2.5 Where are we with multihazards, multirisks assessment capacities?

Jochen Zschau

2.5.1 Why do we need a change in the way we assess natural risks?

2.5.1.1 Multirisk assessment versus single-risk assessment for disaster risk management

A given location on Earth may be threatened by more than one hazard. One of the challenges of disaster risk management (DRM) is to prioritise the risks originating from these different hazards to enable decisions on appropriate and cost-effective mitigation or preparedness measures. However, comparability between risks associated with different types of natural hazards is hampered by the different procedures and metrics used for risk assessment in different hazard types (Marzocchi et al., 2012). A common multirisk framework is needed being designed around a homogeneous methodology for all perils. In addition, many of the natural processes involve frequent and complex interactions between hazards. Examples include the massive landslides triggered by an earthquake or floods and debris flows triggered by an extreme storm event.

> *Risk globalisation and climate change are great challenges that require a shift in the way we assess natural risks from a single-risk to a multirisk perspective.*

The chain of events — referred to as cascade or domino effects — can increase the total risk, and the secondary events may be more devastating than the original trigger, as shown in the 2004 Indian Ocean tsunami or the 2011 tsunami in Japan (Zschau and Fleming, 2012). Even independent events, if they occur at the same time and at the same place (e.g. hurricanes and earthquakes), may generate greater loss than the sum of totally separated single events.

The consequences of disastrous events are often propagated through the human-made system, causing interrelated technological, economic and financial disruptions, which may also result in social and political upheavals on all spatial scales. Even worldwide economies could potentially be disrupted by major disasters through their impact upon global supply chains (Zschau and Fleming, 2012). In addition, the impact of one hazard may increase the potential harmful effect of another hazard. For example, by changing vegetation and soil properties, forest fires may increase the probability of debris and flash floods (Cannon and De Graff, 2009). Similarly, a building's vulnerability to ground shaking may increase due to additional structural loads following volcanic ash fall or heavy snowfall (Lee and Rosowsky, 2006; Zuccaro et al., 2008; Selva, 2013). Vulnerability in these cases would be highly time variant.

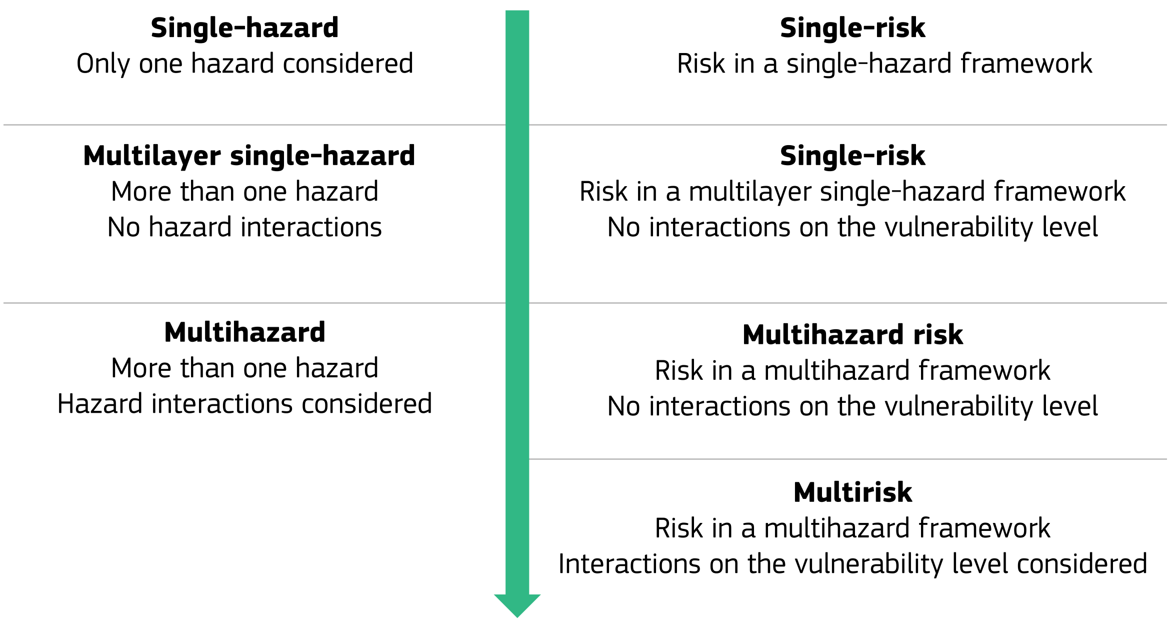
Multihazard risk approaches start from single-hazard risk assessments. Figure 2.19 attempts to capture the transition from single-hazard to multihazard risk as well as the definitions used. Single-hazard risk is the most common method.

2.5.1.2 Emerging challenges: risk globalization and climate change

The risks arising from natural hazards have become globally interdependent and, therefore, not yet fully understood. The ongoing 'urban explosion', particularly in the Third World, an increasingly complex cross-linking of critical infrastructure and lifelines in the industrial nations as well as an increasing vulnerability due to climate change and growing globalisation of the world's economy, communication and transport systems, may play a major part (Zschau and Fleming, 2012, Gencer, 2013). These factors are responsible for high-risk dynamics and also constitute some of the major driving forces for disaster risk globalisation. Communities are affected by extreme events in their own countries and become more vulnerable to those occurring outside their national territories. The effects of a destructive earthquake in Tokyo, for instance, may influence London through shaky global markets and investments; or a disaster in a global city such as Los Angeles may affect developing economies like Mexico and can put the already vulnerable poor into further poverty (Gencer, 2013). In addition, the increased mobility of people can spatially enlarge the scale of natural disasters. This was demonstrated, for example, by the fatal tsunami disaster of 2004 along the coasts of the Indian Ocean, where the victims did not only come from the neighbouring countries, but included nearly 2 000 citizens from Europe, for instance, most of whom had been visiting resorts in the affected region during their Christmas holidays when the tsunami struck. Globalisation is not

FIGURE 2.19

From 'single-hazard' to 'multirisk' assessment and terminology adopted here.
Source: courtesy of author



the only reason for the growing interdependencies and the high dynamics seen in the risks from natural hazards. Climate change may be another important factor. According to IPCC (2014), it is very likely that extreme events will occur with higher frequency, longer duration and different spatial distribution. Climate change is also projected to increase the displacement of people, which will lead to an increase of exposure to extreme events. They will be exposed to different climate change impacts and consequences such as storms, coastal erosion, sea level rise and saltwater intrusion (Nicholls and Cazenave, 2010).

A multirisk modelling approach will be required in order to capture the dynamic nature and various interactions of the hazard and risk-related processes driven by both climate change and globalisation. Moreover, the sought-after solutions for risk assessments are no longer exclusively aiming at the best possible quantification of the present risks, but also at keeping an eye on their changes with time and allowing to project these into the future.

2.5.2 Towards multirisk assessment methodology: where do we stand?

2.5.2.1 Sources of our present knowledge: the role of EU-funded projects

The Agenda 21 for Sustainable Development (UNEP, 1992), the Johannesburg Plan for Implementation (UN 2002), the Hyogo Framework for Action (UNISDR, 2005) and the Sendai Framework for Disaster Risk Reduction (UNISDR, 2015) promote multihazard risks of natural hazards. Together with the International Decade for Natural Disaster Reduction (IDNDR) from 1990 to 1999 and the following permanently installed International Strategy for Disaster Reduction (ISDR), they constitute a worldwide political framework for the initiation of a multitude of scientific projects in the risk research community (Zentel and Glade, 2013). These projects include global index-based multihazard risk analysis such as Natural Disaster Hotspots (Dilley et al., 2005) or INFORM (De Groeve et al., 2015). They also include regional multihazard initiatives like the cities project for geohazards in Australian urban communities (Middelmann and Granger, 2000), the Risk Scape project in New Zealand (Schmidt et al., 2011) and the platforms HAZUS (FEMA, 2011) and CAPRA (Marulanda et al., 2013) for the automated computation of multihazard risks in the United States and Central America, respectively.

The European Union funded projects on multihazard and multirisk assessment within its framework programmes FP4, FP5, FP6 and FP7. The TIGRA project (Del Monaco et al., 1999) and the TEMRAP project (European Commission, 2000) were among the first attempts to homogenise the existing risk assessment methodologies among individual perils. The European Spatial Planning Observation Network (ESPON) compiled aggregated hazard maps weighting the individual hazards by means of expert opinion and taking into account various natural and technological hazards in Europe (Schmidt-Thomé, 2005).

A multirisk assessment framework should allow for the comparison of risks and account for dynamic vulnerability as well as complex chain reactions on both the hazard and vulnerability levels

Quantitative, fully probabilistic methods for multihazard and multirisk assessment were developed in a series of FP6 and FP7 projects: Na.R.As. 2004-2006 (Marzocchi et al., 2009), ARMONIA 2004-2007 (Del Monaco et al., 2007) and MATRIX 2010-2013 (Liu et al., 2015). Their results allow independent extreme events (coinciding or not coinciding) as well as dependent ones, including cascades, to be treated on both the hazard and the vulnerability levels. Moreover, these projects have time-dependent vulnerability taken into account. Their methods were applied in the CLUVA project 2010-2013 to future projections of the influence of climate change on natural hazards and urban risks in Africa (Bucchignani et al., 2014; Garcia-Aristizabal et al., 2015 a, b, 2016) as well as in the CRISMA project 2012-2015 to crisis scenario modelling for improved action and preparedness(Garcia-Aristizabal et al., 2014).

In addition, projects in Europe funded on a national or regional basis have contributed significantly to our present knowledge on multirisk assessment. The German Research Network for Natural Disasters (DFNK), which had undertaken comparative multirisk assessments for the city of Cologne (Grünthal et al., 2006), gives an example of this. The Piedmont region project in Italy, with a focus on a methodological approach for the definition of multirisk maps (Carpignano et al., 2009), and the ByMuR project 2011-2014 on the application of the Bayesian probabilistic multirisk assessment approach to natural risks in the city of Naples (Selva, 2013) are two other examples. Furthermore, the Centre for Risk Studies of the University of Cambridge in the United Kingdom is presently one of the first to systematically address the globalisation aspect of risk. The centre is currently setting up a global threat taxonomy and a risk assessment framework aiming at macro-catastrophe threats that have the potential to cause large-scale damage and disruption to social and economic networks in the modern globalised world (Coburn et al., 2014).

2.5.2.2 Multilayer single-risk assessments: harmonisation for risk comparability

In order to assist decision-makers in the field of DRM in their prioritising of mitigation actions, one has to understand the relative importance of different hazards and risks for a given region. This requires the threats arising from different perils to be comparable with each other. However, this is difficult, because different hazards differ in their nature, return period and intensity, as well as the effects they may have on exposed elements. Moreover, the reference units, such as ground acceleration or macroseismic intensity for earthquakes, discharge or inundation depth for floods and wind speed for storms, are different among the hazards. This does not only hamper the comparability between the threats, but it also makes it difficult to aggregate the single perils in a meaningful way in order to assess the total threat coming from all the hazards in a region. These problems exist independently of whether hazard interactions and/or interactions on the vulnerability level are important or not. Thus, to overcome them, and as a first step towards a full multirisk assessment, one may treat them in the context of a multilayer single-hazard/risk assessment approach, ignoring the interactions but harmonising and standardising the assessment procedures among the different perils.

Three major standardisation schemes can be distinguished in this context (Kappes et al., 2012; Papathoma-Köhle, 2016). They make use of:

- matrices — hazard matrix, vulnerability matrix and risk matrix;
- indices — hazard index, vulnerability index and risk index; and
- curves — hazard curves, vulnerability curves and risk curves.

They are applicable on all three assessment levels: hazard, vulnerability and risk, respectively.

Matrices

A hazard matrix applies a colour code to classify certain hazards by the intensity and frequency (occurrence probabilities) determined qualitatively, for instance 'low', 'moderate' and 'high (Figure 2.20). Based on this, one can compare the importance of hazards and one may derive the overall hazard map by overlaying the classification results of all single hazards. An example of this approach is the risk management of natural hazards in Switzerland (Figure 2.20, redrawn from Kunz and Hurni, 2008; see also Loat, 2010). The European Commission-funded Armonia project (Applied Multi-Risk Mapping of Natural Hazards for Impact Assessment) has proposed a similar classification scheme (Del Monaco et al., 2007). Likewise, the French risk prevention plans (Cariam, 2006) follow this kind of approach.

Like in the 'hazard case', overarching matrix schemes also exist on the vulnerability level. So-called damage matrices, for example, are discrete approaches to vulnerability assessment that oppose relative damage or damage grades to classified hazard intensities in a matrix. The resulting vulnerability (fragility) is either qualitatively described (few, many or most), for instance as the proportion of buildings that belong to each damage grade for various levels of intensity (see Grünthal, 1998 in relation to the European macroseismic scale), or quantitatively described as the probability to reach a certain damage grade (Tyagunov et al., 2006).

For the aim of comparing and aggregating risks coming from multiple hazards, assessment procedures are required that combine both hazard and vulnerability information. Various authors (e.g. Sterlacchini et al., 2007; Sperling et al., 2007; Greiving, 2006) have suggested matrix schemes that fulfil this requirement. The European Commission (2010) proposed a risk matrix that relates the two dimensions, likelihood (probability) and impact (loss), for a graphical representation of multiple risks in a comparative way (Figure 2.21). Distinct matrices were suggested for human impact, economic and environmental impact and political/social impact, as these categories are measured with distinct scales and would otherwise be difficult to compare.

Indices

Apart from the matrix-based approaches described above, index-based approaches are another means to achieve comparability in the multilayer single-hazard and -risk context. The methodology of composite indicators allows to combine various indicators to obtain a meaningful measure.

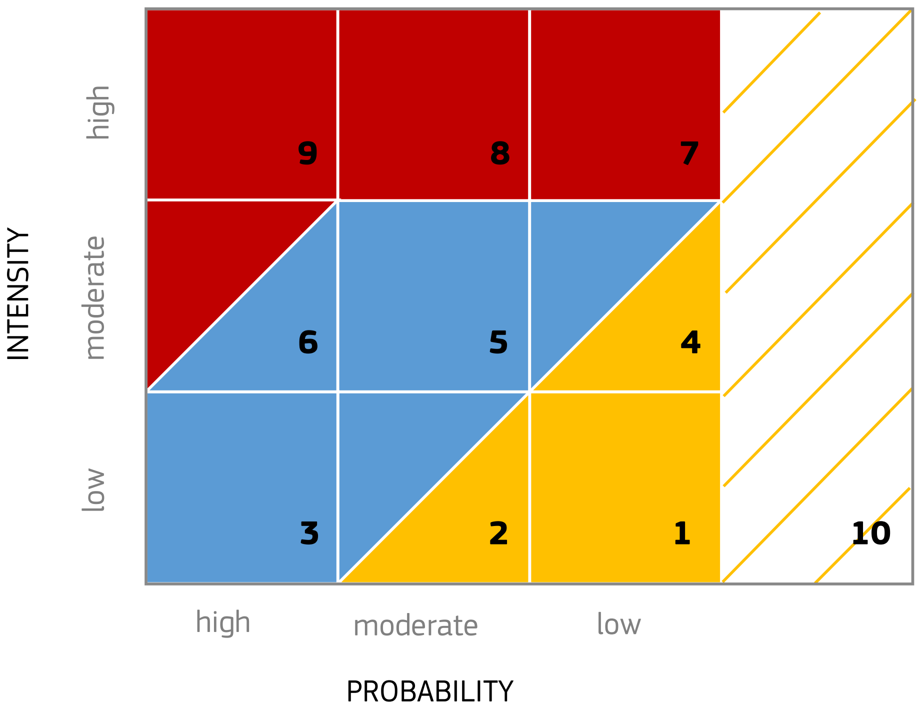
An example of an index-based approach on the hazard level is global Natural Disaster Hotspots (see also Chapter 2.5.2.1), which is an aggregated multihazard index calculated from the exposure of a region to various hazards and is used to identify key 'hotspots', where the exposure to natural disasters is particularly high. A more recent example was put forward by Petitta et al. (2016) who suggested a multihazard index for extreme events capable of tracking changes in the frequency or magnitude of extreme weather events.

Vulnerability indices (see also Chapter 2.3) are already widely used in the socioeconomic field, including multihazard settings, as for example in the studies of Wisner et al. (2004), Collins et al. (2009) and Lazarus (2011), but they are rarely hazard specific (Kappes et al., 2011). In contrary , physical vulnerability is regarded as hazard- specific. An increasing number of studies is now available that applies hazard-specific vulnerability indicators to, for instance, tsunamis (Papathoma et al., 2003), floods (Barroca et al., 2006, Balica et al., 2009; Müller et al., 2011), landslides (Papathoma-Köhle et al., 2007; Silva and Pereira, 2014) and mountain hazards (Kappes et al., 2011). In various cases the indicators are combined with the PTVA (Papathoma Tsunami Vulnerability Assessment) method (Papathoma and Dominey-Howes, 2008).

Going from vulnerability indices to risk indices is another solution to achieving comparability in the multilayer single-risk context. As a risk indicator includes hazard information in addition to vulnerability information, such a step also allows the aggregation of the risks coming from different perils. Dilley et al. (2005), who computed hazard and vulnerability for natural hazards on a global scale and weighted the hazard with the vulnerability index to calculate risk, gave an example. For the derivation of the multihazard risk, all single-hazard

FIGURE 2.20

Swiss hazard matrix
Source: Kunz and Hurni (2008)



risks were added up.

All three levels of an index-based approach, i.e. the hazard, vulnerability and risk levels, are addressed in the ongoing European project INFORM (see also Chapter 2.5.2.1), where separate indices for hazard and exposure, vulnerability, lack of coping capacity and risk are developed in order to identify countries where the humanitarian crisis and disaster risk would overwhelm national response capacity.

Curves

More quantitative methods for assessing natural threats in a multilayer single-hazard approach are based on 'curves' ('functions').

Hazard curves present the exceedance probabilities for a certain hazard's intensities in a given period. Vulnerability curves graphically relate the loss or the conditional probability of loss exceedance to the intensity measure of a hazard (for instance ground motion, wind speed or ash load) in order to quantify the vulnerability of elements at risk. When the probability of exceeding certain damage levels is considered, the curves are referred to as 'fragility curves'.

One may easily combine vulnerability curves with the corresponding hazard curves to arrive at a measure of risk. This could be the average loss per considered period, the so-called average annual loss or expected annual loss, if the period is 1 year. It could also be a risk curve, which graphically relates the probability of loss exceedance within the period under consideration to the loss coming from all possible hazard intensities. As exceedance probabilities and loss are not expressed in hazard-specific units, they are directly comparable among different hazards and can easily be aggregated to an overall multilayer single risk.

Figure 2.22 shows the annual exceedance probability of direct economic loss from earthquakes, floods and storms in the city of Cologne (Grünthal et al., 2006). Storms turn out to be the dominant risk at return periods lower than 8years (largest loss!). Floods take over for higher return periods up to 200 years and earthquakes become the dominant risk for return periods higher than 200 years.

A comparison between the risks from the different perils can be accomplished based on the expected average loss within the considered period represented by the area under the risk curve (Van Westen et al., 2002).

Fleming et al. (2016) demonstrated that one may also easily aggregate the single-hazard-specific risk curves to obtain a 'total risk' curve without considering potential interactions between the hazards. Figure 2.23 shows the wind, storm and earthquake risks for the city of Cologne. The various aggregations of the risk probabilities, for instance for loss in the order of EUR 100 million, indicate enhanced loss probabilities from between 15 % and 35 % for the individual hazards and up to 56 % in 50 years when combined.

FIGURE 2.21

Risk matrix proposed by the European Commission
Source: European Commission (2010)

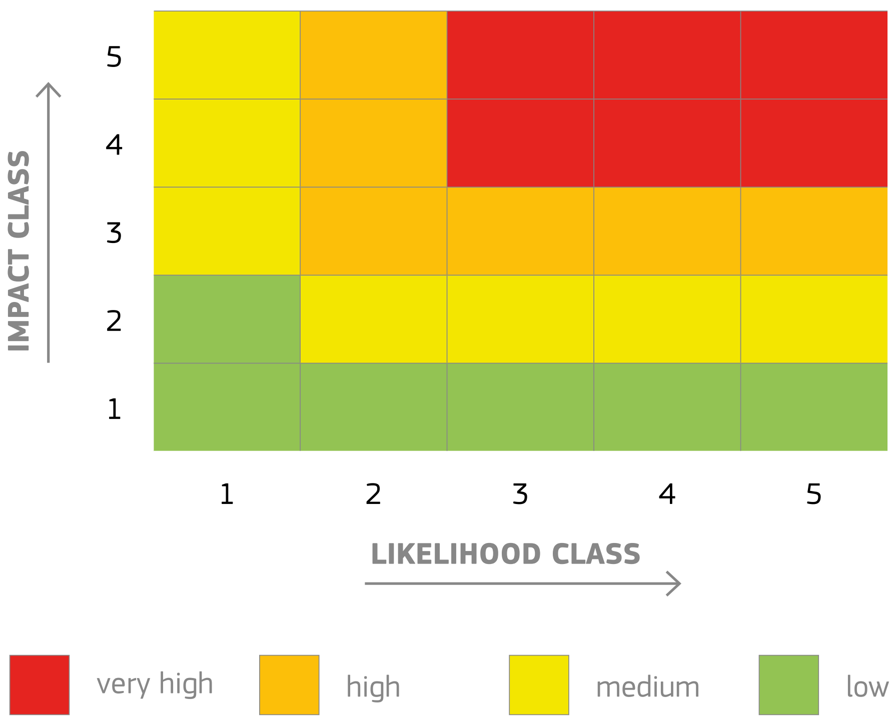


FIGURE 2.22

Risk curves for the city of Cologne
Source: Grünthal et al. (2006)

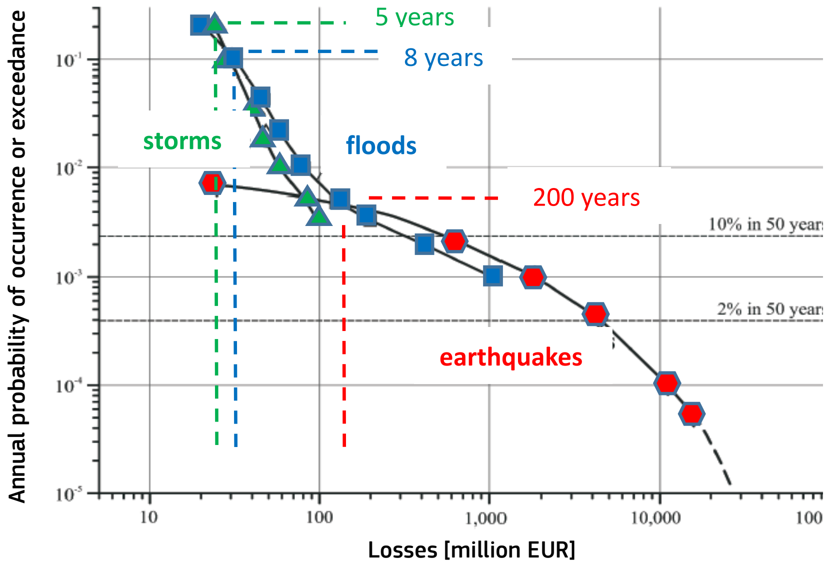
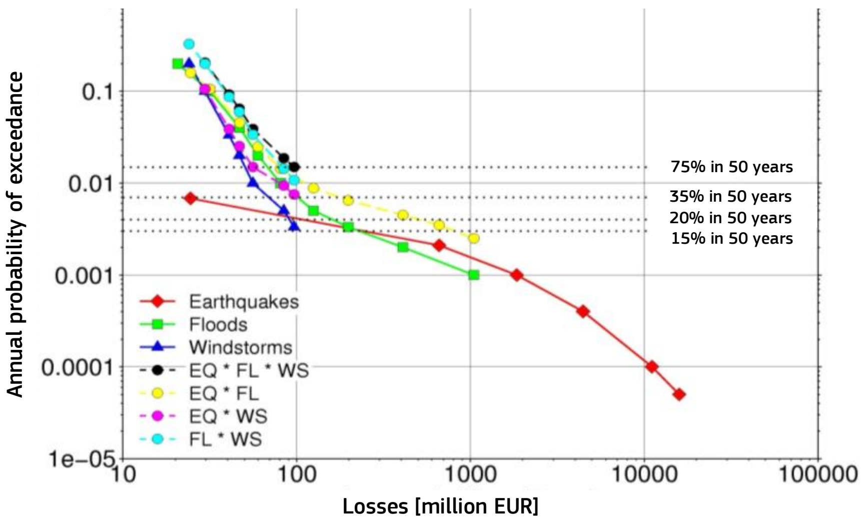


FIGURE 2.23

Risk curves and their aggregations for the city of Cologne
Source: Fleming et al. (2016)



Hazard, vulnerability and risk curves are the quantitative equivalent to the hazard, vulnerability (damage) and risk matrices. On the other hand, there is a distinct difference between them: the curves only make use of two dimensions, frequency and impact, to characterise risk, whereas matrices use three dimensions, by additionally introducing colour codes. The third dimension expresses different levels of risk from 'low' to 'high' with different colours, which gives extra weight to either the impact or the likelihood (see, for instance, Figure 2.21).

This is an added value of risk matrices, since the additional colour code makes it possible to compare high-probability and low-consequences events with low-probability and high-consequences ones, for instance. To extract similar information from risk curves, probabilities and loss can simply be multiplied (P×L). The lines of equal loss–probability products, P×L, in a logarithmic risk curve plot would be straight diagonal lines (Figure 2.24, left). In the case of a single-risk scenario with a given annual probability, the loss-probability-product directly represents the average annual loss (impact). This is not the case for the risk curve, which includes the loss from all possible hazard intensities. However, one may easily show that in this case it represents the contribution to the average annual loss per increment of logarithmic probability. Thus, from additionally displaying the exceedance probability as a function of the loss-probability-product instead of the loss alone, one may learn which part of the risk curve, in terms of return periods, will contribute most to the average annual loss. In the case of Cologne (Figure 2.24, right), storms and floods contribute the most in the range of small return periods, whereas for earthquakes the return periods of around 1 000 years have the highest contribution to the average annual loss.

The probabilistic concept of risk curves is used for both economic losses of a potential disaster and the indirect, socioeconomic impacts, as long as these are tangible. As examples, Garcia-Aristizabal et al. (2015a) mention losses in work productivity, losses due to missing income, costs of evacuation and the costs of medical assistance as well as effects of the loss of functionality of systems and networks including disruptions of productivity and the means of production. Garcia-Aristizabal et al. (2015a) also describe how the information from the socioeconomic context can be integrated straightforwardly into the quantitative multi-layer risk framework by harmonizing the metrics of the different loss indicators and producing the single loss exceedance curves and their sum, respectively, equivalent to the methodology used for direct losses. However, this needs to introduce quantitative vulnerability/fragility information for each of the different indicators or even their respective vulnerability/fragility curves, which still is the bottleneck of the method.

2.5.2.3 Hazard interactions: cascading events and Co.

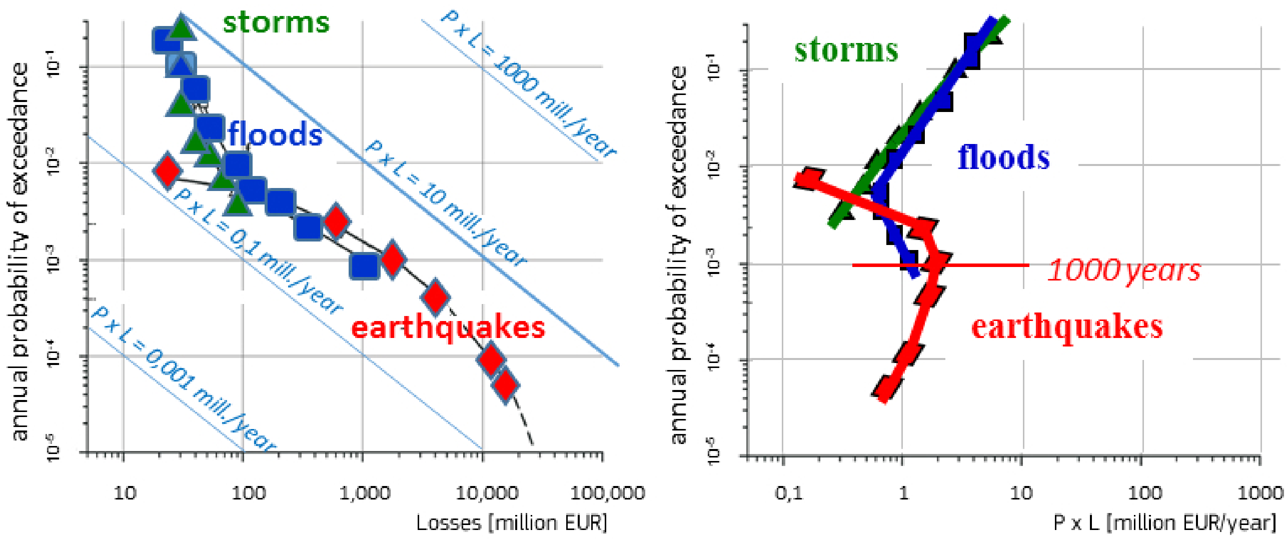
Multilayer single-risk assessments, as described in the previous section, analyse the risks coming from different perils separately. Assuming independence between the hazard-specific risks, they simply add them up to obtain the overall hazard in a region. However, in a complex system like nature, processes are very often dependent on each other, and interact. There are various kinds of interactions between hazards that often lead to significantly more severe negative consequences for the society than when they act separately. A multilayer single-risk perspective does not consider this, but a multihazard approach does.

Classification of hazard interactions

The complexity of interactions between hazards has led to a multitude of terms in use for describing different types of interdependencies. The term ‘cascades’ has been used, for instance, by Carpignano et al. (2009), Zuccaro and Leone (2011), Choine et al. (2015) and Pescarol and Alexander (2015); ‘chains’ by Xu et al. (2014), among others; and ‘interaction hazard networks’ by Gill and Malamud

FIGURE 2.24

Risk curves and P x L - curves for the city of Cologne (Exceedance probability versus loss (left) and versus its product with loss (right)
Source: courtesy of author



(2016). Further terms in use are 'coinciding hazards' (Tarveinen et al., 2006; European Commission, 2010), 'coupled events' (Marzocchi et al. 2009), 'domino effects' (Luino, 2005), 'follow-on events' (European Commission, 2010) and 'triggering effects' (Marzocchi et al., 2009). More of such terms are presented and explained in Kappes et al. (2012).

Gill and Malamud (2014, 2016) suggested classifying the different hazard interaction types into five groups (Box 1). In the first group, the 'triggering relationship', the secondary (triggered) hazard, might be of the same type as the primary (triggering) one or different, for instance an earthquake that triggers another one or a rainfall event that triggers a landslide, respectively. In the second group, the 'increased probability relationship', the primary hazard, does not directly trigger a secondary event but changes some aspects of the natural environment, leading to an increase of the probability of another hazard. For instance, in the event of a wildfire, vegetation is destroyed, which can result in an increased vulnerability of a slope to landslides (Gill and Malamud, 2014). In the third group, 'decreased probability relationship', the probability of a secondary hazard is decreased due to a primary hazard (third group), therefore it does not pose a problem to risk management. Gill and Malamud (2014) gave the example of a heavy rainfall event that increases the surface moisture content, whereby reducing the depth to the water table and consequently decreasing the probability of a wildfire. Similarly, the spatial and temporal coincidence of events, the 'coincidence relationship' (fourth group), may be considered as some kind of interaction, because although independent of each other, together they can increase the impacts beyond the sum of the single components if the hazards had occurred separately in time and space. An example can be seen in the coincidence of the Mount Pinatubo volcano eruption in 1991 with Typhoon Yunya (Gill and Malamud, 2016), where the combination of thick and heavy wet ash deposits with rainfall triggered both lahars (Self, 2006) and structural failures (Chester, 1993). In the fifth group, the 'catalysis/impedance relationship' between hazards, a triggering relation between two hazards may be catalysed or impeded by a third one. A volcanic eruption, for instance, can trigger wildfires, but this triggering interaction may be impeded by a tropical storm.

Furthermore, anthropogenic and technological hazards may interact with natural hazards, not only by the trigger and increased probability relationships, but also by catalysis/impedance relationships. These may include, for example, storms impeding an urban fire-triggered structural collapse or storm-triggered floods, which are catalysed by a blocking of drainage due to technological failures.

Based on geophysical environmental factors in the hazard-forming environment, Liu et al. (2016) proposed a different classification scheme for hazard interactions by distinguishing between stable environmental factors, which form the precondition for the occurrence of natural hazards, and trigger factors, which determine the frequency and magnitude of hazards. Dependent on these environmental factors, one may divide the hazard relationships into four classes: independent, mutex (mutually exclusive), parallel (more than one hazard triggered in parallel) and series relationships (one hazard follows another). Classification schemes for hazard interactions help to ensure that all possible hazard interactions among different hazards are considered in a

BOX 2.1

Classification of hazard interactions

Source: Gill and Malamud (2014, 2016)

- (1) Triggering relationship
- (2) Increased probability relationship
- (3) Decreased probability relationship
- (4) Coincidence relationship
- (5) Catalysis/ impedance relationship

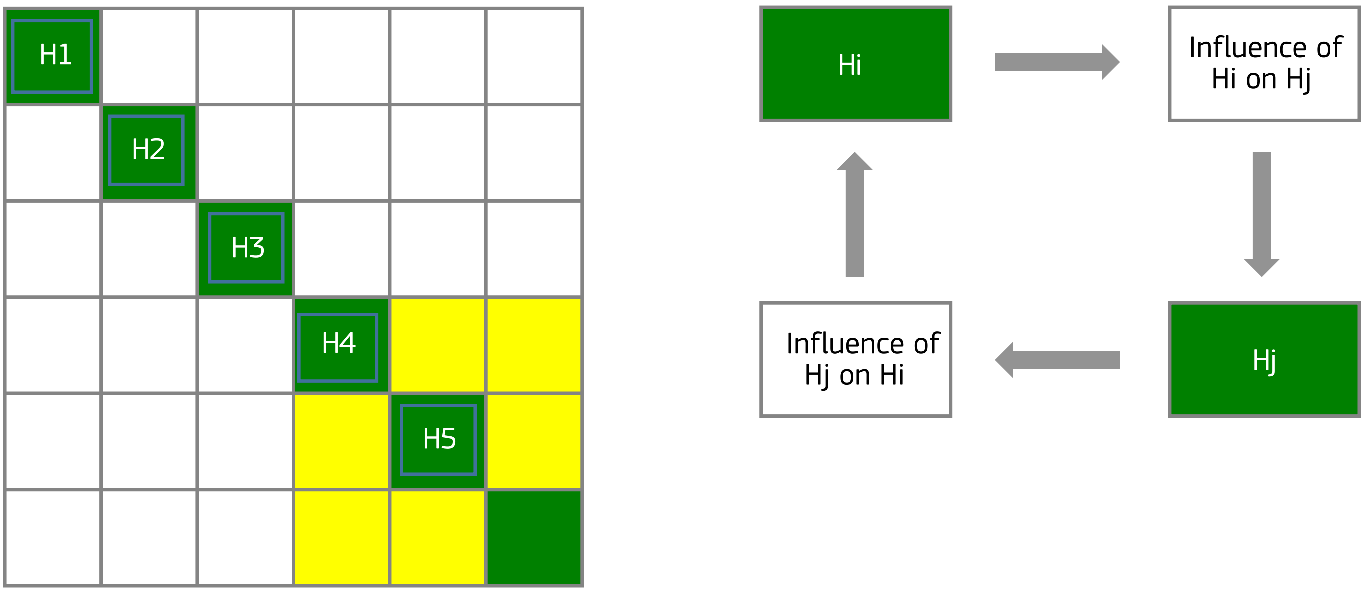
multihazard risk assessment (Liu et al., 2016).

Methods

Among the available methods to integrate hazard interactions into disaster risk assessment, there are qualitative, semi-quantitative and quantitative ones. Qualitative methods settle for qualitative descriptions and classifications of interactions with the aim of identifying the most important hazard relations in a region. Semi-quantitative approaches are mainly based on so-called hazard-interaction matrices (not to be confused with the hazard matrix addressed in Chapter 2.5.2.2). They offer a structured approach to examine and visualise hazard interactions and to see how strong these interactions are, aiming not only at the identification of important hazard relations but also at getting insight into the evolution of the system when different hazards interact. This kind of matrix has been used, for instance, by Tarvainen et al. (2006), De Pippo et

FIGURE 2.25

Matrix approach for the identification of hazard interactions.
Source: Liu et al. (2015)



Slides (H4)	2	2
0	Debris flows (H5)	2
1	1	River floods (H6)

0 – No interaction

1 – Weak interaction

2 – Medium interaction

3 – Strong interaction

Slides (H4)	Deposits only	Cut off a flow in a water course
No interaction	Debris flows (H5)	Change of river bed morphology
Erosion / saturation of deposits	Re-mobilisation of deposits	River floods (H6)

al. (2008), Kappes et al. (2010), Gill and Malamud (2014), Mignan et al (2014) and Liu et al. (2015). Figure 2.25 gives an example of how this matrix approach can be used in multihazard assessment: first, the matrix is set up in a way that all potentially interacting hazards in the region under consideration are occurring in the matrix's diagonal (Figure 2.25a). The possible interactions are described in a clockwise scheme (Figure 2.25b), which results in the influences of a hazard on the system appearing in the related matrix row and the influences of the system on the hazard in the hazard's column (Figure 2.25c). In addition, a coding between 0 and 3 is used (Figure 2.25d) to semi-quantitatively describe how strong the interactions are between the different hazards, respectively, and are entered into the matrix (Figure 2.25e). Liu et al. (2015) propose this scheme to be used as second level in their three-level framework from qualitative to quantitative multirisk assessment in order to decide whether it is justified to go to the third quantitative level of assessment or not.

Gill and Malamud (2014) have used a similar kind of matrix to characterise the interaction relationships between 21 natural hazards, both qualitatively as well as semi-quantitatively. This matrix identifies and describes hazard relations and potential cascades as well as characterises the different relationships between the intensity of the primary hazard and the potential intensity of the secondary hazard in both the triggering and increased probability cases. Moreover, they were able to indicate the spatial overlap and temporal likelihood of each triggering relationship.

Quantitative methods for integrating hazard interactions into disaster risk assessment are mainly based on event tree and fault tree strategies (see the event tree example in Figure 2.26 for volcano eruption forecasting) combined with probabilistic approaches for quantifying each branch of the tree. Among them, the concept of Bayesian event trees, where the weight assigned to a branch of a node in the tree is not a fixed single value but a random variable drawn from a probability distribution function, is of particular interest. It allows the rigorous propagation of uncertainties through the different computation layers when simulating all the hazard relations in a complex chain. The event tree structure (Newhall and Hoblitt, 2002; Marzocchi et al., 2004, 2008, 2010; Selva et al., 2012) is particularly suitable for describing scenarios composed by event chains. Neri et al. (2008), for instance, compiled a probability tree for future scenarios at the volcano Mount Vesuvius, including various eruption styles and secondary hazards associated with them. Marzocchi et al. (2009, 2012) also employed a probabilistic event tree to analyse triggering effects in a risk assessment framework. Moreover, Neri et al. (2013) used a probability/scenario tree for multihazard mapping around the Kanlaon volcano in the Philippines. However, the available quantitative studies in this field that explicitly consider hazard interactions remain rare (Liu et al., 2015).

The probabilistic framework to be combined with an event tree strategy for quantifying hazard interactions has been discussed in Marzocchi et al. (2004, 2008, 2010 and 2012); Selva (2013); Garcia-Aristizabal and Marzocchi (2013); Gasparini and Garcia-Aristizabal (2014); and Garcia-Aristizabal et al. (2015a). It is equivalent to the probabilistic framework for the multilayer hazard assessment introduced in Chapter 2.5.2.2, where the single hazards are quantified by their hazard curves, respectively, and are combined with vulnerability curves to obtain the probability of potential loss. The difference, however, is that in the case of interactions between two perils, the secondary hazard's probabilities for all possible intensity scenarios will form a hazard surface rather than a hazard curve (Figure 2.27).

So far, vulnerability has been considered as static. Like exposure, vulnerability is also highly dynamic regardless of whether it is physical, functional or socioeconomic

This is because the probability of a hazard event that has been affected by another one depends on the intensities of both the primary and secondary events.

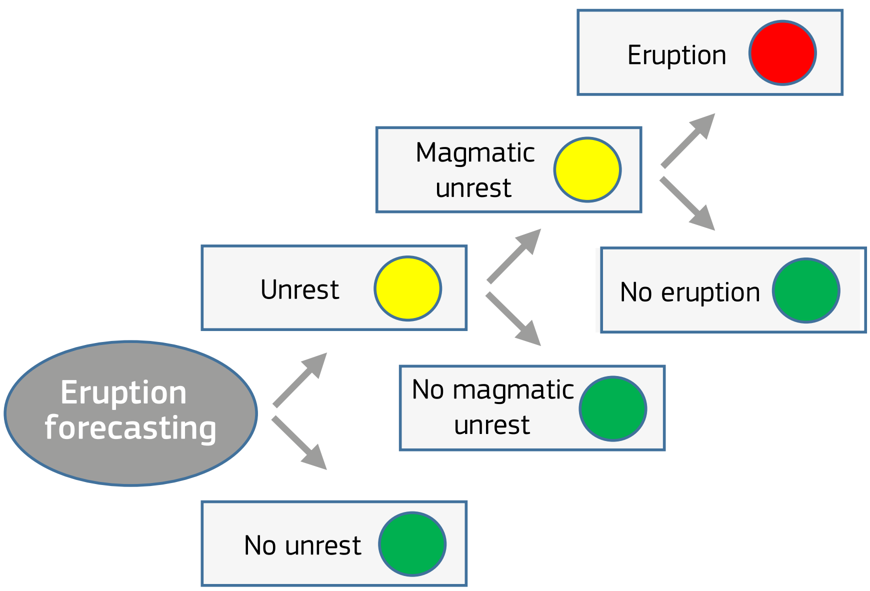
Long-term event databases on a certain hazard may already contain the secondary events arising from interactions with other primary hazards (Marzocchi et al., 2012). Hence, for long-term problems, e.g. when the tsunami hazard over the next 50 years is to be assessed, there is no need to apply a multihazard methodology. A multilayer single hazard one would do, as was demonstrated by Garcia-Aristizabal et al. (2015b) with regard to future projections of the climate-related triggering of floods, drought and desertification in the area of Dar es Salaam (Tanzania) until 2050. However, in the short term (e.g. hours to days), for instance, when heavy rain changes the landslide occurrence probability in a time horizon of a few days, a multihazard approach is necessary to account for this interaction.

Marzocchi et al. (2012) also gave a simple example showing how the adoption of a single-hazard perspective instead of a multihazard one could be misleading in a short-term problem. Their example addresses the possible collapse of a pipe bridge in the Casalnuovo municipality in southern Italy, which has an increased probability, when volcanic activity triggers heavy ash loads. The collapse in an industrial centre could cause an explosion and subsequent air and water contamination. In this example it appeared that one would underestimate the probability of a pipe bridge collapse and, hence, the industrial risks (explosion, contamination) that might follow from it by more than one order of magnitude, if the secondary ash loads from volcanic activity were neglected.

A full hazard curve to quantify hazard interactions is still rare, although Garcia-Aristizabal et al. (2013) have shown that this is possible when they presented hazard curves for volcanic swarms and earthquakes triggered by volcanic unrest in the region of Naples.

FIGURE 2.26

Event tree scheme for eruption forecasting
Source: Selva et al. (2012)



Application to climate change

Based on the concept of risk curves above, it is not immediately visible the extent to which the probabilistic framework is also suitable for treating the interactions of climate change with natural hazards. The reason is that the framework has its origins in stationary processes, whereas an impact of climate change on natural hazards, resulting in more or less gradual changes regarding the hazards' frequencies and their intensity extremes, represents a non-stationary process. The methodology applied to it has to account for this (see, for instance, Solomon et al., 2007; Ouarda and El Adlouni, 2011; Seidou et al., 2011, 2012). The problem is rendered even more difficult by the fact that the probabilities of future extremes could be outside the data range of past and present observations and, hence, we cannot draw on experience, i.e. on existing data catalogues. A solution to the problem comes from extreme value theory, as this theory aims at deriving a probability distribution of events at the far end of the upper and lower ranges of the probability distributions (Coles, 2001), where data do not exist or are very rare.

The generalised extreme value distribution, combined with a non-stationary approach (the so-called non-stationary GEV model), is therefore, widely applied today to predict the effects of climate change on meteorological hazards. Examples are El Adlouni et al. (2007) and Cannon (2010) for precipitation, Siliverstovs et al. (2010) for heat waves, Seidou et al. (2011, 2012) for floods and Garcia-Aristizabal et al. (2015b) for extreme temperature and precipitation. How this approach can be integrated into the above probabilistic framework for multihazard and multihazard risk assessment was demonstrated by Garcia-Aristizabal (2015b), who succeeded in harmonising the outcome of the non-stationary GEV model application to Dar es Salaam in Tanzania in the form of time-dependent, high-resolution probabilistic hazard maps and hazard curves.

2.5.2.4 Dynamic vulnerability: time- and state-dependent

The different types of vulnerability dynamics

One may distinguish between two types of vulnerability dynamics, the time-dependent and the state-dependent one. In the first, we refer to more or less gradual changes of vulnerability with time. In the second, vulnerability depends on a certain state of a system that may change abruptly, due to a natural hazard event, for instance. If a load on a system (e.g. snow on a roof) determines the relevant vulnerability state, the expression would be 'load-dependent vulnerability'; if it is about a pre-damage state (e.g. a building that has been pre-damaged by a seismic main shock and threatened by aftershocks), the term 'pre-damage-dependent vulnerability' is employed.

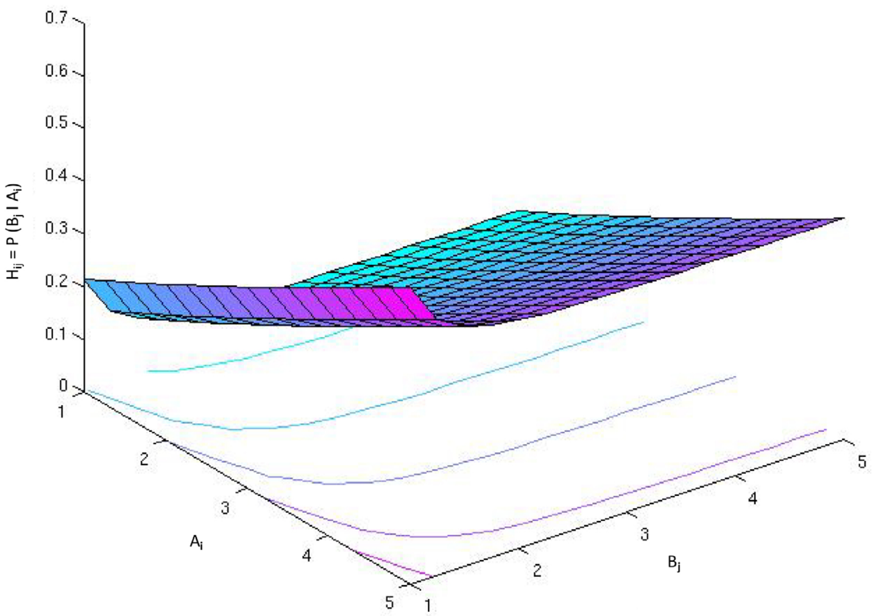
The term 'time-dependent vulnerability' is used in the engineering community for distinguishing between the gradual deterioration of a building's fragility due to corrosion and the abrupt changes when an earthquake strikes.

Time-dependent vulnerability

Time-dependent vulnerability dynamics may have many origins, depending on the problem under consideration and the dimension of vulnerability involved, i.e. social, economic, physical, cultural, environmental or institutional (for the dimensions of vulnerability see Birkmann et al. 2013). Vulnerability changes due to the ageing of structures, for instance, have been addressed by Ghosh and Padgett (2010), Choe et al. (2010), Giorgio et al. (2011), Yalcinev et al. (2012), Karapetrou et al. (2013) and Iervolino et al. (2015 a), among others. Münzberg et al. (2014) pointed to power outages, where the consequences and hence the vulnerability of the public may progressively change within hours or days. Moreover, Aubrecht et al. (2012) made short-term social vulnerability changes in terms of human exposure in the diurnal cycle subject of discussion. In the long term, especially when regarding the possible effects of climate change and globalisation over the next decades, the interacting social, economic and cultural factors will probably be the most important drivers of vulnerability dynamics. These include demographic, institutional and governance factors (IPCC, 2012; Aubrecht et al., 2012; Oppenheimer et al., 2014). Some of them could be related to the rapid and unsustainable urban development, international financial pressures and increases in socioeconomic inequalities, as well as failures in governance and environ-

FIGURE 2.27

Example of a hazard surface, Hij, describing hazard interaction as a probability surface that depends on all possible intensities, Ai and Bj, of the primary event 'A' and of the secondary event 'B', respectively
Source: Garcia-Aristizabal and Marzocchi (2013)



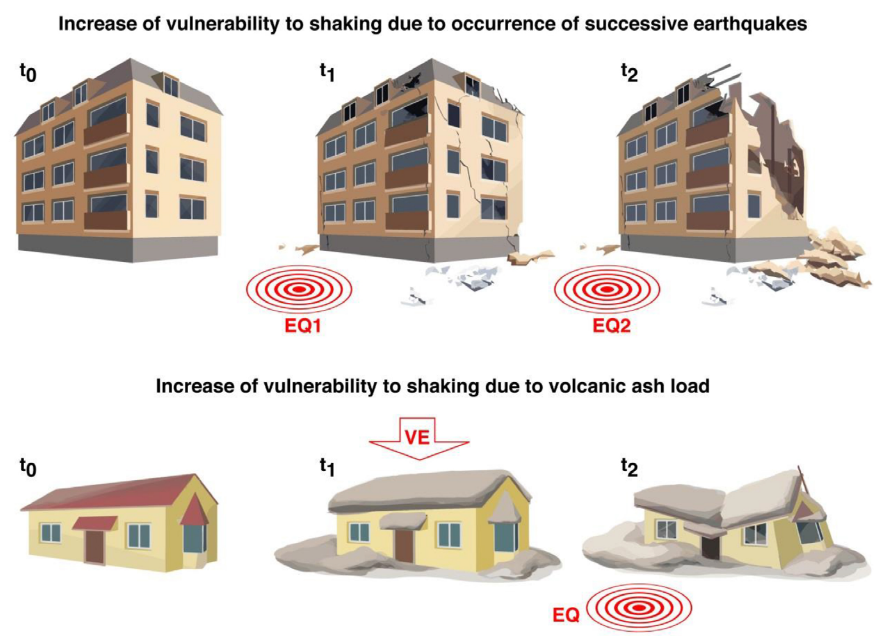
mental degradation (Oppenheimer et al. 2014).

State-dependent vulnerability

The more abrupt state-dependent vulnerability changes occur when two hazards interact on the vulnerability level and the first one alters the exposure or the state of exposed elements in a way that changes the response of the elements to the second one. This second event may or may not be of the same hazard type as the former, and is either independent or dependent on the first one. An example for load-dependent vulnerability can be found in Lee and Rosowsky (2006), who discussed the case of a wood-frame building loaded by snow and exposed to an earthquake. Accordingly, Zuccaro et al. (2008), Marzocchi et al. (2012), Garcia-Aristizabal et al. (2013) and Selva (2013) gave the example of the seismic vulnerability of buildings loaded by ash due to volcanic activity (Figure 2.28, below). In addition, Selva (2013) presented an example for state-dependent exposure. In this case, strong local earthquakes changed the exposure to a tsunami by people escaping from their damaged buildings and concentrating in seaside areas, which is where tsunamis hit. Pre-damage-dependent seismic vulnerability/fragility is important for earthquake aftershock risk assessment (Figure 2.28, above) and so has been addressed by Bazurro et al. (2004), Sanchez-Silva et al. (2011), Polese et al. (2012, 2015) and Iervolino et al. (2015a, 2015b), among others.

FIGURE 2.28

Two examples of state-dependent seismic vulnerability: pre-damage-dependent vulnerability (above) and load-dependent vulnerability (below) Source: Mignan (2013)



Integration into a probabilistic framework

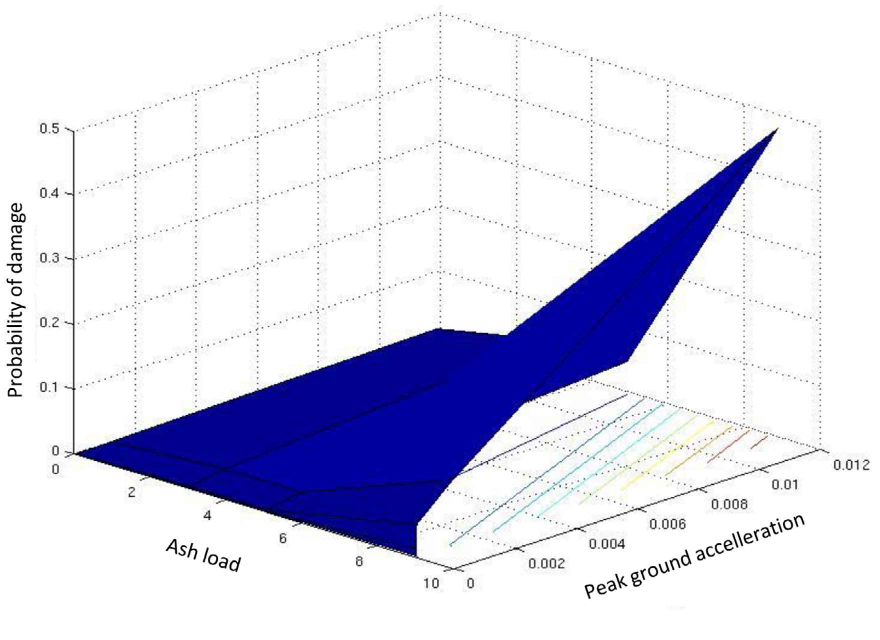
In the case of the ageing of structures, whereas one may easily integrate time-dependent vulnerability into a probabilistic multirisk assessment approach, for instance by means of time-dependent fragility functions (see Ghosh and Padgett, 2010; Karapetrou et al., 2013), this is not the case for the long-term vulnerability changes relevant to climate change and globalisation. Despite the existence of a few studies in the climate change research community that have made an attempt to project probabilistic risk curves into the future (e.g. Jenkins et al., 2014), the use of vulnerability/fragility curves does not seem to be common. According to Jurgilevich et al. (2017), the main bottleneck in assessing vulnerability and exposure dynamics and projecting them into the future is poor availability of data, particularly for socioeconomic data. Another bottleneck relates to the uncertainty and accuracy of the projections. Whilst one might have data about the future population, these data are often useless for assessing the future levels of education, income, health and other important socioeconomic aspects. This may be the reason why vulnerability assessments are still mostly based on present socioeconomic data, whereas current climate change projections go up to the year 2100 (Cardona et al., 2012). In light of the significant uncertainties involved in future projections of vulnerability, climate change-related literature has suggested the production of a range of alternative future pathways instead of one most plausible vulnerability scenario (Dessai et al., 2009; Haasnoot et al., 2012, O'Neill et al., 2014, among others). Still, dynamics of vulnerability or exposure are presently only included in half of the future-oriented studies related to climate change. Moreover, the inclusion of dynamics in both is observed in less than one third of the studies oriented to the future (Jurgilevich et al. 2017).

Following Garcia-Aristizabal and Marzocchi (2013), Garcia-Aristizabal et al. (2015 a) and Gasparini and Garcia-Aristizabal (2014), the situation is different for the pre-damage- and load-dependent vulnerabilities. One may easily integrate them into a probabilistic multirisk approach by extending the above framework for multilayer single-risk and multihazard risk assessment to account for hazard interactions on the vulnerability level.

The main difference of such an extended multirisk approach compared to the former one is the fact that vulnerability/fragility is introduced into the multirisk framework as a vulnerability/fragility surface instead of a curve (see Figure 2.29). This is because vulnerability, in the case of these interactions, depends on both the variable state of the exposed elements as well as on the intensity of the secondary event. In the case of load-dependent fragility/vulnerability, a load, for instance an ash load due to volcanic activity (see the fragility surface in Figure 2.29), determines the variable state of the exposed elements. For pre-damage-dependent fragility/vulnerability, the load parameter of the fragility/vulnerability surface is substituted by a parameter describing the pre-damage state.

FIGURE 2.29

Ash load-dependent, two-dimensional seismic fragility surface
Source: Garcia-Aristizabal and Marzocchi (2013)



In order to get a feeling of how different the results of the multirisk approach can be from those of the single-risk approach, let us take the example of seismic risk in the Arenella area of Naples, which was modified by ash loads. Garcia-Aristizabal et al. (2013) found that, in this case, the expected loss from earthquakes was remarkably sensitive to the thickness of an ash layer from volcanic activity assumed to load the roofs of the area's buildings. Whereas for a 24-cm ash layer the expected loss from earthquakes increased by less than 20% compared to the case without load, it reached an amplification factor of six for a 41-cm thick layer.

A simple example demonstrating what the effect of pre-damage-dependent vulnerability may quantitatively amount to can be deduced from the damage- and pre-damage-dependent fragility curves provided by Abad (2013) for a hospital in Martinique (French West Indies). For a ground motion of 5 m/s2 at the building's resonance, the probability of reaching a damage state 4 (near to collapse or collapse) is found from their curves to be roughly 7 % if pre-damage is not accounted for. On the other hand, assuming a pre-damage state 3 on a scale up to 4 results in a collapse probability of more than 30 %, an increase of nearly a factor of five.

Iervolino et al. (2015b), among others, have extended the concept of pre-damage-dependent vulnerability to account for the accumulation of damage in a series of aftershocks. Moreover, Sanchez-Silva et al. (2011) and Iervolino et al. (2013, 2015a) proposed to take into account both age-dependent and state-dependent vulnerabilities in one model of the time-variant failure probability of structures.

Matrix city

The 'Matrix city' framework, proposed by Mignan et al. (2014) for a quantitative multihazard and multirisk assessment that accounts for interactions on both the hazard and the vulnerability levels and considers time-dependent vulnerability, is conceptually quite different from the one introduced so far. It consists of a core simulation algorithm based on the Monte Carlo method. This method simulates a large number of stochastic hazard-intensity scenarios, thereby allowing for a probabilistic assessment of the risk and for the recognition of more or less probable risk paths. As each scenario is represented by a time series, the method is also appropriate for assessing the risks associated with non-stationary processes, such as the hazards and/or vulnerabilities under climate change. Intra- as well as interhazard intensity interactions are introduced by a so-called hazard correlation matrix.

This matrix is of the same type as the hazard interaction matrix used by Gill and Malamud (2014) for qualitatively and semi-quantitatively characterising interaction relationships between natural hazards, but by entering the one-to-one conditional probabilities of the secondary hazards it is applied in a quantitative way. For creating a hazard/risk scenario, the Monte Carlo method draws the probabilities from a Poisson distribution. So far, Matrix city has only been used with generic data to demonstrate the theoretical benefits of multihazard and multirisk assessment and to show how multirisk contributes to the emergence of extremes. It has been successfully tested, but 'identifying their real-world practicality will still require the application of the proposed framework to real test sites' (Mignan et al., 2014).

2.5.3 Implementation of MRA into DRM: Present state, benefits and barriers

2.5.3.1 State of implementation

Multirisk is not systematically addressed among DRM in EU countries (Komendantova et al., 2013a, 2013b, 2014, 2016; Scolobig et al., 2013, 2014a, 2014b). Single-hazard maps are still the decision support tool most often used in DRM, even more often than single-risk maps. Along with the missing link between scientific multirisk assessment and decision-making in DRM comes a general lack of integrated practices for multirisk governance.

2.5.3.2 Expected benefits

The practitioners involved in the Matrix study emphasised the following benefits:

- ranking and comparison of risks.
- Improvement of land-use planning, particularly as the multirisk approach provides a holistic view of all possible risks. It may influence decisions about building restrictions, which themselves may influence urban and economic planning, for example by regulating the construction of new houses and/or economic activities.
- Enhanced response capacity, because a multirisk approach would allow planning for potential damage to critical infrastructure from secondary events and preparation for response actions.
- Improvements in the efficiency of proposed mitigation actions, cost reductions, encouraging awareness of secondary risks and the development of new partnerships between agencies working on different types of risk.

2.5.3.3 Barriers

Barriers to effectively implementing multirisk assessment into DRM are found in both the science and practice domains as well as between them. In addition, individual perceptual and cognitive barriers may play a role in both domains (Komendantova et al., 2016).

Barriers in the science domain mainly relate to an unavailability of common standards for multirisk assessment across disciplines. Different disciplines use different risk concepts, databases, methodologies, classification of the risk levels and uncertainties in the hazard- and risk-quantification process. There is also an absence of clear definitions of terms commonly agreed across disciplines, including the term 'multirisk' itself, for which there is no consensus as regards its definition. These differences make it hard for various risk communities to share results, and hence represent a barrier to dialogue on multirisk assessment.

A lack of quantitative information on the added value of multirisk assessment is perhaps more worrying for risk managers than for scientists. The risk managers who participated in the Matrix study pointed out that there are not enough quantitative multirisk scenarios or their comparisons with single risk ones available from which they could learn about the added value of multirisk. Furthermore, they miss criteria or guidelines that would help them to select the scenarios to be included in a multirisk assessment. Most worrying for them, however, seem to be the strong limitations quantitative multirisk assessment methods, in their opinion, have when one regards their user friendliness. According to them, a high degree of expertise is often required to use the scientific tools, resulting in a restriction of their application to only a narrow number of experts.

Multirisk is presently not systematically addressed among DRM in EU countries. The barriers to the implementation of MRA include a lack of agreed definitions

Moreover, poor cooperation between institutions and personnel, especially when risks are managed by authorities acting at different governmental levels, was identified as a major reason for a lack of integrated practices for multirisk governance in the practical domain (Scolobig et al., 2014a). Decentralised and centralised governance systems have their own weaknesses and strengths in this regard (Komendantova et al., 2013a; Scolobig et al., 2014b). Furthermore, in some cases a multirisk approach is perceived as competing with rather than complementing single-risk approaches. The Matrix study also argued that in many European countries the responsibility for DRM has steadily been shifted to the local level (often to the municipal level) without providing sufficient financial, technical and personnel resources for implementing necessary programmes (Scolobig et al., 2014a). This is a clear obstacle for implementing multirisk methodologies.

Finally, there are individual cognitive barriers to implementing multirisk assessment approaches into the DRM decision-making processes, i.e. barriers related to how people perceive the problem of multirisk. Komendantova et al. (2016) presented the case of the 1995 Kobe earthquake in Japan, where the hazard was underestimated, simply because large earthquakes had been absent during the previous decades. Similar consequences are observed when building codes for earthquake-resistant structures are not followed, a problem that still exists all over the world, including in Europe. Individual cognitive barriers may only be overcome by raising awareness.

Overcoming these barriers will require a long-term commitment on behalf of risk modellers and officials as well as strong partnerships for a ‘step-by-step’ approach to progressively implementing multirisk methodology into practice.

2.5.4 Conclusions and key messages

Partnership

A better integration of scientific knowledge of multirisk assessment into developing policies and practices will require a long-term commitment from both sides, science and practice, and building new partnerships between them. Such partnerships should enhance the knowledge transfer between science and practice and, among others, should help involve practitioners as well as their requirements in the scientific development of multirisk methodology at an early stage. Common efforts will be particularly necessary for simplifying existing methods for practical use. Furthermore, scientists are asked to provide practitioners with more scenarios demonstrating the added value of multirisk assessments in various situations, and together they should collaborate in establishing criteria for appropriate scenarios to be included in a multirisk assessment.

More specifically, it might also be worthwhile considering the common development of a multirisk rapid response tool for assessing potential secondary hazards after a primary hazard has occurred. As lack of data is a crucial weakness in multirisk assessments, partnerships should also extend their collaboration to sharing data and building common integrated databases, in particular for demographic, socioeconomic and environmental data.

Such partnerships could be realised with common projects or by creating so-called multirisk platforms for common methods and data, and/or establishing so-called local multirisk commissions, institutional areas with an interdisciplinary and multisector character for discussing and acting on multirisk issues.

Knowledge

Although a theoretical framework for multirisk assessment and scenario development is in place, there is still a need for further harmonisation of methods and particularly terms across the scientific disciplines. Moreover, more quantitative scenarios on present and future risks in a multirisk environment are needed, particularly with regard to potential indirect effects and chain-shaped propagations of damage into and within the socioeconomic system. Such scenarios are still rare, mainly because of two reasons. First, the comprehensive databases needed for a multirisk assessment either do not exist, are not freely available or are insufficient; there is a need for establishing such databases between the disciplines. Second, quantitative fragility/vulnerability information, in particular fragility/vulnerability curves and surfaces, respectively, have so far been developed only for a few specific cases, mostly related to the direct impact of a disaster, but hardly to its indirect consequences; these, however, in many cases may be more important than the direct ones.

Therefore, the scientific knowledge base needs to be extended to quantitative vulnerability information, vulnerability curves and surfaces for indirect disaster impacts as, for instance, the loss in work productivity, loss of the functionality of systems and networks, costs of evacuation, costs of medial assistances and much more.

Innovation

A multi-risk modelling approach will be required in order to capture the dynamic nature and the various interactions of the hazard and risk related processes driven by both climate change and globalization. Moreover, solutions for risk assessments are needed that are no longer exclusively aiming at the best possible quantification of the present risks but also keep an eye on their changes with time and allow to project these into the future.

The future challenges have two dimensions, one focused on empowering good decisions in practice and another on improving our knowledge base for better understanding present and future risks

Developing an integrative model for future risk that considers not only the potential climate change-induced hazard dynamics, but also the potential dynamics of complex vulnerability components and the involved uncertainties will require the expertise of all these disciplines. A strong partnership will be required between the natural sciences, the social and economic sciences, as well as the climate change research community.

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