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D2.1

Initial Framework and Guidance Protocol Document

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D2.1 Initial Framework and Guidance Protocol Document

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Abstract

This report is the first output of Work Package 2, and it presents a prototype MYRIAD-EU framework for multi-hazard, multi-sector, systemic risk management together with the initial guidance protocols for framework implementation. The framework is based on a systems dependency perspective and co-development process. This report offers a detailed overview of the systemic risk perspective and engagement with MYRIAD-EU and external stakeholders in the process of framework development. The framework itself is designed as an iterative process consisting of six steps: (1) finding a system definition, (2) characterization of direct risk, (3) characterization of indirect risk, (4) evaluation of direct and indirect risk, (5) defining risk management options, and (6) accounting for future system state. It is designed to incorporate single, multi-, and systemic risk assessments, depending on the context of the analysis and the needs of stakeholders. The report also presents a set of initial guidance protocols, designed as a set of questions to be asked when working through the six steps of the framework. Both the framework and the guidance protocols will be further refined throughout the MYRIAD-EU and the following feedback from the framework implementation in the pilots.

Dissemination level of the document

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Executive Summary

As recent hazard events have made apparent, natural hazards and their impacts can spread across geographical, administrative and sectoral boundaries in our increasingly interconnected world (Challinor et al., 2018; Ward et al., 2022). These effects can take the form of, for instance, loss of life and living standards as well as enormous economic damages. The latter can be direct or indirect ones, i.e., follow-on effects, that affect various economic sectors at once.

Events such as the Hunga Tonga-Hunga Haʻapai eruption, which, in turn, resulted in ashfall, a tsunami, and approximately 70 earthquakes of moment magnitudes ranging from 4.4 to 5.0 have demonstrated the impacts of multi-hazard events (Witze, 2022; Fakhruddin & Singh, 2022). Due to the interrelationships between multi-hazards and the dependencies between the elements of a system, the impacts of these types of events can surmount those of several single hazards (Kappes et al., 2012).

Multi-hazard events also lay bare the need for new ways of assessing and managing the risks emanating from such hazard events. As of now, most risk assessment and management approaches do not account for these types of hazards and the interrelationships between them. Rather, they most often focus on and provide management approaches for single hazards and single risks (De Angeli et al., 2022; Ward et al., 2022), which leads to risk governance and policies regularly disregarding multi-hazards (Komendantova et al., 2014; Scolobig et al., 2017).

The MYRIAD-EU project sets out to fill the gaps within this field of risk research and bring about a paradigm shift in risk assessment and management which can be applied to multi-hazards and multi-risks. To do so, several key concepts are defined and brought together, such as the different types of multi-hazards and their associated interrelationships. MYRIAD-EU differentiates between triggering, amplifying, and compound hazards. Multi-risk is defined according to Zchau (2017) as a risk generated from multiple hazards and interrelationships between these hazards (and considering also interrelationships on the vulnerability level). It also applies a systems perspective, and the analysis and management of systemic risk form a key part of the project (with the notion of systemic risk becoming increasingly prominent in disaster risk research, in general). A system is defined as a set of (partly) interconnected elements with clear boundaries. This connectedness, or dependency, lies at the heart of the notion of systemic risk: only through the existence of dependencies between the elements of a system can systemic risk arise. In other words, the higher the dependency between its individual elements, the easier single failures (i.e., individual risks of a system's element) can cascade throughout a system and develop from a single risk into a systemic one.

How to determine what it means to be "at risk", whether an individual element is part of a system and how to decrease risk by changing the dependencies between two of several elements of the system are some of the project's major contributions. To tackle these challenges, a framework for multi-hazard, multi-sector, and systemic risk management was developed, the prototype of which is presented in this report. The framework was developed from an extensive literature review as well as input from experts within and outside the project, spanning from researchers to practitioners and sectoral representatives. A workshop was held to present the prototype framework, gather feedback, and gain insights into practitioners' and experts' experiences. The information gathered in the workshop was, in turn, used to update the prototype framework.

Rather than providing guidelines on how to apply pre-described methods, tools, and approaches, the framework should be seen as guidance for the implementation of multi and systemic risk assessment and management. Depending on who applies the framework, different approaches and tools will prove more suitable than others, i.e., the solution to the issue at hand will be case-specific. A series of guiding questions, so-called guidance protocols, were drawn up to help in the implementation of the framework. The guidance protocols follow the structure of a stepwise analysis consisting of six steps: (1) finding a system definition, (2) characterization of direct risk, (3) characterization of indirect risk, (4) evaluation of direct and indirect risk, (5) defining risk management options, and (6) accounting for future system state.

While a (potential) lack of data and the complexity of the framework itself and its underlying principles are the prototype's major drawbacks, there are numerous benefits to applying it. These include that: (1) stakeholder engagement and co-production are at the center of the process, (2) it is highly flexible in addressing single- to multi- and systemic risk, (3) indirect risks are explicitly accounted for, (4) a system of a systems perspective is applied, which enables risk management on various scales, (5) it guides towards determining forward-looking and sustainable solutions and (6) it accounts for risk dynamics.

1. Introduction

1.1 Background

In an ever-increasingly interconnected world, natural hazards and their impacts cross geographical, administrative, and sectoral boundaries (Challinor et al., 2018; Ward et al., 2022). For instance, the 2011 flooding devastated Thailand and resulted in far-reaching ripple effects across supply chains in the automobile and electronics industries (Carter et al., 2021). Similarly, the Russian heatwave in 2010 happening at the same time as the Indus Valley flooding in Pakistan, which led to a shortfall of cereals to international markets (Challinor et al., 2018; Hildén et al., 2020). More recently, on January 15th, 2022, the Hunga Tonga-Hunga Ha'pai volcano erupted near the South Pacific nation of Tonga, resulting in ashfall and triggering a combined pressure wave (far-field) and displacement (near-field) tsunami (Witze, 2022), as well as around 70 earthquakes of moment magnitude between 4.4-5.0 (Fakhruddin & Singh, 2022). The eruption generated tsunamis that were observed globally (Lynett et al., 2022), reaching the shores of New Zealand, Russia, and causing an oil spill and two casualties in Peru (Fakhruddin & Singh, 2022). The eruption and resulting tsunami happened while the region was impacted by tropical cyclone Cody, which made tsunami detection more difficult due to cyclone-related storm surges (Lynett et al., 2022). In the immediate aftermath of the eruption, the situation was compounded by the introduction of COVID-19 in Tonga due to aid arrivals through international relief efforts (Witze, 2022). The eruption and tsunami resulted in severe impacts, with initial direct economic damage of US$90.4 million and projected (not calculated) follow-on multi-sectoral losses and indirect effects in tourism, commercial, agricultural and infrastructural sectors (GFDRR, 2022). Additionally, Tonga's telecommunication system was heavily impacted due to reliance on the submarine telecommunication fibre-optic cables, making it challenging for the Government of Tonga to effectively communicate, coordinate and determine situation and needs on the ground (Dominey-Howes, 2022).

Events like the Hunga Tonga-Hunga Ha'pai eruption and other examples above depict the complexities and far-reaching impacts of multi-hazard events and reflect a need for beyond-the-state-of-the-art assessment and management of multi- and systemic risks of hazards across different sectors and systems (Ward et al., 2022). However, current risk assessments and management methodologies and approaches in practice as well as in the existing academic literature remain largely unconcerned with these types of risks with key gaps in assessing and managing multi- and systemic risks (UNDRR, 2021; Machlis et al., 2022; De Angeli et al., 2022; Sillman et al., 2022; Ward et al., 2022).

In this Deliverable 2.1, we present a conceptual framework for individual, multi- and systemic risk analysis and management with potential application to a range of natural hazards (for hazards overview, see UNDRR (2020) and Murray et al., (2021)) and a variety of sectors, developed within the MYRIAD-EU Horizon 2020 project (myriadproject.eu) Work Package 2). Additionally, we present an initial overview of guidance protocols for the operationalization of the framework to serve as the first step towards framework implementation in MYRIAD-EU pilots. The framework is founded on an emerging multi-hazard and multi-risk scholarship (Section 1.2) and with roots in systemic risk thinking (Section 1.3. and Section 3) and will therefore be discussed first.

Starting with the concept of a "framework", in line with the Merriam-Webster Dictionary[1], one can define the term *framework* as a *"basic conceptual structure (as of ideas)*" or, in line with the Oxford Dictionary, as "*a set of beliefs, ideas or rules that is used as a basis for making judgments, decisions, etc*.". Similarly, we define a framework as "*a frame one can work with*". It is important to emphasize that the framework presented herein does *not* prescribe specific tools, methods, and approaches for undertaking disaster risk assessments. Rather, it provides a broad frame capable of incorporating a variety of tools, methods, and approaches already developed and those that will be developed as a part of MYRIAD-EU. We are especially interested here in how multi-hazards and multi-risks can be embedded within a framework that is broad enough to include single hazard and single risk analysis and which is, additionally, able to incorporate systemic risks. In other words, the framework should enable its user to conduct single-, multi-, and systemic-risk assessments based on context- and case-specific needs and stakeholder preferences.

The report is organized as follows: In Sections 1.2 and 1.3 we first introduce multi-hazards, multi-risks and systemic risk. We then provide more detailed reflections and discussions of challenges and ways forward for a systemic perspective in **Section 2**. **Section 3** then gives a short background on the framework development. Here, we introduce the prototype MYRIAD-EU framework and a detailed explanation of its steps. **Section 4** provides an indicative example of the implementation of the framework. This is followed by **Section 5** in which we further reflect on the framework, including its benefits and limitations and further steps in its development. **Section 6** then introduces initial guidance protocols while **Section 7** provides concluding remarks.

1.2. Multi-hazards and multi-risk

Rarely is the same geographical location exposed to just a single hazard type; often, rather a multiplicity of hazards occurs. The United Nations Office for Disaster Risk Reduction (UNDRR) defines multi-hazards as "*[t]he selection of multiple major hazards that the country faces, and the specific contexts where hazardous events may occur simultaneously, cascadingly or cumulatively over time, and taking into account the potential interrelated effects*." (UNDRR, 2016) Central to this definition and conceptualization of multi-hazard is the fact that multi-hazards refer to both multiple single hazards affecting a place and interrelationships between these hazards (e.g., an earthquake triggering a landslide, or a drought increasing the probability of a wildfire).

[1] https://www.merriam-webster.com/dictionary/framework [Accessed on May 16 2022]

Box 1: Definitions of disaster risk components

Hazard: A process, phenomenon or human activity that may cause loss of life, injury or other health impacts, property damage, social and economic disruption, or environmental degradation. (UNDRR, 2016)

Vulnerability: The conditions determined by physical, social, economic, and environmental factors or processes which increase the susceptibility of an individual, a community, assets, or systems to the impacts of a hazard. (UNDRR, 2016)

Exposure: The situation of people, infrastructure, housing, production capacities and other tangible human assets located in hazard-prone areas. (UNDRR, 2016)

Multi-hazards might lead to impacts greater than the sum of impacts of single hazards, especially due to their interrelationships (Kappes et al., 2012), and should therefore be collectively considered in the assessment and management of disaster risks (Ming et al., 2022). However, current approaches remain focused on single hazards with a lack of a clear framework for assessment and management of risks due to multi-hazards (De Angeli et al., 2022; Ward et al., 2022), and a lack of integration of multi-hazard approaches into policy, practice, and governance (Komendantova et al., 2014; Scolobig et al., 2017). There is a growing body of literature on hazard interrelationships (e.g. Ciurean et al., 2018; Curt, 2021; De Angeli et al., 2022; de Ruiter et al., 2020; Duncan et al., 2016; Gill & Malamud, 2014; Kappes et al., 2012; B. Liu et al., 2016; Tilloy et al., 2019) with different terms often used to describe similar interrelationship mechanisms (De Angeli et al., 2022; Tilloy et al., 2019). In MYRIAD-EU, we use the term "interrelationships" as the collective noun for the links between hazards. An overview of hazard interrelationships used in this report, and in line with the MYRIAD-EU D1.2 Handbook of Multi-hazard, Multi-Risk Definitions and Concepts (Gill et al., 2022), is as follows:

1. **Triggering interrelationship**: One hazard can trigger another hazard to occur. For instance, the 28 September 2018 earthquake at Palu (Bradley et al., 2019) triggered landslides, or a storm in November 2000 which triggered landslides in Tuscany, Italy (Casagli et al., 2006). Triggering hazards can result in hazard cascades, chains or networks when the primary hazard sets off a secondary hazard which then triggers a further hazard (Gill & Malamud, 2014; Tilloy et al., 2019; De Angeli et al., 2022).
2. **Amplification interrelationship**: Amplification interrelationships (named ''changed condition'' in Tilloy et al. (2019) or ''increasing probability'' in Gill and Malamud (2014)) refers to a situation where one hazard changes the probability or magnitude of another hazard (probability can be both decreased and increased) by changing environmental conditions for the occurrence of another hazard (Curt, 2021). For instance, drought can increase the probability of a wildfire (Clifford & Booth, 2013; Richardson et al., 2022).
3. **Compound hazards**: Situation in which two or more hazards may impact the same region and/or time period with impacts different (greater, lesser) than their sum (MYRIAD-EU Work Package 1, 2022). Compound interrelationships can take different forms: They can, for instance, include interrelationships in which different hazards originate from the same

primary event or a large-scale process (Tilloy et al., 2019). This was the case, for example, for compound coastal floodings in the UK (Hendry et al., 2019) or compound drought and heatwave events in the Brazilian Pantanal (Libonati et al., 2022).
Furthermore, they can take the form of a primary hazard simultaneously triggering multiple secondary hazards (e.g., a storm could simultaneously trigger floods and landslides, or a volcanic eruption can produce and trigger multiple hazards to occur at the same time).
Another form of compound interrelationship is that of two independent hazards impacting the same region and/or time period (or in close succession), such as an earthquake followed by a period of extreme cold. These *independent hazards* can occur with no underlying interrelationship between them (Tilloy et al., 2019). For instance, the 1991 eruption of Mount Pinatubo in the Philippines coincided with Typhoon Yunga (Gill & Malamud, 2014).
Recently, there has been an increased interest in *consecutive disasters*, another form of compound hazards. Consecutive disasters refer to a case in which one or more disasters occur after each other and their associated direct impact overlaps in space while the recovery from the initial event is still ongoing (de Ruiter et al., 2020). For example, northern Croatia was hit by a 5.5 magnitude earthquake on 22 March 2020 (Stepinac et al., 2021), and then again on 29 December 2020 with a 6.4 magnitude earthquake (Tondi et al., 2021). Interactions at the vulnerability level are of importance in consecutive disasters; for instance, Hurricane Matthew in 2016 impacted Haiti which was still in the process of recovery after the catastrophic 2010 earthquake (Curt, 2021).

It is important to point out that many authors provide different definitions and classifications of multi-hazard interrelationships and that there is no general consensus. The three categories described above were identified by summarizing commonalities between hazard interrelationships proposed in the literature (Ciurean et al., 2018). Furthermore, while hazard interrelationships have recently been receiving more attention, it is worthwhile noting that interrelationships exist at the level of risk and risk components (i.e., between hazard, exposure, and vulnerability), which are important to consider in multi-hazard scenarios and multi-risk assessments (Gill et al., 2022). These interrelationships become prominent already in the description of hazard interrelationships in the examples above (for instance, with compound hazards where hazard interrelationships are described also through impacts). However, the interrelationships on the risk and risk-component side remain understudied (Gill et al., 2022).

Over the last decade, there has been increasing interest in introducing multi-hazards in risk assessments. In this paper, we adopt the IPCC definition of disaster risk as a product of hazard (H), exposure (E), and vulnerability (V) (IPCC, 2012) (definitions in Box 1), while disaster risk assessment is defined as '*'a qualitative or quantitative approach to determine the nature and extent of disaster risk by analysing potential hazards and evaluating existing conditions of exposure and vulnerability that together could harm people, property, services, livelihoods and the environment on which they depend*' (UNDRR, 2017). Zschau (2017) provides a classification of risk assessments, distinguishing between four different types of risk assessments: (1) single-risk: risk in a single-hazard framework; (2) single-risk: risk in a multilayer single-hazard (i.e., multiple single hazards) framework with no interrelationships on vulnerability level; (3) multi-hazard risk: risk in a multi-hazard framework (i.e., hazard interrelationships considered) with no interrelationships on the vulnerability level: (4) multi-risk: risk in a multi-hazard framework where both interrelationships at hazard and vulnerability levels are considered. Interrelationships at the vulnerability level (i.e., dynamic vulnerability) refer to vulnerability changes regarding the different hazards a vulnerable element (e.g., built environment, people) is exposed to over time (Gallina et al., 2016). For instance, the vulnerability of a building will be different for floods and an earthquake and can also change in a multi-hazard scenario (e.g., a building hit by a flood after an earthquake) (de Ruiter et al., 2021). In their recent article, de Ruiter & van Loon (2022) describe three aspects of the dynamics of vulnerability, including the underlying dynamics of vulnerability (e.g., population immigration and displacement), changes in vulnerability during long-lasting disasters (e.g., droughts), and changes in vulnerability during compounding and consecutive disasters (e.g., a disaster weakening socioeconomic networks). Although not explicitly referred to in Zschau's (2017) classifications above, a full multi-risk framework should also consider dynamics of exposure; for instance, people moving to a floodplain following a fire where their exposure to floods is increased. In line with findings of the MYRIAD-EU D1.2 Handbook of Multi-hazard, Multi-Risk Definitions and Concepts (Gill et al., 2022), we acknowledge that Zschau's (2017) proposed methodology is not easily distinguishable and it may require further refinement. However, it is useful for distinguishing different levels of disaster risk assessments, especially in the context of the framework proposed in this report, as the framework is flexible enough to operate on the spectrum of single to multi- and systemic risk assessments by focusing on dependencies (be it hazard, vulnerability, or exposure related) as the overarching concept.

In more detail, several authors have provided an overview of different approaches for multi-hazard and multi-risk assessment (e.g. Ciurean et al., 2018; Gallina et al., 2016; Terzi et al., 2019; Tilloy et al., 2019; Zschau, 2017) with detailed methodologies and assessment frameworks available (e.g. De Angeli et al., 2022; Z. Liu et al., 2015; Marzocchi et al., 2012; Mignan et al., 2014; Schmidt et al., 2011). Current approaches can usually be classified as qualitative, semi-quantitative, and quantitative (Zschau, 2017), applied depending on the research purpose and characteristics of the analysis (Wang et al., 2020). In their review, Ciurean et al. (2018) outline narrative descriptions, hazard wheels, hazard matrices, network diagrams, hazard maps, hazard and risk indices, system-based and physical modeling, probabilistic and statistical approaches. While there has been advances in going from single risk to full multi-risk assessment frameworks, risks of natural hazards are still primarily considered separately, skewing the decision-making process and management options (Schmidt et al., 2011; Zschau, 2017; Schlumberger et al., 2022). Even in the context of multi-hazards, most risk assessments still primarily address the issue of multi-hazards by overlaying multiple single hazards without considering interrelationships between hazards (e.g. Gautam et al., 2021; Pourghasemi et al., 2020; Skilodimou et al., 2019). The challenges associated with the assessment of multi-hazards and multi-risks remain numerous, including a lack of a unified standard and definitions for hazard interrelationships, the inclusion of dynamic vulnerability and exposure, comparability of hazards due to different characteristics, data requirement, level of complexity, uncertainty in multi-hazard, multi-risk assessments, spatial and temporal dynamics (De Angeli et al., 2022; Kappes et al., 2012; Terzi et al., 2019; Wang et al., 2020; Zschau, 2017). The major challenge is the unavailability of common standards and mature methods for a full multi-risk assessment (Wang et al., 2020; Ward et al., 2022; Zschau, 2017) [7,37,45]. As will be suggested within this framework, the concept of dependency (or more broadly: connectedness) can be used to provide a unifying approach to these challenges that are able to incorporate single to multi-hazard as well as risk approaches. Dependencies play a key role in systemic risk analysis and are therefore discussed next in more detail.

1.3. Systemic Risk

With standard application in other contexts (e.g., financial systems), the concept of systemic risk, and its analysis and management, is gaining rising traction in research on disaster risk reduction and climate change (UNDRR, 2022). Systemic risks challenge the conventional approach to risk analysis and management (Schweizer, 2019). This emerged due to inherent characteristics of systemic risk. For instance, Renn (2021) identifies four major components of systemic risk, namely: (1) complexity, (2) uncertainty, (3) ambiguity and (4) ripple effects beyond the source of risk. Additional characteristics are tipping points, non-linear developments, and a lack of public awareness and adequate policies for these risks (Schweizer et al. 2021), as well as the fact that systemic risks are interdisciplinary and multi-sectoral, trans-boundary and global in nature (UNDRR, 2021). Due to these characteristics, systemic risks challenge and overburden existing risk management and create new challenges for risk assessments, policy making, and governance (Renn et al., 2020).

The defining feature of systemic risk is the concept of interdependencies within the elements of the system (also called feedback loops, interactions, interconnections, interlinkages, and intertwined (Sillman et al., 2022)). In this work, we define a system according to Handmer et al. (2020) as a *"set of interconnected elements (e.g., geographical areas, decision-makers, climate-related risks, risk drivers, etc.) within a defined system boundary*". Systemic risk arises due to interdependencies between the elements of the system. In the absence of interdependencies, one can refer to individual risks which describe risks to the individual elements in the system. These risks exist due to individual events that have a direct impact on the element in the system, independently from the rest of the system (Hochrainer-Stigler et al., 2020). However, failures of the individual elements in the system may trigger systemic risk and therefore, individual and systemic risk needs to be assessed and managed together (Hochrainer-Stigler et al., 2018, 2020).

Despite a growing understanding of the importance of systemic risks (e.g., due to the 2007-2008 financial crisis and the COVID-19 pandemic), classic approaches for analyzing and assessing systemic risks are inadequate (Renn et al., 2020; Sillman et al., 2022) ; however the appropriate analysis of systemic risk is a prerequisite for its proper management (Hochrainer-Stigler et al., 2019). While there are a number of emerging methods for systemic risk analysis, including copula-based approaches (Hochrainer-Stigler et al., 2018) and agent-based modeling (Poledna et al., 2018), there is a need for an integrative and holistic approach allowing for analytical perspectives based on a variety of data (e.g., observational, experimental, simulations, quantitative, and qualitative) (Renn, 2021; Renn et al., 2020).

Equally important in this context is the explicit inclusion of human agency aspects (e.g., through decision-making processes at various levels) that are vital for understanding how systemic risk may be realized and governance aspects to reduce such types of risks (Hochrainer-Stigler et al., 2019). As will be discussed in Section 2 next, the topics within systemic risk analysis can be made fruitful for multi-hazard and multi-risk analysis using a clear system definition and dependencies as the link for establishing a risk continuum from single to multi to systemic risk analysis.

2. Systemic Perspective and Risk Continuum

Given the sizable complexities involved when it comes to multi-hazard and multi-risk analysis (Section 1.1), we start with simple examples to introduce the main concepts.

Detailed information will be provided in the subsequent sections using the steps of the presented framework (Section 4). To start with, risk due to (natural) hazards is usually seen as being a function of the hazard, the exposure, and vulnerability (UNDRR, 2016). Hazard events are inherently random and probabilistic approaches are therefore often used to quantify the risk related to these events (Grossi et al., 2005). It is obvious but worthwhile to repeat that regarding exposure, humans are formulating to what kind of risk they are exposed to or which risk they want to analyze or manage and therefore are "at risk" (OECD, 2003). This is important as different individuals may define exposure differently and therefore would select different management options to reduce the risk, even for the same hazard.

To avoid confusion, we start with the simplest case, namely an individual that is exposed to some risk. We will call this an "Individual (Element) at Risk". As our focus is on natural hazard events, we further assume that this risk is pure downside risk, i.e., risk realized only in the form of losses. In our forthcoming example and according to the risk definition above, we therefore implicitly assume that the individual is exposed and vulnerable, which we indicate through the term "is at risk". Note that the individual element at risk can be a household or a geographic area of a given risk bearer as well (e.g., the government or an insurer). The definition of an individual element at risk is case specific and may be different depending on the system under study, e.g. depending on the scales (e.g., spatial, political, policy-wise). Again, for simplicity, we assume for the moment that we have an individual that is "at risk" (Individual Element 1 at Risk) due to one hazard type and being exposed and vulnerable to it. There are many methods available on how to deal with such individual risks for single hazards and we do not go into detail here (see for example Grossi, 2005) Rather, we now introduce another element at risk which opens up the notion of a system as discussed next.

The additional element we call "Individual Element 2 at Risk". Each of the two elements can look at their own risk individually and can also perform risk analyses to inform the management of their risk. Now, we assume that one wants to look at the two individual risks simultaneously. For example, Element at Risk 1 could solely be concerned about the risk of Element at Risk 2. Or, if Element at Risk 1 and Element at Risk 2 have some common interests, Element at Risk 1 could be interested in both risks. When looking at Element at Risk 1 and Element at Risk 2 simultaneously, one can introduce the term "system" as a set of (partly) interconnected elements. Furthermore, we can now introduce the term individual risk and define it as the risk an individual element is exposed to inside the system. We will call systemic risk the risk on the system level due to the interconnection/interconnectedness of the elements inside the system (Section 1.3).

In the current example, the system consists of two interconnected elements. However, there may be the case that there is also an Individual Element at Risk 3 (Element 3). As we have not introduced this element (or is of no interest to the risk bearer of the system), the given system just consists of the two individual elements at risk (as presented in Figure 1). This brings us to one of the very important cornerstones of the framework proposed herein, namely that the system under study must always have clear boundaries. In other words, the system needs to be defined in terms of what is inside the system and what is outside of it (Hochrainer-Stigler et al., 2018). How the system boundaries are defined is, for example, crucial in determining how improvement will be measured for a given intervention (Churchman, 1971). Additionally, while an intervention (i.e., risk management option) may be seen as an improvement within a narrowly defined system boundary, it may not be seen as an improvement at all if the boundaries are expanded. An example of such a case would be downstream risk shifting in the management of flood risk: building structural flood protection such as dikes protects the population and assets upstream but increases the risk for the downstream population. More generally, there may be divergent views of decision-makers regarding the system boundaries and interactions. A clear definition of these boundaries is essential to help provide an actionable decision-making basis and analyze potential conflicts between different stakeholders. Therefore, as presented in Section 1.2 above, we define a system as a "set of interconnected elements (e.g., geographical areas, decision-makers, climate-related risks, risk drivers, etc.) within a defined system boundary" (Handmer et al., 2020). Note that in the case of no connectedness between the two individuals in our example, the systemic risk analysis approach would be the same as the individual risk analysis approach. Things, however, change quite significantly if dependencies between the individual elements are assumed. This will be discussed next.

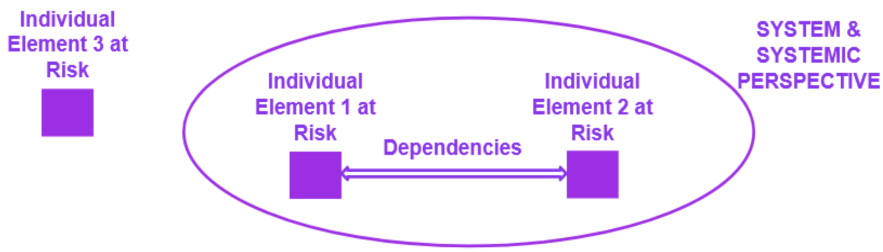

Figure 1: Simple example of three individual elements at risk and under a systemic perspective (i.e., with interdependencies between elements of the system).

The incorporation of dependencies or, more generally, connectedness (in case one does not know in which way elements are dependent) between elements into a given framework is a difficult task due to the complexities that can arise. Many different disciplines have suggested various ways forward, most prominently within complexity science and systemic risk analysis. We implement the latter using Figure 1 as our starting point and present a quantitative example next to set the stage for our discussion. Hence, we again assume two Individual Elements at Risk and a system that is composed of these two elements, which are assumed to be interconnected or dependent (Figure 1). We further suppose that in the past, losses occurred for Individual Element at Risk 1 and Individual Element at Risk 2 and that they estimated a loss distribution based on data on these past losses. Furthermore, we assume that they are sending these loss data to an agent at the system level (presuming that there is also someone who is taking a systemic perspective, i.e., a look at both individuals simultaneously). This agent uses the loss data and finds some correlation of losses.

We use the example from Hochrainer-Stigler (2020) in the following example: Individual Element at Risk 1 estimates a Gamma distribution (using the loss data) with shape parameter 1 and scale parameter 2. Therefore, the average annual loss for Element 1 is 2, and the variance is 4. As Element 1 is interested in tail events, it also looks at a possible 100-year event loss which it calculates to amount to 9.2. Individual Element at Risk 2 also estimates a Gamma distribution but with the shape parameter 7.5 and scale parameter 1. In this case, the mean and variance are 7.5 and 7.5, respectively. The 100-year event loss would amount to 15.3. Hence, extreme losses are much higher for Element 2 compared to Element 1 with the shape of the distribution being quite distinct. Importantly, the decision maker on the system level looks at the losses simultaneously (here in the form of a scatterplot of individual losses) and notices that there seems to be some connection between the losses of the individual elements (see scatter plot in Figure 2).

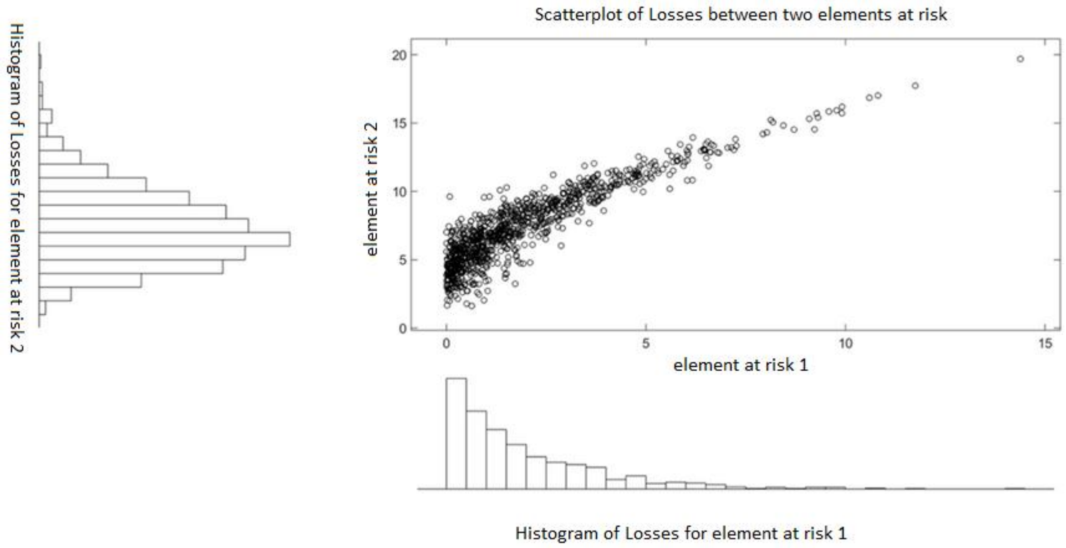

Figure 2: Example of two individual elements at risk (Histogram on left and bottom) and correlation through a scatter plot analysis on the system level (middle). The individual histograms are indicating the frequency of losses while the scatterplot is showing the relationship between the losses.

As the relationship between the individual losses seems non-linear instead of a simple Pearson correlation, they use a so-called copula approach (for an explanation see Hochrainer-Stigler et al. (2018)) for determining the obvious non-linear relationship between Element 1 and 2 losses, and using some simulation techniques the risk bearer is able to estimate losses on the system level as well. For example, a 100-year event would cause losses of about 22 currency units. The important point for our discussion is that on the system level, the risk can be reduced by changing the dependency between the two elements (see Hochrainer-Stigler 2020 for the technical details). If the two elements, for example, were fully independent, the 100-year event would only cause losses of about 19 currency units. As is very often the case, the dependencies of a system can be changed only from a top-down approach (i.e., at the system level) and the individual risk can rather be changed through a local bottom-up approach. Both top-down and bottom-up approaches are fully compatible, as for the systemic risk to realize, the individual risk needs to realize first. Therefore, our example should give motivation for an integrated perspective to risk assessment and management where both bottom-up, as well as top-down approaches to risk analysis and management, are needed and dependencies can be used as the key link.

It has already been noted that in Figure 1, the system is composed of two interconnected elements and Individual Element at Risk 3 is not used within the risk analysis. This should emphasize the need to clearly define the boundaries of the system at hand. Who defines the system boundaries and for what reason(s) is an important question that needs to be addressed, not least to indicate conflicts between potential risk bearers and interactions that may or may not (yet) be incorporated in the analysis. It may be the case that an insurance provider merely insures risks affecting Element 1 and Element 3. Their system, therefore, comprises only these two elements while from a system perspective for Element 1 and Element 2 (which could be the government, for example), the system comprises different elements. Furthermore, the insurer might only consider asset losses by the individuals while for the government, follow-on effects (e.g., economic growth-related issues, or indirect effects) may be risks as well. More generally, on the country level, an insurer would see their system as all assets insured against a particular risk and that may only relate to some areas where a risk arising due to a certain hazard could manifest. Meanwhile, for the government and businesses, the system is not only comprised of the assets relevant to the insurer but also other additional individuals who may be affected indirectly due to a hazard occurrence (e.g., through disruption of supply chains). Therefore, even in the case of the same hazard, the exposure may be different for different risk bearers and also the risk they are exposed to.

More generally speaking, different perceptions of the importance of system elements or sub-systems within the system need to be assumed at the conceptual level but can be identified at the practical level (e.g., as explained by way of the comparison of insurance or government perspective, but it also could be thought of regarding equality aspects or distributional justice in the context of climate change, see as one example in regards to a global funding pool for disaster losses Hochrainer-Stigler et al. 2021[2]). Furthermore, divergent views of decision-makers need to be assumed. Views can diverge on the system boundaries and interdependencies as well as the profound and sometimes large changes interventions may entail for stakeholders within the system and its sub-system (and also across interconnected and interdependent systems). The explicit definition of the system and its internal complex networks of interdependencies are needed for tackling these challenges, necessitating also (as will be discussed) a multiple-line of evidence approach and iterative and participatory processes including co-development of strategies on different system levels. We defined a system as a set of (partly) interconnected elements with clear boundaries. We now additionally introduce the definition of *"system of systems"* as a system in which elements can again be seen as systems. Figure 3 shows a possible system of systems approach based on different scales and possible actors involved.

[2] For more information on policy aspects see Deliverable 1.3 by Schlumberger et al. (2022).

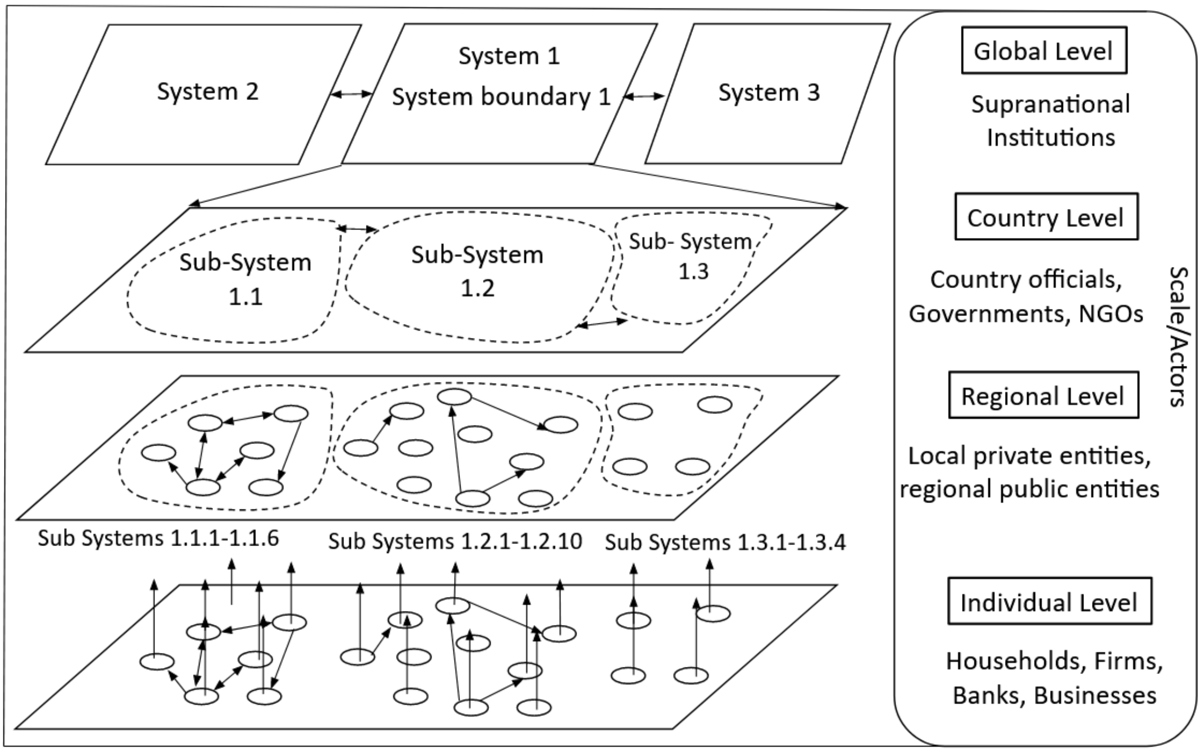

Figure 3: A system of systems approach using system boundaries as an overarching principle

Once it is explicitly defined what belongs to a system and what is outside the system (i.e., which elements the system is comprised of), the next step is to focus on the dependencies between the elements in the system (see the discussion in the next paragraph). This idea of a clear system definition was beneficial in other non-hazard and risk-related disciplines such as systemic risk research where the main focus lies on the network dynamics of a system (i.e., the interaction between the elements of the system and the individual contribution to systemic risk), and are particularly prominent in the ecological domain (Borrvall et al., 2000) and in banking and finance (Haldane & May, 2011) but are also present in many other constructed environments such as in food and other lifeline systems (Gaupp et al., 2020). In summarizing, our definition should provide the possibility to look at quite diverse system types as it can be based on geographical areas decision-makers and governance levels, climate-related risks, or climate risk drivers. Additionally, as the individual elements of a system can be viewed again to be systems – so-called subsystems – with interconnected and interdependent elements (Figure 3) complexity can be further enhanced if needed.

As indicated above, a clear definition of a system including its boundaries opens up a focus on dependencies inside the system. More importantly, the concept of dependency also opens up a promising way forward to simultaneously include single and multi-risk as well as systemic risk within one unifying framework. Using the example in Figure 1 and asking what a multi-hazard as well as multi-risk situation could look like, the dependency between the elements can act as a guiding principle. However, as the example in Figure 2 has shown, dependencies may be different in magnitude depending on the risk realizations or other pre-existing conditions. Generally speaking, the number of secondary failures due to primary failures can be related to the notion of dependency as depicted in Figure 4, which suggests a risk continuum between individual risk and systemic risks (in the classic sense of full failure of the system, systemic risk as used here has a broader notion). Viewed from a systemic perspective, using a system definition and including a system of systems approach, the so-called failures can be reinterpreted as events that cause consequences due to dependencies. The stronger the dependencies are, the more the system level will be affected, e.g., systemic risk dominates. What kind of dependencies these may be is not discussed yet and is highly context-specific However, the amount and strength of dependencies within a system between the elements can be used for separating strategies from a top-down perspective as well as a bottom-up perspective which have quite different instruments at hand. As depicted in Figure 4, in the case that individual events (e.g., hazards) do not cause failures, these can be seen as individual risks (right hand of the systemic risk ratio in Figure 4). On the opposite end, as primary failures often cause secondary failures (or cascades), systemic risks may dominate. As will be discussed, dependencies, either from a hazard or risk perspective, can be used to provide a risk continuum that comprises single, multi- as well as systemic risks. In that way, an integrated framework can be built that can incorporate previous single-risk and hazard analyses without any major challenges.

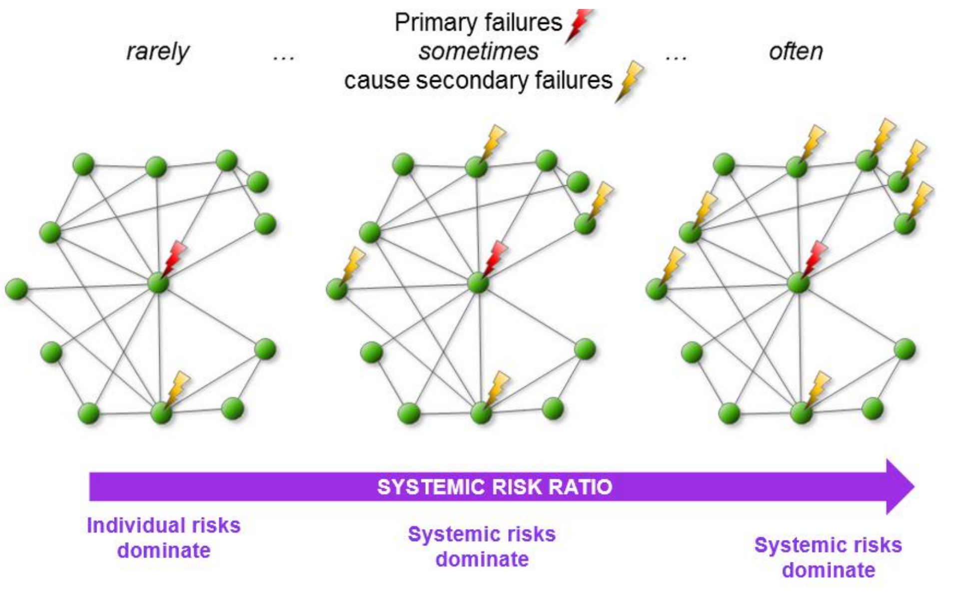

Figure 4: The continuum between individual risks and systemic risks. System components (green circles) interact (black lines) in a networked system (e.g., Hazards, Sectors, Time). Owing to these interactions, primary failures (red flashes) can trigger secondary failures/events (orange flashes). The systemic-risk ratio (blue arrow) measures the proportion of all secondary failures (Adapted from Hochrainer-Stigler et al., 2020)

As mentioned previously, systemic risk, based on dependencies between the elements of the system and system of systems" perspective, can be managed through bottom-up and top-down approaches. It is important to note that dependencies of the elements within a given system may also change depending on the hazard impact (e.g., very large losses) or on resources available to deal with losses (e.g. financial ones such as savings or having insurance or not) (see Hochrainer-Stigler et al. 2019). As an illustration, Figure 5 shows an example of wildfire risk looking at tail and spatial risk dependencies in Australia, which can be easily extended to other hazard risks as well. As described by Handmer et al. (2020), in the case that there are no dependencies between different regions (i.e., states), local level (i.e., bottom-up) wildfire management is appropriate. In the case of dependencies, however, system level (i.e., top-down) wildfire management is needed. As has been seen in recent events, wildfire risk and its spreading across large regions can increase significantly for compound events, in this case during very low precipitation and very high-temperature situations across large regions (both of them can also be dependent) and therefore need special considerations. One practical way forward using this kind of approach can take the following form: First, it may be worthwhile to look at the system disregarding any kind of interdependencies. From this perspective, the individuals of the systems should deal with their respective risks themselves and implement management measures on their own. Then, one could gradually include dependencies and determine the changes to risk on the individual as well as that systems-level these types of individually taken management measures would bring about due to the interdependencies within the system. These changes to risks should be looked at and dealt with from a systems-level perspective. The gradual increase in dependencies during stress situations enables the link to the idea of how multi-hazard and multi-risk situations may be different compared to single-risk assessment.

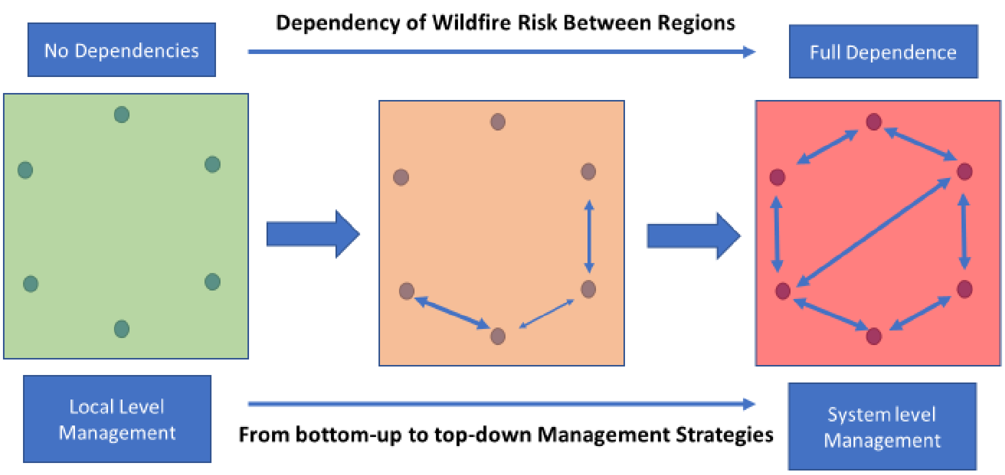

Figure 5: Local states (dot) and system level (square) wildfire risk on a continuous scale based on a spatial dependency (arrows) of wildfire risk between local states. The larger the dependency between states, the more system-level management is additionally needed (Adapted from Handmer et al. 2020). A top-down and bottom-up approach to manage risk according to dependency levels.

Obviously, the dependencies and systems at hand can be very complex and there is the need to decide which level of complexity a given risk bearer wants to engage with. That is especially important as there are usually only limited resources available to deal with this task (e.g., be it regarding monetary, personal, or data-related issues). Hence, the level of "optimal complexity" is case specific and has to be addressed from the risk bearer side on the system level (as the focus on multi-hazard and multi-risk is about dependencies). If no dependencies or single hazards are assumed, the system-level approach is the same as the individual elements used risk-based approach. Note, as risk bearers drive the decisions or processes inside the system and know the specific "language" developed in the specific system, the framework has to be embedded within a co-development process (see for example the discussion in Luhmann, 1995). From a framework- and scientific perspective, one cannot assume a golden bullet in the form of one approach; rather a toolbox-based approach that can take different needs into account and is useful on a case-by-case basis. As the multi-hazard and multi-risk framework presented here is based on dependencies, it means that all previously developed single-hazard, as well as single risk assessment approaches, can be used as well (e.g., which could provide a lower bound to multi-hazard and multi-risk in the sense that for any coherent risk measure, the correlated risk represents higher risk than the uncorrelated, see for instance Artzner et al. 1999).

To summarize, the utility of a systems perspective and systems definition, as well as the importance of top-down and bottom-up approaches have been introduced). Moving forward, we will again work with the classic definition of risk being a function of the hazard, exposure, and vulnerability. We note that all these dimensions can change over time (de Ruiter & van Loon, 2022; Gill et al., 2022). Also, some different forms of dependency could be assumed, such as in the case of multi-hazard and multi-risk situations (i.e., different hazard interrelationships as discussed in Section 1.1). Furthermore, depending on specific risks, a temporal dimension will also come into play, including indirect effects due to, for instance, business interruption or social unrest. In other words, risks will not stay the same and may increase or decrease on various system levels depending on decisions made on different levels. To be able to track progress and identify emerging issues, we will distinguish between the Current System State and Future System State(s). Such a process includes pathways on how to reach desirable system states over time and how to maneuver through the respective risk space under deep uncertainty. This requires the monitoring and updating of risks as well as iterative approaches to deal with these risks (including different tools to assess, measure, and manage risks as, for example, provided by a toolbox approach). This is part of the framework and will be discussed in Section 3 further below.

3. Prototype MYRIAD-EU framework for systemic, multi-sectoral, multi-risk analysis

The framework focuses on how risks arising from natural hazards (individual, multi-, and systemic risks) can be analyzed, assessed, and managed. It has a stepwise and iterative approach, comprising six major steps. Furthermore, it is developed to be useful for real-world decision makers and therefore follows a pragmatic approach while taking the main ideas described in Section 2 explicitly into account. The elements of the framework are illustrated in **Figure 6**. In the subsections below, we first describe how the framework has been developed, and then briefly describe the six steps as well as the cross-cutting issues in the framework (i.e., stakeholder involvement, individual and systems perspective/ bottom-up and top-down actions).

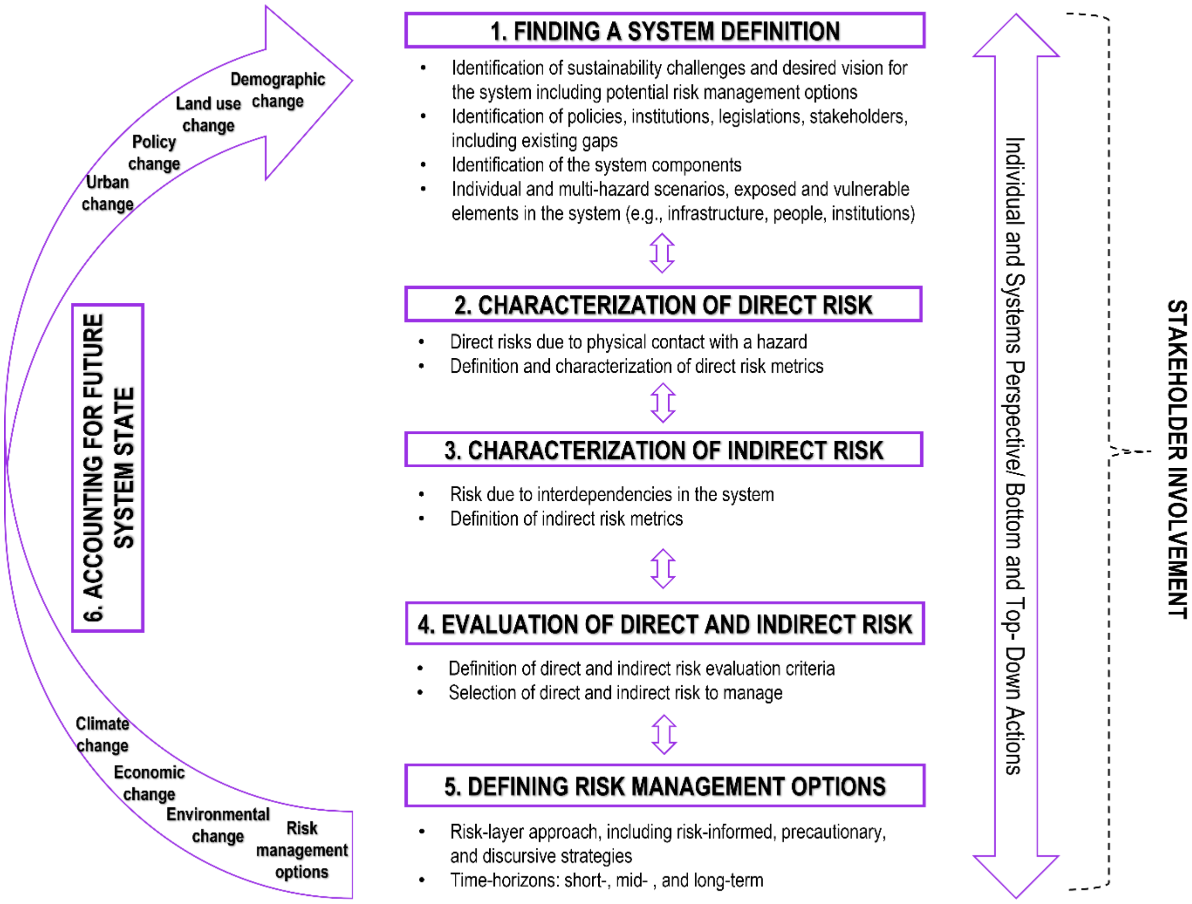

Figure 6: Prototype framework for individual, multi-, and systemic risk analysis and management (*authors' own*)

3.1. Approach to prototype framework development

The primary task of the MYRIAD-EU Work Package 2 (WP2) is to develop and test a harmonized framework for multi-hazard, multi-sector, systemic risk management. The framework is accompanied by a set of practical guidelines for carrying out a multi-hazard risk assessment, formalized in documented guidance protocols. The framework was (and is being) developed through an iterative process based on: i) the existing literature, ii) co-production with MYRIAD-EU partners and external experts, and iii) through testing it in MYRIAD-EU pilots.

The prototype framework presented in this report was developed based on an extensive review of the literature, with a specific focus on the existing multi-hazard and multi-risk assessment frameworks and approaches to systemic risk assessment and management, as presented in Sections 1 and 2. Close interactions with WP1 and other researchers and practitioners within other WPs were done to further develop the framework. Furthermore, in February 2022, the initial framework was then presented to representatives of MYRIAD-EU partners where initial feedback was given. Based on the feedback, the framework was updated and extensively discussed with non-MYRIAD-EU experts, practitioners, and scientists during the MYRIAD-EU joint WP1/WP2hybrid Workshop held at the International Institute for Applied Systems Analysis (IIASA) in Laxenburg, Austria on the 11th and 12th of April 2022.

The overall aim of the workshop was to present the prototype framework, have an informed discussion and to learn from the participants what is needed (from their perspective) to create the framework and update the prototype framework. The main agenda points of the workshop were as follows:

- Presenting the prototype framework for multi-hazard, multi-sector, systemic risk management
- Gathering initial feedback on the prototype framework and getting expertise and experiences from both internal MYRIAD-EU participants from other WPs and external experts: first step in the co-development process
- Having a discussion beyond the MYRIAD-EU Pilots as the framework should be general enough to be applicable on any scale and by decision makers.
- Presenting some of the WP1 outcomes[3] and discussing how these feed into the framework development and project overall

The workshop had a total of 62 participants, including representatives of MYRIAD-EU consortium partners (*n*=37), external experts in the field of multi-risk (*n*=17), and MYRIAD-EU pilot representatives and wider sectoral representatives (n=8). External experts were identified in a process of consultation with MYRIAD-EU researchers and represented a mix of academic researchers, representatives of the multilateral organizations (e.g., World Bank, United Nations Office for Disaster Risk Reduction), and MYRIAD-EU pilot stakeholders.

The workshop was interactive and held in a hybrid format, with roughly half of the participants joining in person, and the other half online. It was facilitated by representatives of WP1 and WP2 and consisted of plenary lectures and discussions as

[3] The aim of WP1 (Diagnosis) was to establish a common baseline. Objectives included: establishing a set of common multi-hazard, multi-risk concepts, and indicators for use throughout the MYRIAD-EU project (Handbook – D1.2), review of qualitative and quantitative methods, models and tools relating to multi-hazard, multi-risk management (WIKI platform – D1.1) and a review of policies, policy-making processes and governance at multiple scales relevant to multi-hazard, multi-risk management (Report – D1.3).

well as interactive discussions in smaller groups. Examples of in-person discussions and MIRO discussions on the framework are given in Figure 7.

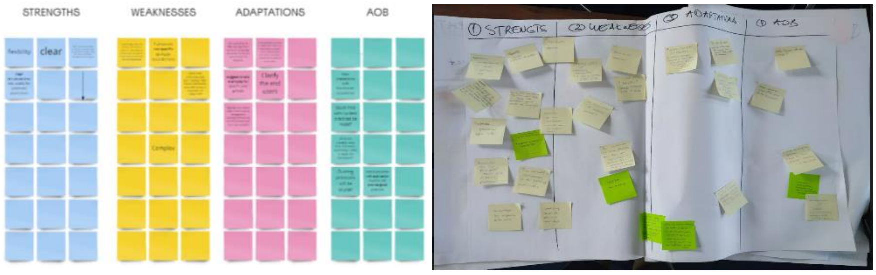

Figure 7: Example of framework feedback activities in the workshop. The upper picture shows inputs through one of the online discussions using MIRO.com while the lower ones were gained in in-person discussions.

The feedback from the workshop was used to update the design of the framework and come up with the framework presented in Figure 6 and described in detail below. Details of the workshop feedback will be presented in Section 5.

3.2. Step 1: Finding a System Definition

At the very start of the framework, one needs to develop an understanding of the system under consideration. In the first instance, this refers to a delineation of clear system boundaries and identification of elements of the system. System boundaries will allow for a clear identification of system elements and answer the question of which elements lie within the system and which do not. System boundaries can take different forms, for instance, geographical and/or administrative bounds (a city, a region), policies (e.g., a national disaster risk management policy), or even hazards and related risks (e.g., flood risk, drought risk). As outlined by Sillmann et al. (2022), setting system boundaries and identifying elements that are inside or outside the system is important from the perspective of reducing the complexity of the system. Setting system boundaries will allow for a clear identification of system elements and how these interrelate (*ibid.*).

A crucial part of system understanding is identifying current and/or future challenges for the system holder (e.g., the government, a specific sector, etc.) through engaging with a specific sustainability challenge (e.g., resilience to multi-hazards to interconnected countries with strong macroeconomic relationships, disaster resilience of islands with strong economic dependence on tourism, etc.) (Ward et al., 2022). The focus on a wider challenge allows for a better integration and contribution of natural hazard research to the wider implementation of sustainable development goals (Sakic Trogrlic et al., 2022). The framework envisions a solution-oriented approach. Therefore, as part of the system definition, stakeholder views on possible solutions for identified challenges or their vision for the future are identified (e.g., in line with the dynamic policy adaptive pathways (Haasnoot et al., 2013)).

A system definition also requires an understanding of the existing governance landscape (i.e., main policies, institutions, and stakeholders guiding the system), including an understanding of the gaps that contribute to the sustainability challenges identified. This can help in, for instance, defining what a desired outcome for the system is as defined in a specific policy (e.g., sectoral policies, disaster risk management policies). Additionally, it facilitates understanding of different perspectives, values, and worldviews of those included in decision-making processes (Scolobig et al., 2017). Last but not least, it also helps take stock of the existing risk management options (e.g., different structural and non-structural measures) and identify potential gaps in this management landscape.

Given that the framework is focused on natural-hazard related risks, a system definition also includes the identification of hazards of interest and associated hazard scenarios (including both single and multi-hazards). Here, different natural hazards of interest can be identified together with their interrelationships (as identified in Section 1.2) (Gill et al., 2021; Gill & Malamud, 2016). An example of a scenario might include triggering and compound interrelationships, i.e., an earthquake triggering a landslide coinciding with a tropical cyclone. In line with Liu et al. (2015), we recognize that for some systems, only a single hazard might be of interest. In that case, there is no need for a multi-risk assessment and one could continue with a standard assessment of disaster risk due to a single hazard. However, due to possible interdependencies within the system, there might still be a need for systemic risk analysis.

Finally, a system definition requires identifying the exposure and vulnerability of system elements (defined in Section 1.3). This would, for instance, include assets and people located in hazard-prone areas (i.e., exposure), together with different dimensions of vulnerability, such as economic, social, institutional, physical, etc.

3.3. Step 2: Characterization of Direct Risk

In MYRIAD-EU Deliverable 1.2, a distinction was made between deterministic risk (single risk scenario) and probabilistic risk (all possible scenarios). In this framework, we refer to risk also in line with the IPCC definition (i.e., focus on hazard, exposure, and vulnerability) and are therefore closer to the probabilistic risk definition. Risk realization can lead to different types of events that may cause different consequences (e.g., changes in the dependencies in the system, see Section 2) and therefore the focus is on risk rather than single events. It is worthwhile mentioning that the classification of disaster losses and damages (i.e., direct, indirect, tangible, intangible) is a matter of extensive discussion within scientific literature with no common agreement on the terminology (Gill et al., 2022). Being simplistic but fitting our needs (and also most of the concepts for direct and indirect risks), we make the following definitions: if an exposed and vulnerable element is affected within the sphere of a hazard causing impacts to it, the element experiences losses. These losses can be of direct nature defined to be caused by the hazard event itself or of indirect nature defined to be consequences of the direct losses. Furthermore, losses can be tangible, defined to be everything that can be touched, or intangible, defined to be everything immaterial. Additionally, these losses may be measurable with market-based methods (e.g. monetary terms) or other indicators (e.g. loss of life) or seen to be non-measurable (e.g. landscape). In more detail, in the following step, we first engage with the notion of direct risk; in other words, the risk that is realized due to direct contact of vulnerable and exposed system elements with a multi-hazard event (or single hazard in the case of multi-hazard being of no interest). This includes risks that are realized due to contact with a primary hazard (e.g., an earthquake) or a secondary event (e.g., a landslide that was triggered by an earthquake).

Direct risk can be expressed in terms of direct losses, which can be tangible (i.e., such as destruction of road infrastructure, houses but also loss of life, some of these can be measured with market-based methods some of them not), and intangible (i.e., loss of quality of life or cultural heritage sites). Given the changing nature of exposure and vulnerability in a multi-hazard scenario, dynamic exposure and vulnerability are considered when determining direct risk (e.g., a building being weakened by an ash fall due to a volcanic eruption is then hit by an earthquake referring to the physical vulnerability of a building; people losing their savings due to a hazard A are then hit by hazard B; migration and displacement of people following an event).

Determining direct risk also includes a selection of direct risk metrics as a measure of risk. These should be set by engaging with stakeholders who can give insights as to which metrics are most important for them (Cremen et al., 2022a). For direct risk metrics, a variety of options is available, such as physical asset losses and casualties, and the proportion of the population experiencing financial loss due to their assets being hit by a hazard (*ibid*). As presented by Poljansek et al. (2017), risk metrics are essential tools for decision-making and engaging with stakeholders in disaster risk management.

3.4. Step 3: Characterization of Indirect Risk

Indirect risk refers to risk realized due to interdependencies within the system (for a discussion of a systems dependency perspective see Section 2). We consider indirect risk only through the lens of losses that occur due to direct risks. These can take the form of, for instance, losses in the agricultural sector due to direct damages to transport infrastructure, which, in turn, influence agricultural supply chains. Just as in the above discussion on direct risk, indirect losses can be both tangible (e.g., loss of industrial production and business interruption losses) and intangible (e.g., impacts on mental health, violation of cultural values). Indirect losses can occur either inside or outside of the area hit by a hazard and often with a time lag (Meyer et al., 2013). In line with the systems perspective, this means that these losses propagate across and beyond system boundaries. As in the case of direct risk, multi-hazard and multi-risk assessment of indirect risk should consider dynamic vulnerability and exposure. In this step, indirect risk metrics are selected and agreed upon in collaboration with stakeholders. Example metrics include the costs of disrupted supply chains or a decrease in purchasing power.

3.5. Step 4: Evaluation of Direct and Indirect Risk

In alignment with the stages of the risk assessment process according to the ISO31010, Poljansek et al. (2019) distinguish between risk identification, risk analysis, and risk evaluation. While we dealt with risk identification in Step 1 and Risk Analysis in Step 2 and Step 3, the next stage in our framework is risk evaluation. The purpose of risk evaluation is to support decision-making (Poljansek et al., 2019). Given the limited resources and mandates of different stakeholders involved, not all direct and indirect risks can be reduced and managed. Additionally, some risks are tolerable/acceptable for the system of interest (e.g., due to insurance coverage) while other risks will need to be further managed. Therefore, evaluation of direct and indirect risk according to the set of pre-agreed criteria (e.g., costs, policies, and legislation reviewed in Step 1) is an integral part of the process of the selection of risk management options (Poljansek et al., 2019). In this step, and based on risk evaluation, the direct and indirect risks which need to be managed are selected.

3.6. Step 5: Risk Management Options

In this step, possible risk management options are discussed and decided upon based on risk evaluation, initial discussions in Step 1, and the results of the direct and indirect risk assessment. There is a wide range of available options for risk management including, for instance, structural (e.g., structural defenses) and non-structural measures (e.g., policies, land zoning, early warning systems) (UNDRR, 2016). Similarly, the Society of Risk Analysis (2015) suggests three types of risk management options, namely risk-informed strategies, precautionary strategies, and discursive strategies (Klinke & Renn, 2002)[4]. There will always be a mix of different types of strategies and measures.

Risk management options need to be selected in collaboration with stakeholders depending on, for instance, the risk metrics agreed up in a decision forum (Cremen et al., 2022a) with a wide range of decision support tools available. A useful approach in discussions on risk management options can be the concept of risk layering, which can be applied both for direct (Mechler et al., 2014) and indirect risk management (Hochrainer-Stigler & Reiter, 2021). Additionally, risk management measures should be considered for different time horizons and planning periods, from the short- to mid- and long-term. In a multi-risk context, the process of selecting risk management measures also needs to pay attention to synergies and trade-offs (i.e., asynergies) between risk management options for different hazards (de Ruiter et al., 2021; Ward et al., 2020).

3.7. Step 6: Future System State

Given the projected changes in risk components (i.e., hazard, exposure, and vulnerability) due to a number of processes, it is of critical importance to consider risk management in the context of these future changes to be able to take risk-informed decisions that will allow for reduced risks in the future (Cremen et al., 2022b). The framework is, therefore, iterative and allows for considering future changes in the system and how these could influence individual, multi- and systemic risk. This step considers changes to risk components due to larger processes (e.g., climate, demographic, political, and land use change) as well as due to changes in the system introduced through risk management options discussed in Step 5 (e.g., risk management is more recently discussed as one of the risk components (Simpson et al., 2021)). Given the effects of these processes, the system itself will change (e.g., the number or condition of the elements at risk or the system boundaries) and the direct and indirect risks it is exposed to need to be evaluated again. Additionally, one needs to consider how proposed risk management options will perform in the future system state and make adjustments accordingly. Existing methodologies for decision-making under uncertainty play an important role in this process (Haasnoot et al., 2013; Kwadijk et al., 2010; Kwakkel et al., 2015).

3.8. Cross-cutting issues

Stakeholder Involvement

The involvement of different stakeholders is integral and important in all steps. For instance, the definition of system boundaries and multi-hazard scenarios of interest will vary between different stakeholders (e.g., stakeholders in the tourism sector vs. an insurance company). Furthermore, the direct and indirect risk metrics, as well as risk management options, should be co-developed with stakeholders (Grainger et al., 2021; Haustein & Lorson, 2021; Smith et al., 2021).

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[4] According to the Society of Risk Analysis (2015), three risk management principles are as follows: 1) risk-informed strategies: treatment of risk using risk assessments in an absolute or relative way; 2) precautionary strategies: strategy of robustness and resilience, features such as safety factors, best available technologies, improvement of conditions for emergency management and system adaptation. Idea to meet uncertainties, risks and the potential for surprises.; 3) discursive strategies: measures to build confidence and trustworthiness, through reduction of uncertainties and ambiguities, clarifications of facts, involvement of affected people, deliberation and accountability.

Individual and Systems Perspectives/Bottom-Up and Top-Down Actions

As introduced in Sections 1 and 2, the framework is based on a system dependency perspective meaning that, based on the level of interdependencies between system elements and different systems (system of systems perspective), it could be used for the analysis of individual, multi- and systemic risk, which cuts across all steps of the frameworks. Similarly, the selection of risk management options will be influenced by the dependencies identified. This allows for more local-level management (bottom-up) if no interdependencies are detected or a more system-level management (top-down) in the case that interdependencies are present.

4. An indicative example towards operationalizing the framework

In this section, we give a detailed explanation of each step and possible ways forward as to how to operationalize the framework. Naturally, social as well as natural science approaches are needed. Therefore, the output for each step can be quantitative as well as qualitative in nature depending on, for instance, data availability or problem setup. Importantly, the framework will not advise on any solutions or give a full set of methods available. It rather indicates how to structure (i.e., through this step-by-step process) one's thinking about multi-hazard and multi-risk analysis and to discover ways forward to tackle corresponding challenges. It, therefore, also does not provide any recommendations about concrete tools to be used - although examples are given as to which dimensions and ways forward could be included.

4.1. Multi-hazard and Direct Risk

As the system definition and its importance was already discussed in some detail, we assume that the decision maker on the system level has clearly identified the system boundaries as well as which elements they assume to be inside their system. As shown in Figure 8, the first step will be to start by including multi-hazard situations, which is straightforward because it represents only one dimension of risk, namely the hazard. We, therefore, suggest starting with the identification of the single and multi-hazards for the system at hand. It is now well known that there are some overarching commonalities between hazard relationships, with three types emerging, also discussed here and presented earlier in Section 1. For our discussion of direct risk, defined as a function of hazard, exposure, and vulnerability, it is important to note that hazards relate to geographic areas and are, therefore, only of interest for potential risk analysis if they are potentially capable of affecting an exposed or vulnerable population or assets deemed to be of value. In the next step, we, therefore, apply a system perspective and relate the multi-hazard situation to the specific areas and, of course, mainly those areas where vulnerable elements are exposed, as illustrated below with the example of flood, earthquake, and fire hazards.

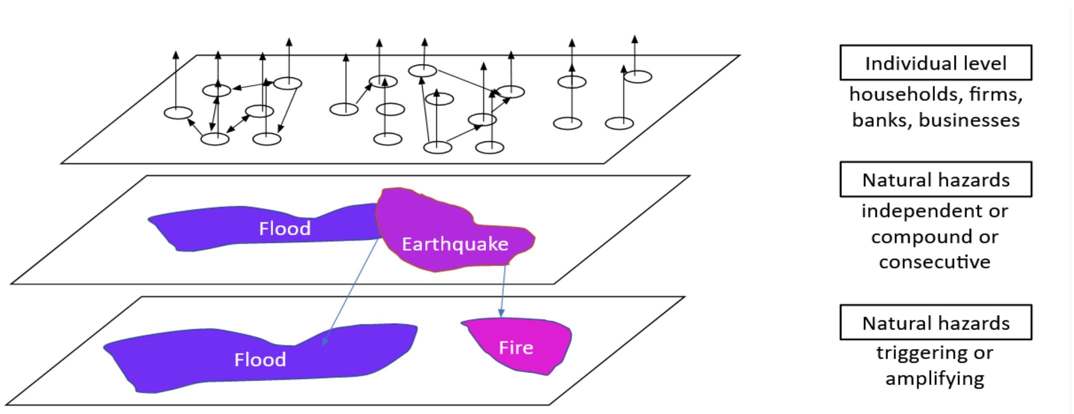

Figure 8: Different types of hazards and hazard interrelationships will affect the exposed and vulnerable elements in a system.

In Figure 8, an example is given of a flood event occurring in the same area in which an earthquake event also triggers fire. If overlayed with the exposed and vulnerable elements within the geographical area, one can observe that the affected elements in the system differ quite substantially when looking at the hazards independently (i.e., only those affected by the flood or the earthquake) or combined, i.e. when taking into account the triggering and amplifying effects due to the interrelationships between hazards in a multi-hazard setting.

Next, we address the more interesting and difficult question of how to integrate these multiple-hazard situations into a multi-risk framework. To do so, one needs to distinguish between different aspects of losses that a hazard or multiple hazards can cause. Starting from a very simplistic perspective, one can distinguish between direct and indirect losses and between tangible and intangible assets. Depending on the system, different types of exposed elements can be identified, e.g., assets such as houses or infrastructure, businesses or environmental assets, or health-related dimensions. In addition, some of the dimensions may be tangible and quantifiable, while others may be intangible and difficult to quantify. Even though this task might prove difficult, all of these losses should be included. Table 1 below provides an overview of possible losses.

Table 1: Definition of direct and indirect losses as well as tangible and intangible ones.

	Tangible	**Intangible**	**Market Value**
Direct losses	Material (in the sense that they can be touched) losses due to direct contact with the respective hazard. Example: Houses, Infrastructure, Forest, Lives, Numbers displaced, Number of injuries.	Immaterial effects Example: Spiritual significance/attachment to place, livelihood disruption.	Direct losses (tangible or intangible) that have a market value or can be reasonably measured in monetary terms or non-market impacts.
Indirect losses	Occur as result of direct impacts. Example: supply chain interruption, loss of income.	Occur as result of direct impacts. Example: impacts on mental health, livelihood development.	Indirect losses (tangible or intangible) that have a market value or can be reasonably measured in monetary terms or non-market impacts.

After the multi-hazard analysis, the direct risk analysis follows. Hence, we restrict our focus solely on direct losses at first, i.e. the losses which were caused by the direct contact with the hazard(s) itself. This also includes losses due to triggered hazards such as fire due to an earthquake in the example above. However, one needs to distinguish the losses caused by the different hazards. The vulnerability of the exposed assets may vary depending on the hazards or it may change due to an initial hazard event (i.e., dynamic vulnerability). One would also have to consider the risk of direct loss because the triggering event has already hit the asset before (e.g., changed vulnerability due to the first hazard). Therefore, a clear distinction is needed by using the concept of direct loss, which refers to the specific hazard that caused the losses for the exposed asset with a specific vulnerability. The time dimension of the hazard can be used for estimating the changes of vulnerabilities due to previous hazards, but the exact moment one hazard hits the exposed and vulnerable element is reserved for the term direct loss and separated into the different hazard types and situations. This means that the direct losses can be determined for each hazard separately even if they are viewed from a multi-hazard perspective. Needless to say, the consecutive time steps can be also continuous, e.g., when a nonlinear Poisson process is used for the occurrence of multiple hazards, or only storylines are considered, e.g., some selected multi-hazards (see Shepard et al. 2020). The table below simply illustrates the conceptual approach of how different losses of interest can be related for each hazard and time dimension. Note that there are not only individual losses, but also losses from a top-down perspective (system levels are considered and may differ from individual losses, e.g., due to different responsibilities, e.g., infrastructure). A possible example of how the direct losses can be listed and put into order can be found below.

Table 2: Example of a table listing individual and system level losses in a direct risk analysis considering multiple hazards and time steps.

Individual 1 Losses:

	T=0	T=1	T=2	T=3
Hazard 1				
Hazard 2				
Hazard 3				
Hazard 4				

Individual 2 Losses:

	T=0	T=1	T=2	T=3
Hazard 1				
Hazard 2				
Hazard 3				
Hazard 4				

System Level Losses:

	T=0	T=1	T=2	T=3
Hazard 1				
Hazard 2				
Hazard 3				
Hazard 4				

Different forms of dependency may matter more on the individual than on the system level. This can be, for instance, because exposure extends over larger areas when considering the system level; therefore, some triggering events that would not affect the individual would still affect the system level. In the example of insurance, a household may just consider two hazards, e.g., floods and landslides, while for the insurer spatial dependencies as well as triggering events across larger areas may be important to be considered, e.g., floods which cause landslides and earthquakes which also cause fire, which are both covered in their insurance portfolios. While the possible combinations can be extensive within real-world applications, only a few can be looked at or seen as relevant. These depends on the system at hand. This, in turn, is ultimately based on the stakeholder/risk-bearer inside the system (as they define what their system is constituted of). The concept of dependencies can take these different possibilities into account, e.g., from single to multi-hazard and multi-risk situations.

To summarize, we suggested a systems approach that distinguishes between elements within and outside without the system. As previously mentioned, system elements can be again systems, leading to a system of systems. Each of them may observe risks they want or have to deal with regarding single and multi-hazard situations. These risks can be differentiated into direct and indirect losses, tangible and intangible as well as market-based (e.g., monetary) and non-market-based dimensions. Direct risk is defined as pure downside risk (i.e., if risk realizes it only causes losses) and is viewed as a function of exposure and vulnerability. The multi-risk situation for direct risk is based on the system which one is looking at over different time horizons as the corresponding exposure and vulnerability may differ. In other words, the transition from a multi-hazard to a multi-direct risk analysis is done by focusing on the potential hazard sequences and updated accordingly assuming possible changes in the exposure and vulnerability. The dependencies between the hazards can be assessed using hazard dependencies as exemplified through the typology of multi-hazard situations explained above. Therefore, a single direct risk assessment can be embedded within multi-hazard risk assessment without any major problems that is, at least conceptually. (For modeling, there are huge challenges to be overcome, some of them may not even be tackled due to the limited resources available from a given systems perspective). In the next step, indirect risk is embedded in the assessment process.

4.2. Multi-hazard Indirect Risk

Up until now, indirect risk was just assumed to include the current situation; however, in reality, decisions made beforehand as well as the cultural or social norms influence it. We again use a systems approach to distinguish between different drivers that influence indirect risk. In addition, we first assume the current system state, regardless of how that system state has evolved. Indirect risk is only looked at from the perspective of losses due to direct risk, which was realized because certain hazards affected those exposed and vulnerable to a hazard. Hence, we are not looking at indirect effects per se but only the ones which can be related to natural hazard events. Thus, we follow a three-step approach: first, we determine the hazard and multi-hazard scenarios. Second, we identify the multi-direct risks (Table 1) for these hazards. Third, we determine the indirect risk. Each step includes many other steps but the overall approach is based on the hazard occurrence. Therefore, our approach is hazard-focused. In summary, multi-risk is always seen in the context of the occurrence of hazard events.

As mentioned earlier, we consider indirect risk, which is simply defined as the consequence of direct risk. In other words, since there is no direct risk without a hazard that can affect an exposed and vulnerable system or individual elements of a system, there is also no indirect risk without the occurrence of losses due to the realization of direct risk. While we could simply stay in the physical and natural world (see Table 1) in the case of direct risk, in the case of indirect risk, we work in systems of possibly highly adaptive individuals as well as in social systems built over time by collective individual behavior, i.e., system of systems. Furthermore, we use the concept of resilience capacities, which can be separated into physical, natural, social, human, and financial capacities (based on the five-capital approach from the sustainable livelihood framework) (Keating et al., 2017). Note that some of these capacities are already included in the definition of direct risk, which is a function of hazard, exposure, and vulnerability. These refer to different types of losses, e.g., physical capacity can include structural stability of assets. We now include other options to deal with these events that are not directly related to the hazard event and direct losses, but also other capacities. In this sense, multi-direct risk vulnerabilities are a subset of resilience capacities (e.g., physical vulnerability of a structure is a subset of physical capacity). These resilience capacities may be specific to the direct losses but may also depend on other hazards and resilience levels. First, we would like to note that indirect risks without any interdependencies/connections between individuals from a system perspective are merely individual risks that may or may not be managed by the individuals themselves. We therefore suggest the following:

1) As a starting point for indirect risk assessment, measurement and management, one should assume a **fully unconnected/independent system**. Here, one can measure individual risk and resilience (e.g., defined as capacities to cope with the direct losses, which can be diverse but ultimately depend on the exposed elements of the individual) and possible failures. One can use risk-layering to design resilience solutions mitigating individual risk to be implemented by managers of individual components (bottom-up). Risk layering will be discussed further below.

2) Consider interdependencies: Measure how interdependencies increase individual risks and evaluate systemic risk. Incrementally increase interdependencies, starting from the most important ones, for both the individual risk and from a systems perspective. Evaluate various restructuring options to develop resilience strategies to mitigate individual and multi-risks to be implemented by system-level decision makers (top-down).

3) Integrate both approaches: Analyze potential trade-offs between individual and systemic resilience. Design a collaborative and iterative process to coordinate and solve these trade-offs.

For example, in the wildfire case mentioned in Section 2 and based on Handmer et al. (2021), a fully unconnected system could be defined as the local wildfire regions that have their own management to deal with the day-to-day wildfire risk. In the case of this fully unconnected system, most of the management strategies are developed for more frequent wildfires, and for additional less frequent but more devastating wildfires. The risk of large wildfires across regions can be due to low precipitation or high temperatures affecting the regions individually (and resulting in higher wildfire risk for the local region), but also simultaneously (as more regions are affected simultaneously the system level options are stressed). In this case, both the system (i.e., across the regions) and individual risk (i.e., in a region) are increasing. The top-down as well as bottom-up approaches are further developed according to their specific objectives (step 2- consider interdependencies) and trade-offs are analyzed according to the different management options considered (step 3 - integrate both approaches).

The assumption of unconnected elements in the first step of indirect multi-risk analysis is to allow the consequences to be considered from an individual perspective independent of any links with others. Additionally, one can assume a systems perspective, in which the individual risk of each of the elements can be different to the individual level due to the hazard interdependencies (e.g., spatially) considered. The temporal dimensions incorporated into the direct risk assessment and the reference to the specific hazard also allow tracking of the indirect risk associated with these hazards and the corresponding loss events and the respective indirect risk they cause (as done in Table 1 but now for indirect risks, due to the complexities involved here we explain this in more detail within section 4.3).

In this respect, multi-hazard and multi-risk assessments are natural extensions of single-risk assessments, i.e., not only individual hazards and direct risks are considered, but also indirect risks arising from these hazards.

4.3. Risk Evaluation and Risk Management

Typically, the individual elements of a system know the key interconnections within a local context and have a very good understanding of those interconnections. Meanwhile, a top-down system-level approach is unlikely to be very detailed although it may provide a broader picture. In this sense, individual elements might also see their risk from a systems perspective, just at a different scale and with only a subset of elements from the other system level in which they are involved. Following the ideas of supply chain risk management for Step 2, the individual elements of the system, as well as the system level itself, have different foci (Figure 9).

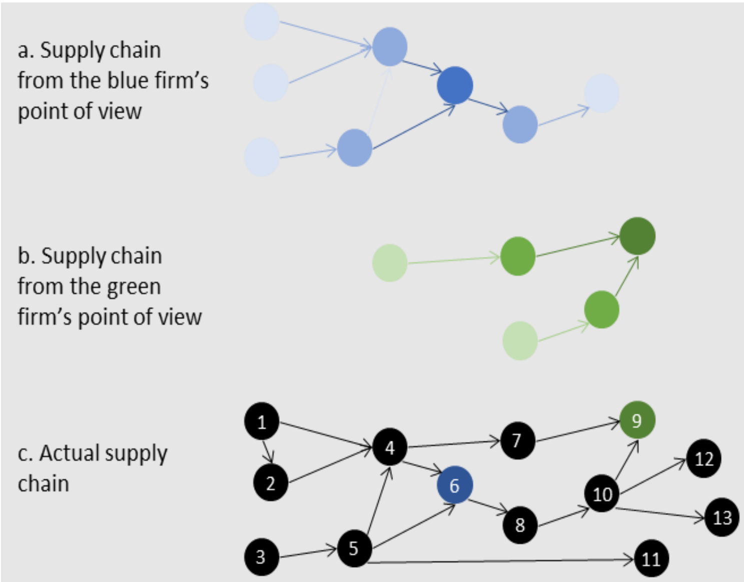

Figure 9: Schematic diagram of a supply chain perceived by two firms (a-b) and how it actually is (c). Each bubble represents a firm, and each arrow represents a supplier–buyer relationship. The blue (a) and green (b) firms share the same supply chain, but their perspective on it is different. One can assume that firms know their tier-two suppliers and clients. The lighter the color of the supplier, the clients, and the linkages, the less information the firm has on them. In panel (c), the entire supply chain is represented and firms are identified by numbers. Source: Celian and Hochrainer-Stigler 2022

More specifically, individual indirect risk is due to the interconnectedness with other individual elements at risk and therefore also refers to the losses and consequences incurred by others (e.g. due to direct risk realization, see Figure 10). From the individual's perspective, this may not include all the connections they can observe or deal with, so from a top-down perspective, the entire structure/network can/should be considered. This is also the level at which system changes can be stimulated or initiated, e.g., for transformational change. This issue is directly related to the models that will use data/information and their optimal level of complexity. Recent findings from system risk research provide some elements that can guide the analysis. Three types of system risk patterns should at least be captured: the "too big to fail" pattern, the "too interconnected to fail" pattern, i.e., firms whose disruption would trigger large domino effects (Battiston et al., 2012), and the "too specialized to fail" pattern, e.g., those firms that are the sole provider of a critical technical component to an entire sector. These patterns, drawn from the study of financial and ecological networks, can be usefully applied to indirect risk in general. The network dynamics perspective helps to identify what can and cannot be done at the local level, and what can and cannot be done at the national, regional, or global level. The way these indirect risks are measured may be different from the direct risks and should essentially focus on the interdependencies/connectedness of the network. In the case of probability-based techniques as an example, a risk level approach can be used for direct and indirect risk management purposes at different levels (Figure 10).

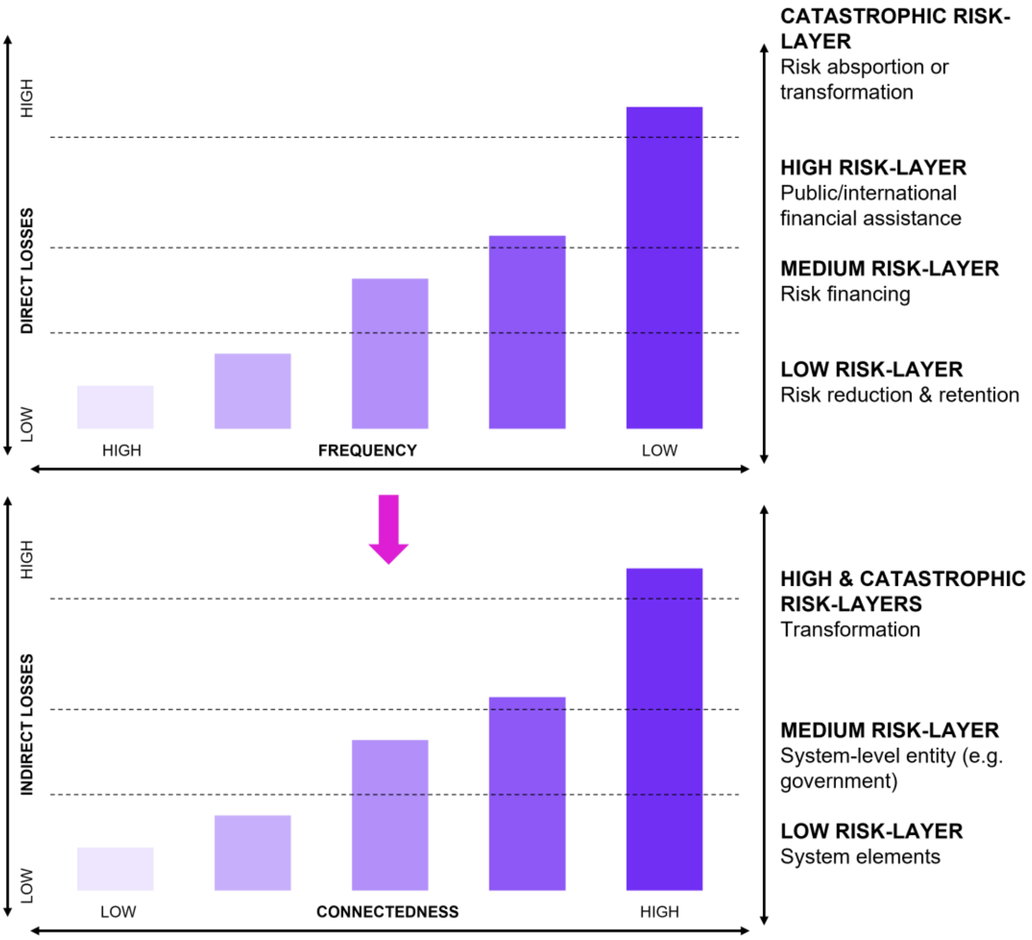

Figure 10: Risk-layers, loss levels and associated probability for direct risks (top bar graph) as well as with associated connectedness for indirect risks (bottom bar graph). For each risk layer, management options and/or respective system levels are given. (adapted after Ghesquiere & Mahul (2010)

Risk-layering is usually done if risks can be quantified in sufficient detail and, given limited or uncertain data, impacts need to be modeled differently and addressed using different approaches. Generally speaking, we suggest following the recommendations of the Society of Risk Analysis (Society of Risk Analysis, 2018) that at least three main strategies can be identified in terms of risk management and governance options to address such risks, including risk-informed strategies (e.g. full probabilistic information is available), precautionary strategies (e.g. in case to avoid tipping points which should be navigated around using for example DAPP), and discursive strategies (e.g., in case of deep uncertainties). While in most cases a mix of these three strategies may be considered most appropriate, in the context of high stakes and high uncertainty, it is sometimes suggested that more weight be given to precautionary strategies and, in the case of interpretive (e.g., openness to different interpretations of specific risk assessments) and normative ambiguity (e.g., openness to different views and values about risk), more weight be given to discursive strategies. In addition, the focus should be on redesigning or enhancing currently existing risk management and governance strategies, rather than developing entirely new governance structures and tools (Figure 10).

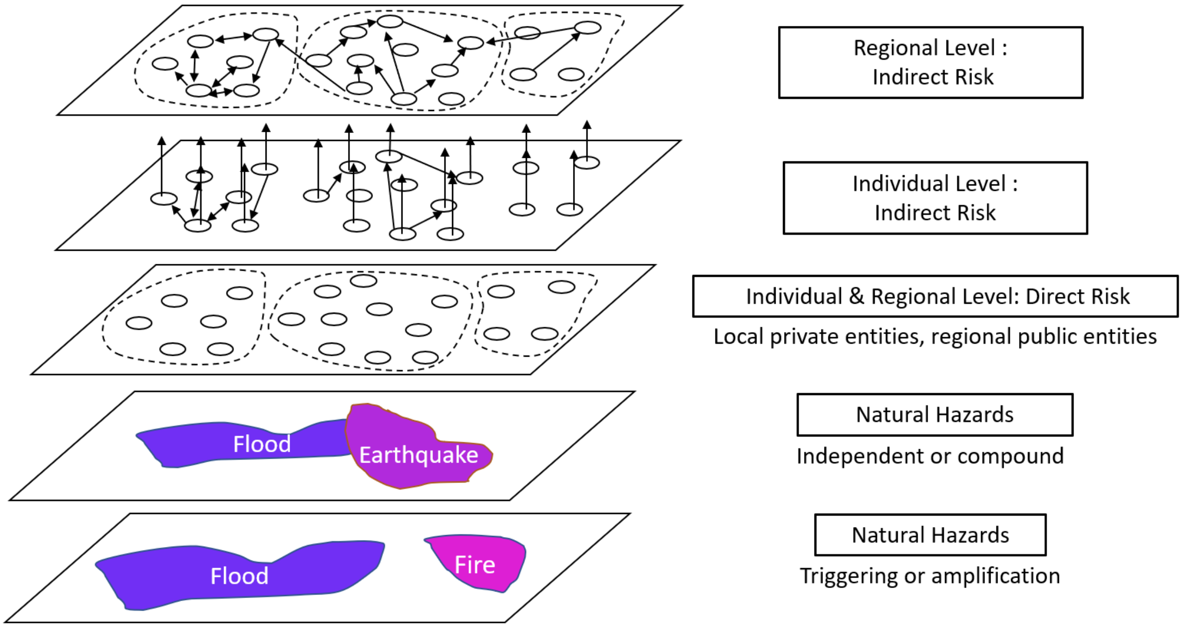

Figure 11: Multi-Hazard Risk and Multi-Risk Analysis for direct and indirect risks.[5]

This brings us to the question of how to respond to disasters, how to manage disaster risks and in what time frame and how to incorporate short- and long-term changes. In general, one may distinguish between short-term (months to 1 year), medium-term (1-5 years), and long-term (over 5 years) change (however, it is case specific). In all these time periods, changes in hazard, exposure, and vulnerability of elements and the system may occur due to individuals' or the system' response as well as their capacities to respond to them. In the next step, we include the additional dynamics that can affect direct and indirect risk following a multi-hazard event. This, we group under the term response, which can include all types of responses that affect both direct and indirect impacts and risk (Figure 5).

[5] The arrows in the figure point to different interdependences between elements of the system.

4.4. Current and Future System State

This step should consider the vision from a broader perspective, such as where this framework is embedded in other systems that do not explicitly consider multi-hazards and risks, and how these developments would change resilience levels and risks over time. This may include broad-scale changes such as sea level rise and social tipping points.

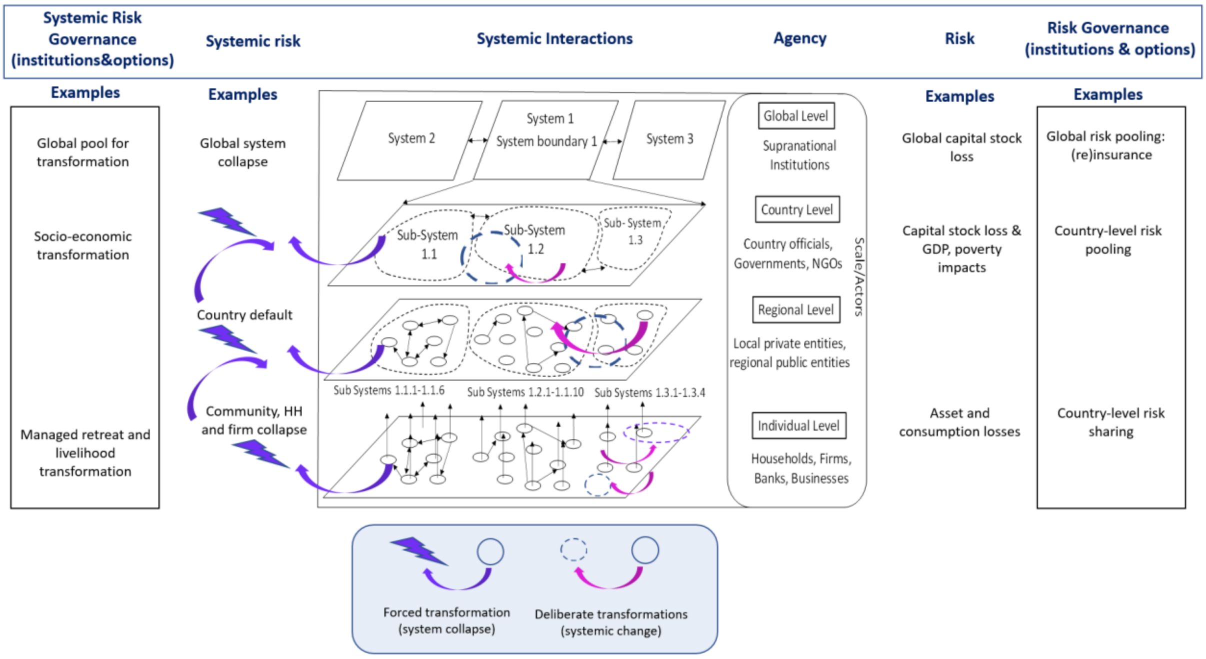

Figure 12: System of systems approach with interaction effects on different scales

The middle part of Figure 12 illustrates a country as one possible conceptual representation of a system of systems, with the boundaries being the political borders and the household level as the smallest sub-system level assumed. Understanding the interrelationship effects, including the negative and positive impacts of hazards (for example multi-hazard events that lead to large-scale migration from the individual to the community up to the country level, see for example Figure 8 as well) and interventions, between elements in a system and across systems (right-hand side of Figure 12 in terms of possible risk-sharing mechanisms) is key for enabling the necessary stakeholder support and buy-in. Regarding the operationalization aspects it should be noted that divergent views of decision makers on the system boundaries and interactions, including consequences and responsibilities, due to multi-hazards and corresponding risks have to be expected. Consequently, ways forward how to manage them from the individual as well as system level may differ significantly across systems. Nevertheless, insights from decision makers can help to provide feasible solutions and actionable ways forward how to jointly manage current and emerging risks on all system and sub-systems level (e.g., left-hand side of Figure 12, including managed retreat or livelihood transformation on the local level as well as transformational approaches for avoiding tipping points).

For a long-term planning perspective, a vision of the future can be used and tested against some emerging threats in terms of multi-hazard and multi-risk situations. This way, such an analysis can be embedded in a broader systems perspective in which this issue is only one - but an important one - that can also drive change in terms of the multiple benefits of disaster risk management across scales, actors, and time periods.

5. Reflection on MYRIAD-EU Prototype Framework

After presenting the framework and an indicative example (Section 4 and Section 5), this section provides some reflections on the prototype framework. We begin by discussing some of the benefits and limitations of the existing framework (Section 5.1), followed by a close look at the feedback received during the WP1/WP2 workshop in April 2022 (Section 5.2). Finally, further steps to develop the framework are outlined (Section 5.3).

5.1. Placing MYRIAD-EU framework in context: benefits and limitations

The MYRIAD-EU framework was designed to overcome several limitations in current approaches for assessing and managing multi-risks. Some of its core benefits are as follows:

- **Strong emphasis on stakeholder engagement and co-production**: As described in Section 3.8, stakeholder engagement is central to the implementation of the MYRIAD-EU framework. In the framework, various types of stakeholders (e.g., local communities through to different levels of government and sectoral representatives to regional and global agencies - depending on the level of analysis) are actively involved and shape different steps of the framework (through, for instance, determining system boundaries and identifying risk metrics). Many existing frameworks do not explicitly take into account stakeholder input in the process of framework implementation e.g., (De Angeli et al., 2022; B. Liu et al., 2016; Schmidt et al., 2011; Simpson et al., 2021), while consultation with stakeholders is envisioned in Liu et al. (2015) and Marzocchi et al. (2012).
- **Flexibility to address single- to multi- and systemic risk**: As previously mentioned, the framework presented here is designed to be flexible enough to operate on the spectrum from single to multi- and systemic risk analysis. This way, it can accommodate different existing tools and methods, and levels of analysis and it can be tailored according to the context (i.e., system of interest) and in line with the needs of stakeholders. If, for instance, in Step 1, there are only single hazards identified as an issue, the analysis can continue through a single-hazard risk assessment where systemic risks could still be of interest due to dependencies within the elements of the system.
- **Explicit focus on indirect risks**: Particularly important in terms of a cross-sector perspective and due to the consideration of interdependencies within system elements, the framework places an explicit focus on indirect risks by providing for them as a separate step. Other available frameworks either do not consider indirect risks (e.g., Liu et al. (2015) focus on direct risks for buildings) or do not place such an explicit focus on risks that arise due to interdependencies between system elements.
- **System of systems perspective allowing for risk management across scales**: By taking a systems perspective and asking for a clear delineation of system boundaries, the framework enables systems at different levels to be viewed from a systems perspective. As a result, it facilitates risk management at different levels and the identification of risk management options at both the local level (i.e.,

bottom-up) and the system level (i.e., top-down). This is helpful in terms of risk governance, clearly defining responsibilities for risk management options at different levels and considering synergies and asynergies between risk management actions. Previous frameworks lack this systemic perspective.

- **Forward-looking and embedded in larger sustainability issues**: The framework starts with the identification of sustainability challenges in the system of concern, enabling the identification of forward-looking disaster risk management pathways. By starting from a sustainability challenge, it also goes beyond simply viewing natural hazard risks through a hazard-oriented lens but takes a risk-informed approach and enables hazards to be considered in the context of sustainability challenges. Emphasizing interdependencies within the system also facilitates risk management solutions that consider all elements of the system. By considering the future state of the system (Step 6), the framework also explicitly considers future risks arising from (i) larger processes such as climate change and land use change and (ii) the adoption of risk management measures.
- **Account for risk dynamics**: The framework considers risk and all its components (i.e., hazard, exposure, and vulnerability) to be inherently dynamic through: (i) the dynamics of exposure and vulnerability in a multi-hazard scenario, (iii) changes in the system considered in Step 6 that directly affect the hazard, exposure, or susceptibility.
- **Integration of different types of data**: The proposed framework allows and asks for the integration and use of different types of data, from a qualitative and narrative implementation of the framework (e.g., the framework could be implemented through a workshop style activity with stakeholders that would engage around the topic of multi-risk management) to a comprehensive quantitative risk assessment (e.g., quantification of interactions between different hazards). The explicit request for the stakeholder engagement warrants the inclusion of qualitative data and focus on co-production. Majority of existing frameworks is based only on quantitative methods used, primarily probabilistic (e.g., Liu et al., 2016; Marzocchi et al., 2012) while a similar approach to integration of both qualitative and quantitative data was proposed by Liu et al., (2015).

The current limitations of the prototype framework are as follows:

- **Complexity**: The framework is complex and requires in-depth technical knowledge to implement the various steps. Moreover, it has not yet been tested in an actual case study to fully capture its complexity. However, the complexity problem will be addressed through: (i) the development of MYRIAD-EU products and services in scientific work packages (WP4-WP6), (ii) the implementation and testing of the framework in MYRIAD-EU pilots where complexities are identified, further refined, and reduced through continuous stakeholder feedback, (iii) the Wiki developed under WP1 sharing a wealth of resources on existing tools and methodologies for multi-hazard, multi-risk assessment and management, and (iv) the development and refinement of dashboard and guidance protocols in WP2.
- **Data availability**: Implementing the framework could potentially require a large amount of data, especially in terms of quantitative analysis, which may not be readily available depending on the system under consideration. However, the framework provides flexibility for different levels of risk analysis and management

(i.e., risk-informed, precautionary, and discursive strategies). As mentioned earlier, the framework incorporates both qualitative and quantitative data, and the level of detail can be adjusted based on data availability, case-specificity, and stakeholders' preferences.

5.2. Towards Co-production of MYRIAD-EU Framework: Integration of WP1/WP2 Workshop Feedback

As described in Section 3.1, in April 2022 a workshop was held where MYRIAD-EU partners and external experts provided feedback on the framework that was used to refine the framework. The framework version presented in the workshop is presented in Figure 13.

The general feedback was that the framework has a clear structure; its stepwise nature was especially appreciated. Participants also emphasized the benefits of a framework that is flexible to accommodate a continuum from individual to multi- and systemic risk analysis, the inclusion of direct and indirect risks, stakeholder engagement, and the relevance of findings to policy and decision making.

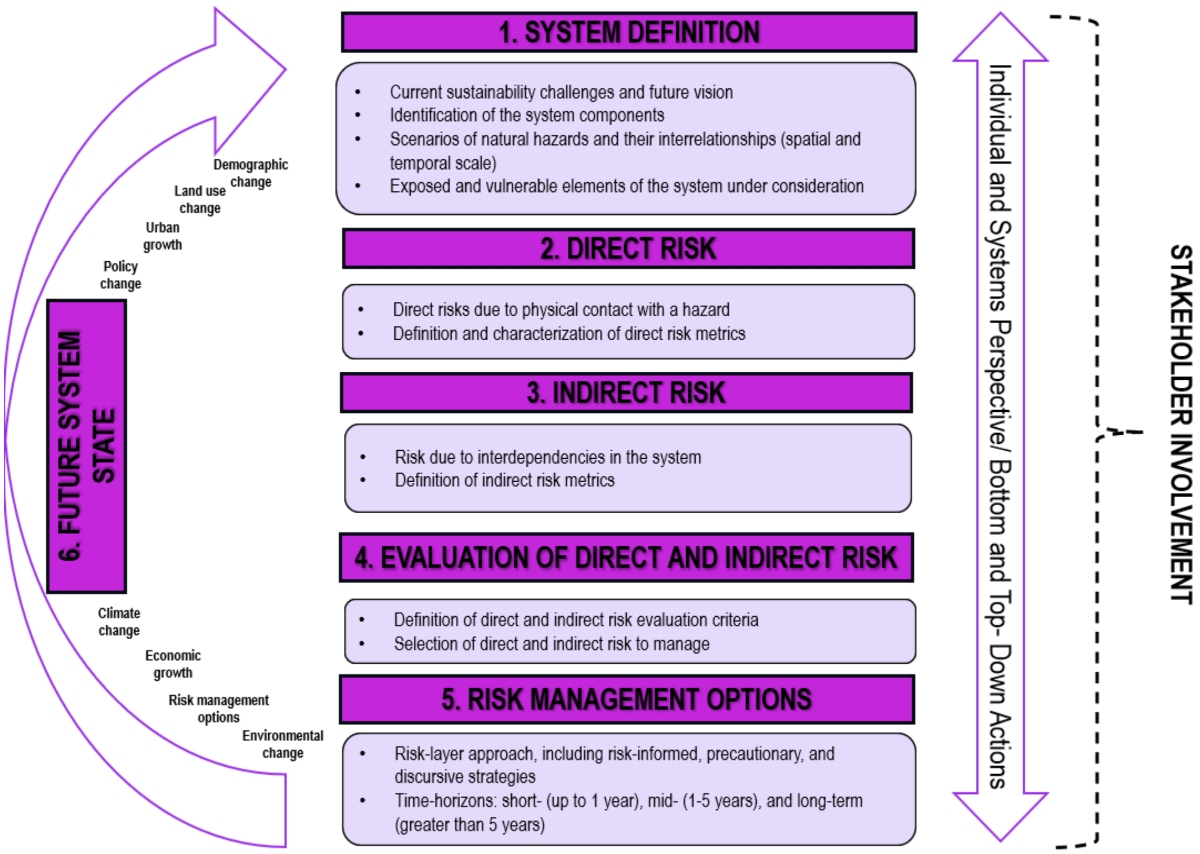

Figure 13: Prototype MYRIAD-EU Framework presented in the workshop

Regarding the required changes, most comments focused on the implementation aspects of the framework, which are discussed below. Several issues were raised during the amendment process and have been incorporated into the new version (Section 3):

- Consistency of language within the framework making sure that various terms are used in the same manner throughout the graphic and accompanying text.
- Include a clear statement of challenges for the system and desired state in Step 1, as well as a mapping of policies, institutions, and stakeholders.
- Already include discussions on possible risk management options in Step 1.
- Emphasize the interaction between different steps.
- Change language in Step 6 and make it more accommodating (e.g., urban growth vs urban change, economic growth vs economic change)
- Align with the stages of the risk assessment process as outlined in Poljansek et al. (2019)

Regarding the implementation aspects of the framework, the general feedback was that the framework is complex and clear guidance is needed for its implementation. These include considerations of best practices for each of the steps and fleshing out the role of stakeholders in each of the steps. Additionally, it includes the integration of diverse views of different stakeholders across different levels of the system (i.e., bottom-up vs top-down perspective), dealing with uncertainties in multi-risk assessment (e.g., arising through modelling of hazards and hazard interactions, data availability for impacts, or projected future changes in system updating) and how to embed existing tools and methods into the various steps of the framework. These issues will be addressed in the guiding protocols of the framework and through the work of scientific work packages. Thus, guiding protocols will be continuously updated based on the results of the scientific work packages and feedback from the implementation of the framework in the MYRIAD-EU pilot projects.

5.3. Future Steps in Framework Development and Refinement

The framework will be implemented, tested, and evaluated during five MYRIAD-EU Pilot Studies. The first step is to present the framework during Pilot Workshop 1 in October - November 2022 and collect feedback that will then inform the further design of the framework. Together with WP3, we will foster an iterative learning process so that user feedback is collected in the Pilots to iteratively update the framework. In the Pilots, we will engage with the Pilot Core User Group, Pilot Stakeholder Group, and other potential user groups. The description of these groups and their respective roles is available in the D3.1 Terms of Reference for Stakeholder Engagement (Ciueran et al., 2022).

After Pilot Workshop 1 (in month 15) and Pilot Workshop 2 (in month 42) and two Pilot-level Focus Group meetings (in months 27 and 36), when stakeholder feedback will be collected, we will make four formal updates to the framework and guidance protocols. The final framework and guidance protocols will then be presented in month 46.

Feedback on the framework from MYRIAD-EU consortium partners will be gathered throughout the project cycle. For instance, meetings with Pilots Leads will be held on a regular basis (e.g., quarterly), in collaboration with WP3, to receive feedback on the framework implementation process, and how its design could be enhanced.

The process of framework implementation will be especially facilitated through guidance protocols, whose initial version will be presented in the following section.

6. Initial Guidance Protocols

6.1. Background to Guidance Protocols

Guidance protocols that accompany the framework are developed with an idea to guide the framework user during the implementation of multi and systemic risk assessment and management. It is important to note that the framework we present is not intended as a process for applying pre-described methods, tools, and approaches. As mentioned in Section 2, from the perspective of the framework and science, one cannot assume a panacea in the form of a single approach; rather, one must adopt a toolbox-based approach that addresses different needs and can be useful on a case-by-case basis.

Therefore, guidance protocols are not designed to offer specifics of how the framework should be implemented. They rather offer a series of broader questions one needs to take into account when working through the framework. Therefore, in the following sections, we will present some initial guiding questions. Throughout the lifetime of MYRIAD-EU, these questions will be revisited and expanded, with the idea of also having different "layers" of guidance protocols, from beginner to intermediate and advanced levels.

The data needed for the guiding questions below can be obtained through a variety of methods. For example, through stakeholder engagement, secondary research based on literature reviews, national, local and regional loss/impact datasets, and by accessing existing data sources through platforms such as OASIS, risk and hazard viewers like ThinkHazard, EM-DAT and GAR.

In addition, it is important to note that the guiding protocols will need to integrate developments from other MYRIAD-EU work packages as they are developed during the MYRIAD-EU lifecycle, particularly due to overlap. The framework aims to bring together all the work that has been done in the different work packages and the implementation in the Pilots. Some examples of work in other work packages (already done or to be done) that can be used as part of guiding protocols include:

- The WP3 *Deliverable 3.1 Terms of Reference for Pilot Core User Group and Stakeholder Groups (M7-48),* provides clear guidance on stakeholder engagement, including general considerations on identification and mapping of stakeholders at the Pilot level. This guidance can provide useful recommendations on how to identify stakeholders relevant for the implementation of the framework in a given pilot, and to some extent on how to collect input from stakeholders. Therefore, this guidance is relevant for the on how to define what is in and what is out of the system in Step 1 of the framework (System Definition).
- *WP1 Task 1.2*, which develops a Wiki Style crowdsourcing platform with examples of qualitative and quantitative multi-hazard, multi-risk methods, models, and tools, including examples of their application. Given that the framework is flexible enough to incorporate already existing approaches, the work of WP1 can be directly used when implementing the framework in the pilots for different steps of the framework (e.g., Steps 1, 2, and 3).
- WP3, for Task *3.3. Defining current challenges and opportunities*, developed a detailed set of guidance for Pilot Leads to conduct stockpiling exercises in the

Pilots. The Pilot leads will undertake a comprehensive stock-taking exercise to identify current challenges and opportunities within their own decision-making context, as well as identify existing research data, methods, knowledge, and gaps. As a part of the task, WP3 developed common guidance protocols and templates for the stocktaking exercise which support the undertaking of two activities: i) define context and boundaries of the assessment, and ii) define the multi-risk conceptual model. For each activity, several aspects should be investigated. The context and boundaries of the assessment include current regulatory context, existing disaster risk reduction plans, past and ongoing research initiatives, in-use models, methods, and tools, system boundaries, and risk criteria. In each of these aspects, there is separate guidance on how to conduct the exercise and collect relevant data and information. For the conceptual model, these include hazards and their interactions, elements at risk and their vulnerabilities, direct and indirect risks, and risk criteria. This guidance will be especially useful in the implementation of Step 1 of the framework (e.g., system boundaries, hazards of interests). However, by giving an initial idea of risk metrics and risk evaluation criteria, it will also be helpful for other steps, for instance, Steps 2, 3, and 4. The current version of the WP3 common guidance is reported in Appendix 2 to Deliverable 3.2a Detailed annual work plan for each Pilot.
- In WP4, *Task 4.2*, an interview methodology for deriving empirical evidence on dynamics and feedback of risk drivers from stakeholders involved in the Pilots will be developed, which can inform different parts of the framework (e.g., Step 1 on hazard scenarios, Step 2 and Step 3 on risk metrics, Step 5 on possible risk management options).
- WP5 will provide multi-hazard event sets and quantification of direct and indirect risk which will directly benefit Steps 1, 2, and 3. (*Task 5.1*, *Task 5.2*, and *Task 5.3*).
- In WP6, *Task 6.1* will develop an approach for systems analysis and stakeholder engagement that allows decision-makers to accurately describe their decision-making context, including system characteristics, objectives and constraints in the current situation, and potential constraints in future situations, which aligns with the proposed framework, especially Step 1 Systems Definition.

The guiding protocols (based on the questions presented below) will be continuously updated across the MYRIAD-EU lifecycle, as the scientific work packages, and respective deliverables, are developing and as we are receiving feedback from the pilots through stakeholder engagement activities (e.g., Pilot workshops, and Pilot focus group discussions).

6.2. Initial Questions to Guide Through the Framework Steps

6.1.1. Initial guiding questions for Step 1: Finding a system definition

The objective of Step 1 is to clearly define which elements are inside the system and which are outside the system, as well as to define current challenges, identify potential solutions, and identify hazard/multi-hazard scenarios of interest.

As mentioned earlier, the boundaries of the system vary depending on *who* sets the boundaries. For example, a homeowner household considers only its own assets such as its house, an insurer considers only the assets it insures, and a national government

considers all the assets of the respective country. In other words, a homeowner may define their system as all the assets they own, an insurer defines their system as all the assets they have insured, while the national government defines their system as all the assets of that country.
Example questions to consider in Step 1 (questions are not in the order of asking nor prescribed, just for your consideration):

- What is the geographical region you are operating in/have responsibility for? For instance, an insurance company might be operating at a national scale while the local government oversees a certain geographical area (e.g., city boundaries).
- What are the main policies that are guiding your work? For instance, national disaster risk management policies, local development plans, transportation, and agricultural policies.
- Who are the other main actors you are collaborating with? For instance, the department of finance in a country might collaborate often with the department of agriculture.
- What are all natural hazards that impact you and/or your work/mandate/the geographical area you are in charge of?
- Do these hazards interrelate in any way? Can you provide us with some examples?
- What hazard scenarios are of interest to you? For instance, if only considering single hazards, it might be frequent and/or more extreme flooding. If considering multi-hazards, it might be different multi-hazard scenarios (e.g., heatwaves increasing the probability of fires or earthquakes triggering landslides).
- Thinking of these hazards and the areas they impact, can you identify exposed and vulnerable elements of your system? For instance, insurance companies are insuring households and companies, and the national government is in charge of all members/components of society, therefore these are the elements exposed that will be of interest. For vulnerability, think of it in a broader sense (e.g., the structural vulnerability of buildings, the economic vulnerability of people and companies, socially differentiated vulnerability by age, gender, and economic status).
- What are your main challenges about natural hazards? Do natural hazards, due to their impacts, affect you in reaching your goals?
- What is your vision for your system (e.g., for a sector)? What are the current challenges (i.e., sustainability challenges) you are experiencing in reaching this goal, and how do natural hazards relate to these challenges/hinder you in reaching the goal?
- What do you think is needed to reduce risk in your area/sector?
- What is important to do for risk management in your area/sector/focus but it is outside of your responsibility? Note: This question might be important for delineating what is outside of the system.
- What are the existing risk management options for the hazards of interest? What are good practices in the existing risk management options and can they be built upon? Which management options are missing, and are there gaps? What is needed to fill these gaps?

6.1.2. Initial guiding questions for Step 2: Characterization of direct risk

The objective of Step 2 is to characterize the direct risk of system elements that have been affected by direct contact with a hazard and to determine direct risk metrics. It should be noted that the affected system elements may be tangible (i.e., physical/touchable) or intangible (i.e., immaterial). In addition, impacts can be measured using market-based methods (e.g., monetary values) or other indicators (e.g., non-monetizable values such as loss of life). For instance, a household may be directly affected by flooding as the house and property will be damaged. Another household may be directly affected by earthquakes as the house and property will be damaged. An insurer may be directly affected by both losses due to claim payments. A government will be directly affected by both losses due to infrastructure losses or giving immediate assistance to households as well as in the failure of insurers (e.g. insurers of last resort).

Example questions to consider in Step 2 (questions are not in the order of asking nor prescribed, just for your consideration):

- What are direct impacts that occur due to contact of the system elements with a hazard/multi-hazard event? For instance, destruction of roads and interruption of transportation due to an earthquake, tourism sites affected, potential loss of life. As mentioned above, think of a variety of direct impacts and take into account both those that are tangible and intangible. Also, note which can be quantified and expressed in monetary terms and which cannot be.
- What are the main direct impacts of interest for the system owner? E.g., the transport sector might be interested in minimizing interruption to the transportation system. What are the metrics for these impacts? For example:
    - Loss of access to health facilities
    - Loss of numbers of fishing and transportation ships
    - Number of insurance claims
- If considering a multi-hazard scenario, how do direct impacts appear in time as the multi-hazard scenario is progressing? For instance, if we have a Hazard X in t=0 with a direct impact I_1, what is the direct impact I_2 of a Hazard X in t=1?
- For a multi-hazard scenario and characterization of direct risk, take into account how vulnerability and exposure change. For instance, buildings can be structurally weakened by an earthquake and, therefore, are more vulnerable in case of a consecutive earthquake. Similarly, a population's exposure to floods might change if people are moved to a flood prone area following a different hazard (e.g., fire).

6.1.3. Initial guiding questions for Step 3: Characterization of indirect risk

The goal of Step 3 is to characterize indirect risk arising because the direct effects of a hazard event can cause indirect effects. There are effects which are not directly caused by the hazard itself but which are still linked to the event. Such damages can often materialize in a different geographical area (i.e., in areas where the hazard did not actually hit) and at a later point in time (i.e., days, weeks, months after the event has taken place). Such indirect effects include, for instance, business interruptions because transportation routes are damaged or because supply chains are disrupted, higher levels of indebtedness, and many more. In Step 3, we characterize which of the system elements defined in Step 1 and based on direct risk in Step 2 would be indirectly affected.

Similar to Step 2, the system elements indirectly affected can be tangible (e.g., bankruptcy of other firms due to supply chain shortages) effects or intangible (e.g., loss of cultural heritage, biodiversity), The indirect effects can either be measured with market-based methods (e.g., expressed in monetary terms) or determined with other indicators (e.g. health issues arising).

Example questions to consider in Step 3 (questions are not in the order of asking nor prescribed, just for your consideration):

- What are the indirect impacts natural hazards have on your system elements? Such effects include, for instance, ripple effects along supply chains causing business or supply chain interruption, change in economic productivity.
- Please note that some of the impacts the system owner is experiencing comes not from the impact on their own system, but due to their connectedness and dependencies on other systems. For instance, small scale business in country X can be impacted due to a hazard impacting production in country Y.
- What are the main indirect impacts of interest for you as a system owner? E.g., the transport sector might be interested in minimizing economic costs to transportation due to drought impacting agriculture. What are the metrics for these impacts? For example:
    - Decreased economic output due to interruptions in supply chains
- Similar to direct risk, think of changes to vulnerability and exposure. For instance, small businesses impacted by supply chain interruptions could have higher vulnerability in a case they are impacted by a hazard directly.

6.1.4. Initial guiding questions for Step 4: Evaluation of direct and indirect risk

The goal of Step 4 is to evaluate the direct and indirect risk characterized in Step 2 and Step 3 and assess them according to a range of evaluation criteria.

Example questions to consider in Step 4 (questions are not in the order of asking nor prescribed, just for your consideration):

- Taking into account different risk metrics considered in Step 2 and Step 3, consider which risks should be acted upon and managed/minimized. Do this based on comparing the results of direct and indirect risk characterization with risk evaluation criteria. Some of the risk evaluation criteria are outlined in the questions below.
- What are the policy/legislative requirements to manage these direct and indirect risks? For instance, if a disaster risk management agency has a legal responsibility for managing flood protection infrastructure in a certain area, they might focus on upgrading the protection. Similarly, insurance agencies will focus on risks that are covered by their policies.
- What is the cost-benefit ratio for risk reduction and management? Stakeholders operate under finite and limited resources, and their decision making might be led by costs versus the benefits.

- What are the different ways to communicate the results of risk analysis as a part of risk evaluation? For instance, maps, matrices, indices and curves?
- Based on the evaluation criteria, what are the risks you will be considering risk management options for in Step 5?

6.1.5. Initial guiding questions for Step 5: Identifying risk management options

The goal of Step 5 is to come up with risk management options for direct and indirect risks selected to be managed in Step 4.

Example questions to consider in Step 5 (questions are not in the order of asking nor prescribed, just for your consideration):

- What risk management options are available/needed for reducing risks you decided through the risk analysis and evaluation process?
- What structural (e.g., physical infrastructure) and non-structural (e.g., land use policies, early warning systems) measures do you need to reduce your risks?
- To what level do these measures reduce risks? Are there any residual risks left?
- What is the process of risk management measures implementation, including timelines, responsibilities, costs?
- In the case you are considering a multi-hazard situation, what are synergies and asynergies between different risk management options? In the case of asynergies, are there any plans in place to manage these?
- What are the time horizons your risk management options correspond to? Are options for short timeframe, medium timeframe or longer timeframes?
- Did you include all stakeholders of interest for your system that would benefit from/be disadvantaged by risk management in the selection of risk management options?
- What is the level at which your risk management options are operating? Are the benefits derived only at the level of your system (e.g., in your sector, your administrative/geographical area) or are they wider and cascade across systems?
- Are the risk management options proposed risk-informed, precautionary or discursive? What are the uncertainties involved?
- Think about how risk management options might influence other sectors and systems.

6.1.6. Initial guiding questions for Step 6: Accounting for future system state

The goal of Step 6 is to consider the future system state, given larger changes (e.g., climate and environmental change) and introduction of risk management options in Step 5. Given the current evaluation and strategies against the effects of multi-hazards, the goal here is to evaluate if these strategies will fail in a future setting and how to navigate risk under different possible futures.

Example questions to consider in Step 6 (questions are not in the order of asking nor prescribed, just for your consideration):

- What are different wider influences that might change your system? Influences can be for instance climate change, urban change, economic change, demographic change. How (and if) these change for instance system boundaries, exposure and vulnerability of system elements, hazard characteristics such as frequency and magnitude).
- Further, consider how the risk management options you selected in Step 5 influence your system and other systems? Do they increase risk somewhere else? How will these perform under future system change taking into account wider influences (examples above).

6.1.7. Some guidance on stakeholder engagement

Stakeholder engagement is crucial across different steps of the framework (see Section 4). Navigating and facilitating a stakeholder engagement process is a delicate task because of the variety of stakeholders who are affected by hazards and involved in the risk management process. There are a variety of approaches to facilitating stakeholder selection, engagement, and management (e.g., various stakeholder identification techniques, participatory online, in-person, and hybrid workshops) that have been covered extensively in WP3's work and should be fully considered.

Some considerations for stakeholder engagement:

- Who are the main stakeholders you need to take into account when assessing risk and selecting risk management options? Make sure to think of stakeholders of a broad spectrum of sectors.
- What are the vested interests of these stakeholders? What are possible conflicts? How will these be managed?
- Are (and if so, to what extent) are these stakeholders part of the decision-making process/involved in determining appropriate risk management options?
- Involve stakeholders in different types of steps by asking questions that were also described in guidance questions for previous steps. For instance:
    - What hazard and hazard scenarios are of interest to you?
    - What are the hazard impacts and which impact metrics should the process of risk analysis focus on?
- Involve stakeholders in decision on the type and format of scientific outputs useful for them. What type of outputs are preferred, e.g., a less technical or more technical?

7. Concluding Remarks

In this deliverable, we presented the prototype MYRIAD-EU framework for multi-hazard, multi-sector, systemic risk management and provided an initial set of guidance protocols to aid in the implementation of the framework within the MYRIAD-EU pilots. The framework was designed as a flexible framework that can incorporate single, multi-hazard, and systemic risk assessments. It is based on a system dependency perspective and consists of six steps: (1) defining a system definition, (2) direct risk characterization, (3) indirect risk characterization, (4) direct and indirect risk assessment, (5) identifying risk management options, and (6) accounting for future system state. The framework presented in this report does not prescribe specific tools, methods, and approaches for conducting disaster risk assessments, but rather provides a broad framework which can integrate a variety of tools, methods, and approaches that have been developed and are being developed in MYRIAD-EU. The original guiding protocols were designed as a series of guiding questions for each of the six steps. Both the framework and guidance protocols will be further developed and refined throughout the MYRIAD-EU project, and especially through the interaction with the pilot stakeholders.

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