution were reported due to failed containment systems at industrial sites. Politically, the crisis highlighted the limitations of Texas's intentionally deregulated and disconnected energy market, which could not draw on external grid support due to its isolation from neighbouring states.

○ **Lacking mitigation** associated with a lower level of risk appetite or decisional thresholds not met, or by technological breakthroughs that changed the landscape of vulnerability.

Examples:

- The 1976 Seveso chemical accident in Italy, which resulted in the release of toxic dioxin into the environment, occurred due to a lack of adequate mitigation measures and low risk appetite from both the company and regulatory authorities. Despite the potential hazards, safety protocols were insufficient, and decisive action was delayed.
- Low political risk appetite and decisional delays also contributed to the cascading impacts of the COVID-19 pandemic. Despite years of warnings from health experts, investments in pandemic preparedness were often deprioritised. Early thresholds for action were not met or acted upon swiftly.

Emergency Response

○ The need for mobilising during emergency response some **particular expertise and resources that are particularly scarce** in the organisation of civil protection machineries and requires the mobilisation of the international community or the creation of new expertise (e.g. restoration of relics, CBRN teams, dosimeter). For example, the

Examples:

- The response to the 2011 Fukushima Daiichi nuclear disaster in Japan required specialised expertise and resources that were scarce within local civil protection organisations. In the aftermath, the Japanese government required the mobilisation of international teams with specialised expertise in radiation management and CBRN (Chemical, Biological, Radiological, and Nuclear) response. This included the use of dosimeters for radiation monitoring and advanced decontamination techniques.

○ Impacts can be associated with **major changes** in national policy or international policies (e.g. 2002 floods and EU floods directives,). Compared to the political actions that can be expected after disasters, HILPs are expected to trigger substantial changes across governance levels. Similarly, they could lead to the development of new technology to mitigate the damages of the event (e.g.1976 Seveso Accident, 2010 Deepwater Horizon oil spill)

Examples:

- The 2010 Deepwater Horizon oil spill triggered sweeping changes in offshore drilling regulations and oil spill response protocols. In its aftermath, the U.S. government overhauled oversight mechanisms, creating the Bureau of Safety and Environmental Enforcement (BSEE), and enforced stricter safety and environmental standards. The spill also accelerated research and development into spill containment technologies.
- The 2002 Central European floods acted as a major catalyst for policy change at European level. In response, the EU Floods Directive (2007/60/EC) was adopted, requiring Member States to assess and manage flood risks through coordinated planning, mapping, and public involvement.

literature. Recent studies, such as Sunderland et al. [26], recommend limiting the use of recurrence rates in risk registers and communications, thus suggesting clearer parameters could be associated with the "remote chance" described in the UK NRR. Risk registers report numerical thresholds for fatalities, casualties, and economic costs, reflecting national risk tolerance, appetite, and perceptions.

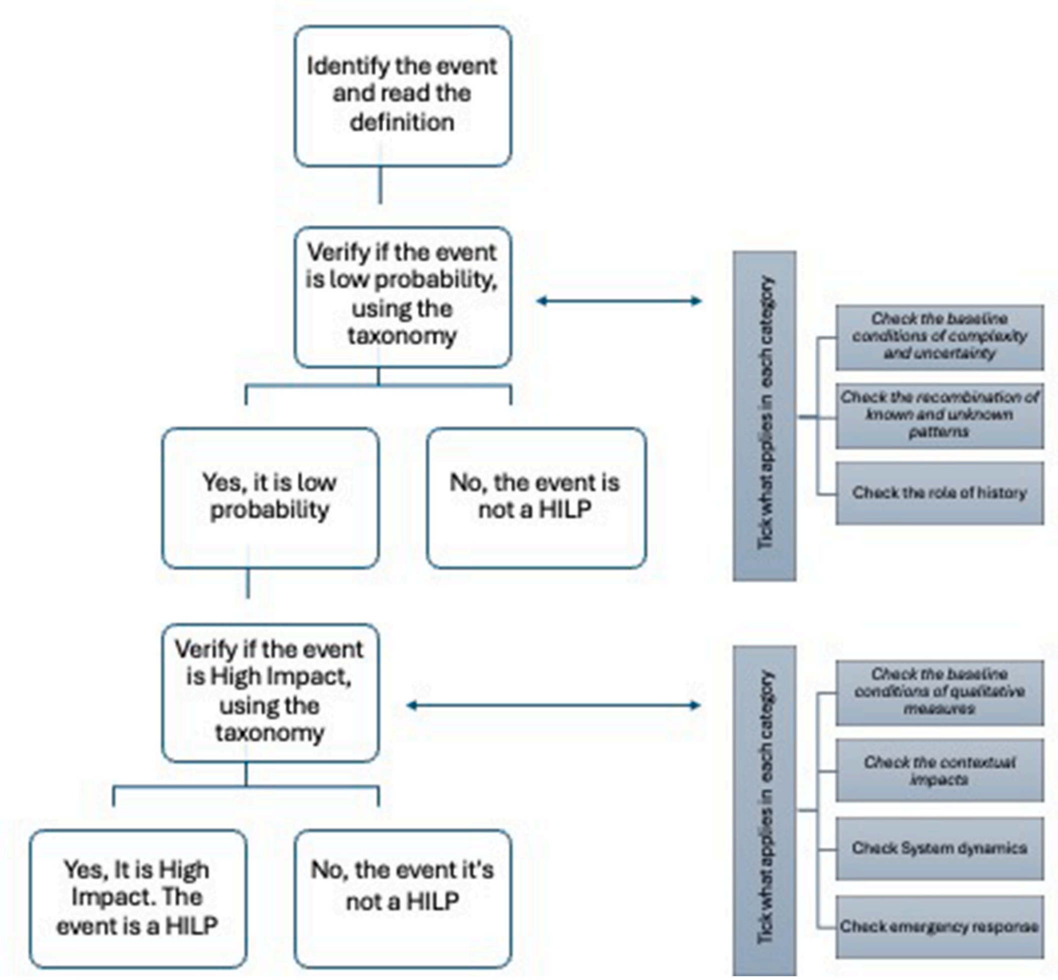

Fig. 2. Illustrative decision tree on how to understand if an event is a HILP or not.

Preliminary thresholds might include over 100 fatalities, economic disruptions in the hundreds of millions of euros, or significant disruptions to critical services (e.g., energy availability). These numbers should be applied flexibly and contextually, as economic costs impact poorer nations more than wealthier ones, and fewer injuries might be perceived as worse in smaller communities. The loss of critical services is increasingly emphasised in risk registers, supporting the replicability of the stress testing approach [13]. Poljansek et al. [27] for the European Commission provides guidance on loss estimation, considering socio-economic factors and distinguishing between immediate (1–5 years) and long-term (25–35 years) risks to prioritise mitigation actions for HILPs. Further considerations will be developed in the theory-building process of the project.

Some caution should be given to consider these values without reference to the context where they are applied. First, it is realistic to think that the numbers reported in the risk registers are heavily influenced by factors such as national risk tolerance, risk appetite, or risk perceptions [28]. For example, a preliminary threshold might be more than 100 fatalities, economic disruptions in the order of hundreds of millions of euros, or considerable disruptions to critical services (e.g., energy usage/availability). Recent literature, such as Sunderland et al. [26], suggests limiting the use of recurrence rates in risk registers and risk communications. Therefore, given the documents reviewed, clearer parameters of reference could be associated with the "remote chance" described in the UK Risk Registers (Cabinet Office, 2025). Following the Dutch Risk Register, it remains debatable whether HILPs would be perceived by stakeholders as "unlikely" or "somewhat likely," due to the influence of cultural and individual components of risk perceptions [26]. It is important to note that the Finnish risk register approaches the topic innovatively, moving away from likelihood assessment altogether and focusing on critical services, converging on the approach of the banking sector on impact tolerance of critical services and stress testing [11,29].

In conclusion, although this integration could be relatively controversial, it could support a more comprehensive shift in those realities where these parameters or benchmarking are part of the existing procedures. In other words, it could support the visualisation and synchronisation of terminology where needed, but there are evident limitations in this approach. It must be noted that the level of uncertainty inherent to the complexity of such events and the qualification issues.

5. Validated definitions of HILPs

5.1. Academic definition

High Impact Low Probability Events, or HILPs, can be scientifically defined as:

Events that must be considered proportionally to the specific context in which they occur.

They are shocks that happen with lower recurrence, distinguished by high levels of uncertainty in their predictability and effects, and by an element of surprise or anomaly in the context of reference. Their impact can be thought of in terms of critical services or critical social functions that have been affected by triggering events, in which existing or dynamic vulnerabilities and capacities have a determinant role in orienting the outcome and development of the crises.

Low probability high-impact events could be associated with a lack or limited availability of historical precursors, with known historical precursors that are far in time or space, happened before some major socio-technological breakthrough, or represent a new combination of previously known risks and vulnerabilities into a "perfect storm". When manifested, HILPs impact an operational reality that could be significantly different from the last known precursor, in terms of both exposure and vulnerability.

In operational terms, HILPs may not meet the threshold for undertaking adequate mitigation action in the public and private sector, due to lack of resources or risk appetite. Although the possibility of these events may be recognised as possible, the resources could be addressed toward a similar but somehow less extreme scenario.

The particular nature of HILPs may require thinking beyond the lessons learned from precursors to mitigate future events and increase resilience to underlying risk patterns and common vulnerabilities between different threats. This may imply the adoption of methodologies including the use of lateral thinking, counterfactual analysis, adaptation pathways, precautionary principle, and scenario stress testing to address uncertainties.

5.2. Operational definition

The operational definition that has been derived after the interviews and feedback process with practitioners is as follows:

High Impact Low Probability Events (HILPs) are rare events which may potentially result in catastrophic impacts such as on people, infrastructure, utilities, critical services and wider societal function. These events are characterised by a lack of precedence and high levels of uncertainty in their predictability and combinations of effects, often coming as surprises or shocks. They may not meet the defined thresholds of mitigation actions, and will require innovative, creative approaches to raise awareness, leverage established capabilities, and enhance short- and long-term preparedness.

6. Taxonomy of HILPS and outliers events

The two tables that follow (Tables 4 and 5) propose a comprehensive taxonomy of HILPs. They are conceived to be used complementary to the definition, providing a "checklist" that could support the identification of outlier events, distinguishing them from other phenomena. We propose the essential properties of what could be considered low probability (Table 3) and what could be high impact (Table 4), that could be used for a tuckbox exercise. We suggest that an event under security or assessment could be a HILPs when it ticks at least one of the boxes for each Section (Low Probability/High Impact), where the first tick box in each section needs to be considered a*n essential condition or condition* sine *qua non*. Please refer to Fig. 2 for a decision tree that simplify the process of using the taxonomy.

7. Conclusions

This perspective emphasises the urgent need to rethink traditional risk assessment and disaster management approaches in light of the complex dynamics associated with High Impact Low Probability and outlier events. **The most significant outcome of this work is the development of validated definitions and a comprehensive taxonomy through the HORIZON AGILE project, offering a structured framework to integrate HILPs into resilience analysis, crisis management, and policymaking.** Our approach directly addresses the fragmentation in the field by providing clear, actionable definitions for both scientific and practitioner communities.

The proposed taxonomy represents an important step towards incorporating low-probability, high-impact events into scenario-building processes, contributing to the potential evolution of traditional risk management practices. Specifically, this work enables the design of tailored training and exercises for stakeholders in highly reliable systems, including civil protection agencies, critical infrastructure providers, and the banking sector. Additionally, the taxonomy holds potential to advance academic research, both in social sciences and modelling disciplines, by providing a systematic approach to studying HILPs.

These tools bridge critical gaps in understanding and operational practice, reshaping how HILPs are addressed in risk registers, legislation, and stress-testing while equipping policymakers to tackle systemic risks effectively. This progress demonstrates that the work effectively addresses the need outlined in the introduction, bridging gaps in the conceptualisation and operationalisation of HILPs.

Further research is essential to explore the cross-disciplinary implications of this work and to refine methodologies for stakeholder engagement. **As part of the next phase of our project, we will develop a novel methodology for promoting tabletop exercises in stress testing, following the approach in complementary steps proposed by** Linkov et al. [13]**.** This will aim to identify common points of failure and enhance stakeholders' capacity to withstand outlier events.

CRediT authorship contribution statement

G. Pescaroli: Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization. **L. McMillan:** Writing – review & editing, Writing – original draft, Conceptualization. **M. Gordon:** Writing – review & editing, Methodology, Conceptualization. **N.Y. Aydin:** Writing – review & editing, Conceptualization. **T. Comes:** Writing – review & editing, Conceptualization. **M. Maraschini:** Writing – review & editing, Conceptualization. **J. Palma Oliveira:** Writing – review & editing, Conceptualization. **S. Torresan:** Writing – review & editing, Conceptualization. **B. Trump:** Writing – review & editing, Conceptualization. **M. Pelling:** Writing – review & editing, Conceptualization. **I. Linkov:** Writing – review & editing, Conceptualization.

Declaration of competing interest

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Data availability

The data that has been used is confidential.

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