MATRIX

New Multi-Hazard and Multi-Risk Assessment Methods for Europe

MATRIX results I and Reference Report / Deliverable D8.4

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Introduction

"The New Multi-HAzard and MulTi-RIsK Assessment MethodS for Europe" or MATRIX project is by definition a multi-disciplinary program, whose results and outcomes, again by default, cross many boundaries in terms of their relevance. Natural disasters by their very nature show no regard for national, social or economic borders, and therefore efforts to mitigate against their negative consequences need to include the ability to communicate the findings of projects such as MATRIX to the broadest possible cross-section of the community. This not only includes other research scientists and engineers, but also civil protection authorities, decision and policy makers, as well as the general public.

It is for this reason that this deliverable, D8.4 "MATRIX results I and reference report", has been produced. In it are relatively short, but specific descriptions of some of the outcomes of the MATRIX project, presented in a manner that would appeal to a wide audience. While these reports generally follow the themes pursued in the work packages into which MATRIX was organized, some effort has been expended in showing how the results from the different work packages relate to each other.

The first report by Parolai et al. details the importance of harmonizing single-type risk assessments, in terms of presenting the risk arising from different hazards in a consistent and comparable form. This is followed by Garcia-Aristizabal et al., who outline the various cascading scenarios that have been identified for the MATRIX test cases. Desramaut et al. next present their assessment of the temporal variations of vulnerability from a systems point of view for the case of Guadeloupe, French West Indies, one of the MATRIX test sites. A multi-level multi-risk framework developed within MATRIX is then described by Nadim et al. The MATRIX-CITY tool and Virtual City concept developed within the project is summarized by Mignan, while Komendantova et al. provide an outline of their results dealing with the multi-risk assessment tools and the response of end-users. A preliminary application of the framework developed by Nadim et al. to the MATRIX test cases is outlined by Fleming et al., with this document concluding with a discussion of the issue of multi-risk and governance provided by Scolobig et al.

We believe the variety of reports presented in this document, while by no means exhausting the outcomes of the MATRIX project, nonetheless provides a sound overview of the project's achievements, allowing the reader (be they researchers, practitioners, or the public) to gain some understanding of the challenges involved in, and need for, a multi-risk approach. The MATRIX consortium is under no delusion that much work is still required, but we are confident that a multi-hazard and risk approach will be of fundamental value to future efforts in disaster risk reduction, especially within the context of the post-Hyogo Framework for Action era.

Comparing and harmonizing single-type risks.

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Introduction

Although the MATRIX project has as its primary concern the interactions between hazards and their associated risks, and how this impacts upon all manner of potential losses, this by no means is meant to replace the assessment of single-type risks. In fact, the project has been at pains to point this out, even while endeavouring to convince various members of the disaster risk reduction community of the necessity for a multi-type approach. For example, following an expert meeting conducted by the European Commission Directorate-General Humanitarian and Civil Protection (ECHO) on risk assessment and mapping for disaster management (Brussels, July 2011) where MATRIX was represented, while the project presentation was well received, one participant commented “I would be happy if I could manage a simple risk assessment. Multi-risk is far away from the reality on the ground.”

Hence, considerable efforts within MATRIX were spent in better understanding the means by which different hazards and risks can be presented in a harmonized and comparable manner, including how individual risks can be combined, and how the associated uncertainties should be presented. Such ability is essential in that it allows a means of comparing the relative importance of different hazards and risks in order to assist decision makers in their prioritizing of mitigation activities.

Risk metrics and scale factors

The first question is therefore what should be employed as the most appropriate risk metric (a matter of “comparing apples with apples”), which would allow the losses from different types of disaster to be meaningfully compared. For example, considering Germany, although the summer 2003 heat wave resulted in the highest number of deaths from an extreme natural event for the period 1980-2010 (9,355 people), the associated economic losses were relatively low (1.65 billion Euros) compared to the floods of 2002 (11.6 billion Euros) which caused the deaths of 27 people[1].

Another problem concerns the spatial and/or temporal scales being dealt with, each of which is, naturally, a function of the hazard in question. Considering spatial scales, different hazards have their own spatial pattern, for example, direct losses from floods are only of a concern to lower-lying areas close to water bodies, and so a flood may be rather localised. By contrast, a major earthquake will affect a much wider area, although again, depending upon geological conditions, there may be considerable spatial variability in the resulting ground shaking (e.g., Parolai et al., 2007).

Similarly for temporal scales, some hazards display a more obvious degree of regularity, such as seasonal winter storms or hurricanes, while others must be considered over much longer time periods, for example, earthquakes and volcanos. The problem, however, is that historical records may not be adequate to gain a proper understanding of what is to be expected over a given time period, let alone potential extreme events. This may lead to the problem where more familiar events (e.g., hurricanes) are seriously considered, while rarer ones (e.g., earthquakes) are neglected, as was the case of older buildings in Kobe, Japan, whose heavy roofs were suitable for seasonal typhoons, but not for rare earthquakes (Otani, 1999).

It was therefore decided within the MATRIX project to generally concentrate on direct losses arising from direct damage to residential buildings over annual time scales and urban spatial scales. The estimated losses or risk curves will then (usually) be expressed in the form of expected loss per annum (in Euros) versus probability. However, alternate means of presenting risk will be mentioned below.

Combining and comparing risks

In the following we call upon the example of Cologne, Germany (see MATRIX deliverables D2.3, Parolai et al., 2014, and D7.5, Fleming et al., 2014) to show how the risk arising from different hazards can be combined and compared. Considering first the risk curves derived for Cologne by Grünthal et al. (2006), who did not take into account potential interactions, we can obtain some idea of what the total risk may be due to several different hazards by employing the following simple formulation:

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[1] http://www.preventionweb.net/english/countries/statistics/?cid=66

$$P_{tot} = 1 - \prod (1 - P_i) \quad (1)$$

where P_{tot} is the total annual probability of exceedance of a given risk (expressed as Euros), and P_i is the probability of exceedance of a given risk *i* (i.e., here represented by earthquakes, landslides and floods). The original three curves of Grünthal et al. (2006), along with the various combinations, are presented in Figure 1 (note, because of limitations in the original results, we cannot combine these risks for the entire range of losses covered).

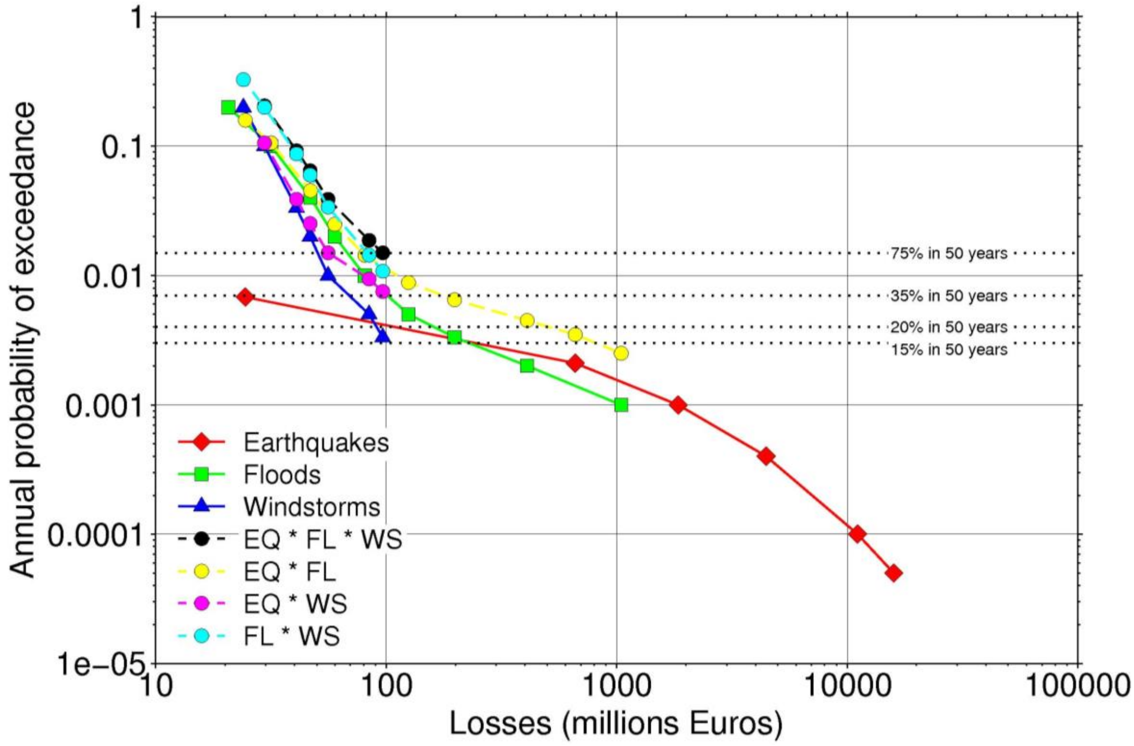

Figure 1: The individual risk curves for the three main hazards (earthquakes – EQ, floods – FL, windstorms – WS) that affect Cologne and their various combinations derived using equation 1.

We note that for the loss range over which all hazards have results, the resulting combination of the three curves differs little from combining only flood and windstorm (the dominate risks for higher probability/lower loss events). However, if we were to consider, for example, all risk-types where losses are of the order of 100 million Euros, we see that the combination of curves will significantly increase the probability of such a level of loss, from 15 to 35% in 50 years for the individual hazards, to around 75% in 50 years when combined.

Another way in which such changes in risk may be presented is by a risk matrix[2]. In fact, as commented upon in Komendantova et al., (2014), end-users tend to prefer such a format as

[2] This matrix follows approximately that employed by the German Federal Office of Civil Protection and Disaster Assistance (BBK, http://www.bbk.bund.de/). See also “Risk Mapping and Assessment Guidelines for Disaster Management”, SEC(2010), Brussels, 21.12.2010, European Commission.

opposed to risk curves. Figure 2 shows an example of a risk matrix for Cologne using examples of the risk arising from the three hazards shown in Figure 1. Included is the summation of the three risks that give an approximate loss of 100 million Euros. These examples are outlined by the ellipse, where the result of combining the windstorm (triangle), earthquake (diamond) and flood (square) is shown by the circle. One can see how the total risk has increased by its movement towards the right, in the case of this figure, moving from "Quite likely" to "Likely". While it must be kept in mind that this figure is only intended for illustrative purposes, one can imagine, based on expert opinion, how the relative distribution of the risks (i.e., the colour scheme) could be altered to better reflect the case at hand.

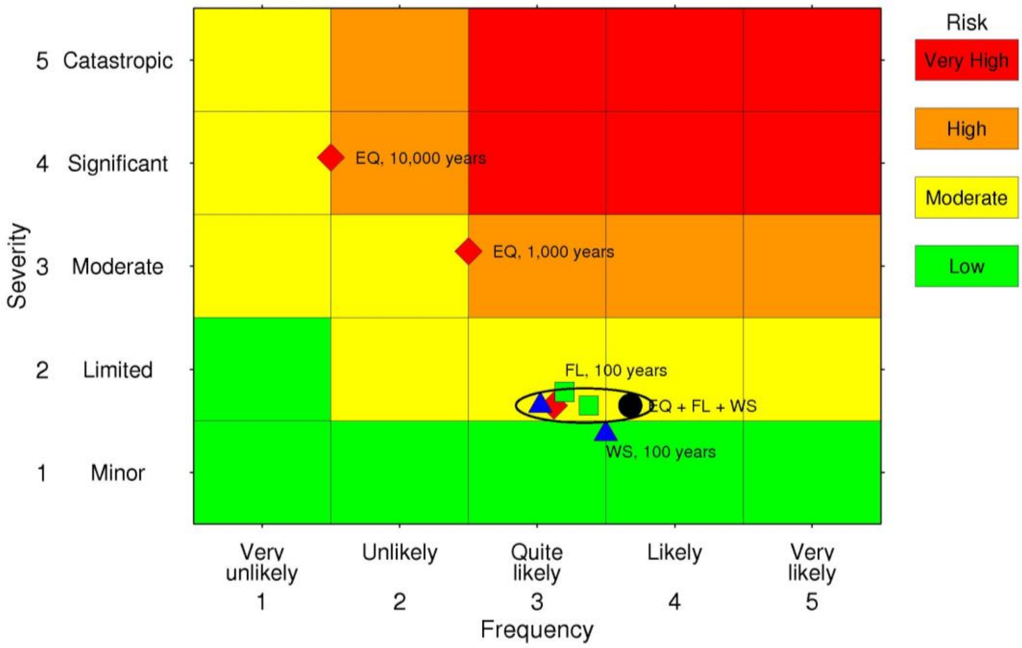

Figure 2: Risk matrix showing how combining the risk associated with individual risks (EQ – earthquake, FL – flood, WS – windstorm, see area) can lead to a significant increase in overall risk. The risk estimates discussed in the text (corresponding to losses of ca. 100 million Euros) are outlined by the ellipse. Note, we divided the loss and probability ranges in Figure 1 into 5 and allocated the frequency and severity accordingly, while the colour scheme employed is purely illustrative and would require expert judgement to properly be assigned.

Next we compare for specific return periods the range of results for each risk type newly calculated for the Cologne test case. For the seismic risk, this involved a logic tree approach that considers a range of hazard input parameters and damage and vulnerability models, resulting in 180 estimates per return period (Tyagunov et al., 2013). The flood estimates employed a hybrid probabilistic-deterministic coupled dyke breach/hydrodynamic model (IHAM, Vorogushyn et al., 2010), run in a Monte Carlo simulation. The windstorm risk was found using the Vienna Enhanced Resolution Analysis or VERA tool (Steinacker et al., 2006) and the building damage estimation method of Heneka and Ruck (2008). All three employed the same metric (direct damage, residential buildings) and total costs (see D7.5 details).

Again, we employ a simple means of determining if the risk arising from two independent hazards for specific return periods are the same. This involves the Wilcoxon's test, a distribution free ranking test that asks the specific question "Are the medians of the two distributions the same?" (Barlow, 1989). We compare a range of values for each pair of hazards (earthquake – flood, earthquake – windstorm, flood – windstorm) and apply a null hypothesis (to 0.05) that the question's answer is in the affirmative. The test involves taking 20 random samples from each pair of distributions, applying the Wilcoxon's test, and doing so 10000 times. This is to reduce the consequence of situations where the random selections of samples are clustered in some way. The return periods we examine are 200, 500 and 1000 years for comparing earthquakes and floods, and 200 and 500 years for floods and windstorms, and windstorms and earthquakes (Figure 3).

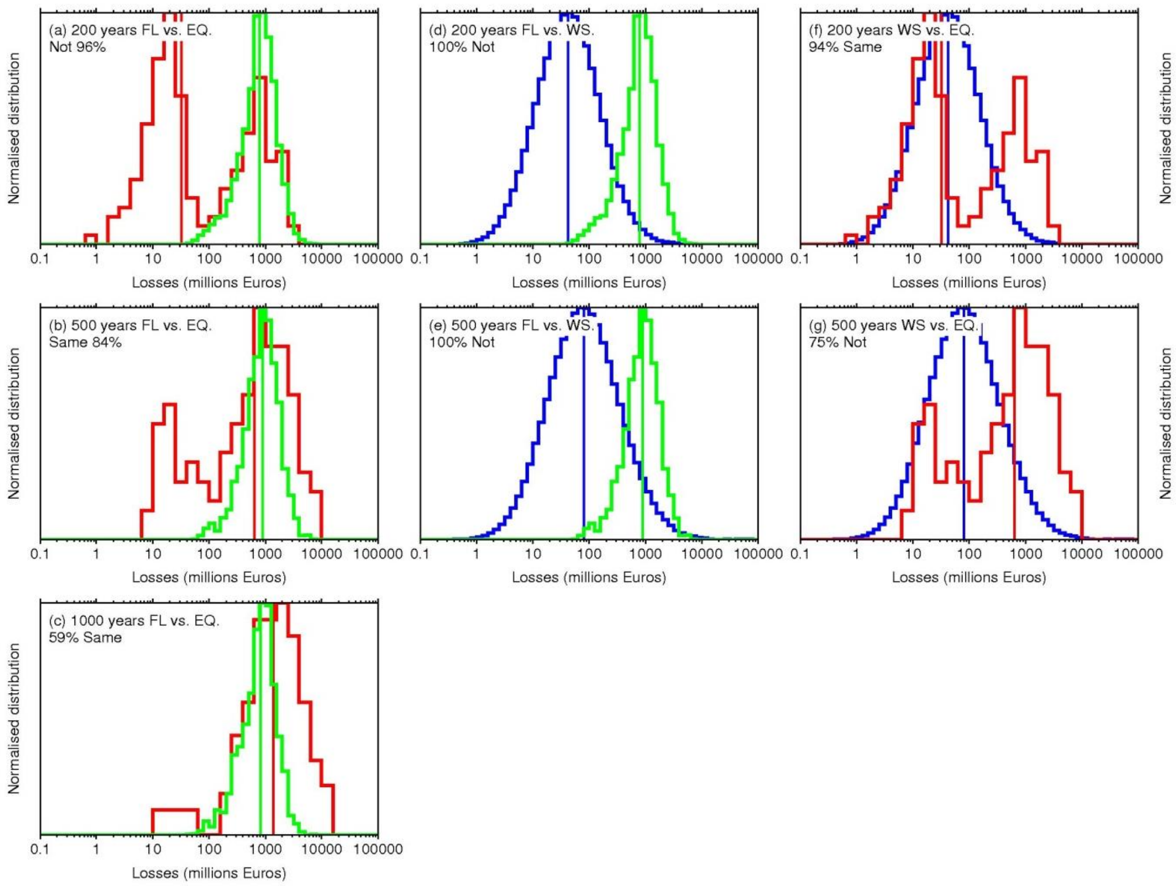

Figure 3: Comparing the distribution of results for each pair of risks. (a-c) Floods (green, FL) and earthquakes (red, EQ) for (a) 200, (b) 500 and (c) 1000 years return periods, (d-e) floods and windstorms (blue, WS) for (d) 200 and (e) 500 years, (f-g) windstorms and earthquakes for (f) 200 and (g) 500 years. The vertical lines of the same colours are the respective medians.

Considering first the earthquake distribution, we see that its bimodal character (a product largely of the choice of the ground motion predictive equations, see D7.5) immediately adds an additional element of uncertainty as to whether the risks it is compared to are equivalent. Considering the results of the Wilcoxon's test, we note for the 200 year return period (Figure 3a) that earthquakes and floods are not equivalent (in contrast to Grünthal et al., 2006, where they appear very similar), but can be considered comparable for 500 years (Figure 3b, in agreement with Grünthal et al., 2006), although for 1000 years (Figure 3c), a definitive comment cannot be made. For the windstorms and floods (Figure 3d-e), for both the 200 (Figure 3d) and 500 (Figure 3e) years return periods, it is obvious (even without applying this test) that windstorms and floods are not equivalent, with floods being of greater concern in both cases. Finally, for earthquakes and windstorms (Figure 3f-g), for 200 year return period (Figure 3f), these appear to be of equivalent importance, while for 500 years (Figure 3g), this does not appear to be the case (with earthquakes of greater importance), in both cases consistent with Grünthal et al. (2006).

Closing comments

We have presented here for the case of Cologne simple methods for combining risk curves, along with a means of graphically showing (risk matrix) how total risk changes as one combines the individual components. Such a presentation scheme is useful in showing how risk changes when interactions are considered (as shown by Mignan in this document[3]. We also examined a means of seeing if a pair of risks is equivalent to one another when considering a range of plausible values for a given return period. The relevance of such an exercise is to do with the decision making process, whereby if the risk associated with two types of hazard is "equivalent", then the required mitigation schemes may need to consider both, or at least help decision makers when deciding on how to allocate resources. For example, while for 200 years return periods, earthquakes and windstorms appear to be equivalent, one would imagine that implementing mitigation actions for earthquake would be much more expensive than those for windstorms. It also shows that one needs to accommodate uncertainties, since simply using, for example, average curves, may yield misleading conclusions about the relative importance of a given combination of hazard types. However, it is also important to note that the actual results would vary as the range of employed input models and parameters are updated and refined (as would be apparent in the earthquake case).

[3] Mignan, A. MATRIX Common IT sYstem (MATRIX CITY) Generic multi-hazard and multi-risk framework - the concept of Virtual City - IT considerations, this document.

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Identifying and structuring scenarios of cascade events in the MATRIX project

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Introduction

The core of the probabilistic assessment of cascading effects within a multi-hazard problem consists of identifying the possible interactions that are likely to happen and that may result in an amplification of the expected damages within a given area of interest. After a detailed review of the state of the art in multi-hazard assessment (MATRIX deliverable D3.1, Garcia-Aristizabal et al., 2013a) and an exercise in defining the cascading effect scenarios of interest for the test cities of the MATRIX project (MATRIX deliverable D3.3, Garcia-Aristizabal et al., 2013b), we have developed a procedure for classifying the main kinds of interactions that can be considered for the quantitative assessment of cascading effects in a multi-risk analysis. In particular, we have identified two possible kinds of interactions, namely: (1) interactions at the hazard level, in which the occurrence of a given initial 'triggering' event, entails a modification to the probability of the occurrence of a secondary event, and (2) interaction at the vulnerability (or damage) level, in which the main interest is to assess the effects that the occurrence of one event (the first one occurring in time) may have on the response of the exposed elements against another event (that may be of the same kind as the former, but also a different kind of hazard). Implicitly, a combination of both kinds of interactions is another possibility, hence in the discussion of the interactions at the vulnerability level, both dependent and independent hazards have been considered.

Identification and structuring of scenarios

A fundamental initial step towards assessing cascading effects is the identification of possible scenarios. The term "scenario" is used in a wide range of fields, resulting in different interpretations in practical applications. In general, a scenario may be considered as a synoptic, plausible and consistent representation of an event or series of actions and events (e.g., MATRIX deliverable D3.3). In particular, it must be plausible because it needs to fall within the limits of what might conceivably happen, and must be consistent in the sense that the combined logic used to construct a scenario must not have any built-in inconsistencies.

To achieve the required complete set of scenarios, different strategies can be adopted, ranging from event-tree to fault-tree strategies. In many applications, an adaptive method combining both kinds of approaches is applied in order to ensure the exhaustive exploration of scenarios. From the multi-risk assessment point of view, the cascading effects scenarios of primary interest are those that produce an amplified total risk when compared to the effects produced by the individual events. With an appropriate set of cascading scenarios, their quantification can be achieved by adopting different strategies, for example, analysing databases of past events, performing physical modelling for the propagation of the intensity measures of interest, and/or by performing expert elicitations in order to obtain information for extremely complex problems, or in these cases with poor data or needing rapid analysis.

Identification of scenarios in the MATRIX test cases

To define some possible cascade scenarios, the 'primary' interactions between hazards were identified. These can be understood as the pairs of hazards where it is theoretically possible to define an event that has the capacity to directly trigger another one (interaction at the hazard level), or in which the additive effects of the loads may lead to a risk amplification. In the matrix-like Table 1, the different hazards considered in the MATRIX project are classified as triggering (running in the x-axis) against the 'triggered' (running in the y-axis) events. In this case, all the possible 'direct' triggering effects are considered. It would also be obvious that it is physically impossible for some hazards to trigger another, e.g., wildfires and volcanoes (although the other way around is certainly a concern, especially for Naples).

Table 2 is a modification of the previous one, where we try to highlight more complex cascade effects. In this case, the number refers to the 'level' (i.e., the position in the sequence of events) at which the given phenomena may be triggered, starting from the initial event being defined as level 0. The numbers in this table are an attempt to represent the different possible sequences of events that can produce different chains of cascade events. Figure 1 in turn allows us to understand better the existing relationships between the different kinds of events and, their relative level in the chain. In this way, the occurrence of different phenomena may be considered from the possible triggering factors.

Table 1: Matrix of all possible direct interactions among the hazards considered within the MATRIX project.

Triggering -> (cause) *Considered hazards* **Triggered** (result)			Triggering events													
						Volcanic								Meteorological events		
			Earthquakes	Landslides	**Volcanic eruption**	*Tephra fall*	*Pyroclastic flows*	*Lava flows*	*Lahars*	*Volcanic earthquakes*	floods	Tsunami	Wildfires	Extreme wind	Heavy precipitation	Extreme temperature
Triggered events	Earthquakes				1[b]											
	Landslides		1		1								1?		1	
	Volcanic	**Volcanic eruption**	1													
		Tephra fall														
		Pyroclastic flows														
		Lava flows														
		Lahars													1	
		Volcanic earthquakes	1													
	Floods			1[a]				1[c]							1	
	Tsunami		1	1	1											
	Wildfires				1			1								1

[a, c] *In specific cases such as, for example, when a landslide (a) or a lava flow (c) reaches and blocks a river.*

[b] *For example, a volcanic edifice collapse.*

Summary of scenarios identified for the MATRIX test cases

Naples test case.

The possible cascading scenarios for the Naples test case are summarized in Table 3. Naples is in fact the test case that may have the largest collection of possible cascade events, with, as can be seen, cascades up to level 4 (landslides from volcanic eruptions) being identified. The most serious interactions appear to be volcanic-seismic relations, with a number of volcanic-related hazards possibly occurring or triggered.

Table 2: Cascades of more than 2 events for the hazards considered in the MATRIX project.

Triggering -> (cause) / Considered hazards / Triggered (result)			Triggering events: Earthquakes	Landslides	**Volcanic eruption (in general)**	floods	Tsunami	Wildfires	Meteorological events: Extreme wind	Heavy precipitation	Extreme temperature
Triggered events		Earthquakes			1						
		Landslides	1		1,4			1?		1	
	Volcanic	**Volcanic eruption**	1[d]								
		Tephra fall	2		1						
		Pyroclastic flows	2		1						
		Lava flows	2		1						
		Lahars	2,3		2					1	
		Volcanic earthquakes	2		1						
		Floods	2	1	3					1	
		Tsunami	1	1	1						
		Wildfires	3		3						1

[d] *In this case, it may be more properly defined as the triggering of volcanic unrest that eventually leads to an eruption.*

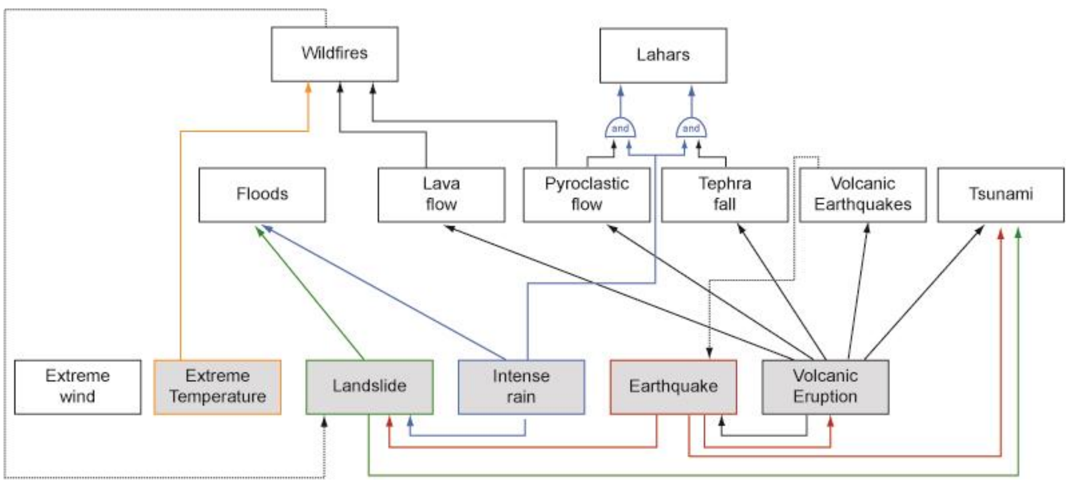

Figure 1: Diagram showing the possible scenarios of cascading events among the hazards considered in the MATRIX project.

Cologne test case:

The next case is Cologne, whose sequence of possible cascading effects scenarios is summarized in Table 4. Cologne is in fact a much simpler example of cascading potential than either Naples or Guadeloupe, but nonetheless, earthquakes and floods display a potential interaction arising from the possibility of an earthquake damaging the flood defences along the River Rhine, hence increasing flood risk.

Table 3: Possible event cascade scenarios for the Naples test case.

									Meteorological events		
			Earthquakes	**Landslides**	**Volcanic eruption (in general)**	floods	Tsunami	**Wildfires**	Extreme wind	Heavy precipitation	Extreme temperature
Triggered events		**Earthquakes**	■		1						
		Landslides	1	■	1,4			1?		1	
	Volcanic	**Volcanic eruption**	1[d]		■						
		Tephra fall	2		1						
		Pyroclastic flows	2		1						
		Lava flows	2		1						
		Lahars	2,3		2					1	
		Volcanic earthquakes	2		1						
		Floods				■					
		Tsunami					■				
		Wildfires	3		3			■			1

[d]*In this case, it may be more properly defined as the triggering of volcanic unrest that eventually leads to an eruption.*

Guadeloupe islands: French West Indies

The final test case, the island of Guadeloupe (French West Indies), is of a similar level of cascade event potential as Naples, although, for example, wild fires are not considered a serious danger. The possible cascading effect scenarios for this case are summarized in Table 5. Again, the earthquake-volcano interactions appear to be the most serious.

Table 4: Possible event cascade scenarios for the Cologne test case.

									Meteorological events		
			Earthquakes	Landslides	Volcanic eruption (in general)	floods	Tsunami	Wildfires	**Extreme wind**	**Heavy precipitation**	Extreme temperature
Triggered events	**Earthquakes**										
	Landslides										
	Volcanic	**Volcanic eruption**									
		Tephra fall									
		Pyroclastic flows									
		Lava flows									
		Lahars									
		Volcanic earthquakes									
	Floods		2*							1	
	Tsunami										
	Wildfires										

**Possible cascade effects proposed (GFZ): Earthquake -> Dyke damage -> Flooding*

Table 5: Possible event cascade scenarios for the French West Indies test case.

									Meteorological events		
			Earthquakes	**Landslides**	**Volcanic eruption (in general)**	**floods**	Tsunami	Wildfires	**Extreme wind (hurricane)**	**Heavy precipitation**	Extreme temperature
Triggered events	**Earthquakes**				1						
	Landslides		1		1,4					1	
	Volcanic	**Volcanic eruption**	1[d]								
		Tephra fall	2		1						
		Pyroclastic flows	2		1						
		Lava flows	2		1						
		Lahars	2,3		2					1	
		Volcanic earthquakes	2		1						
	Floods		2	1	3					1	
	Tsunami										
	Wildfires										

[d]In this case, it may be more properly defined as the triggering of volcanic unrest that eventually leads to an eruption.

Final comments

From the different cascading scenarios identified in each test case, a set of specific scenarios of interest were selected for more quantitative analyses. For example, in the Naples test case, two scenarios were analysed in quantitative terms: first, the effects of simultaneous loads caused by volcanic ash-fall (first effect) and earthquakes (second effect); second, the effects on the seismic hazard of the volcanic seismicity triggered during a volcanic unrest. The results of these analyses are summarized in greater detail in the Naples test case deliverable (D7.3, Garcia-Aristizabal et al., 2013c). In the Guadeloupe (French West Indies) test case, a scenario consisting of landslides triggered by the occurrence of earthquakes after a cyclonic event or a heavy rainfall period was considered. The detailed analysis of this scenario is described in the Guadeloupe test case deliverable D7.4, Monfort and Lecacheux (2013). Finally, in the Cologne test case, a scenario consisting of earthquake-triggered embankment failures and subsequent inundation of the City of Cologne has been analysed, with a detailed description of this scenario found in the Cologne test case deliverable D7.5, Fleming et al. (2013).

The cascading scenarios identified for each test case were important input information to implement the multi-hazard and multi-risk framework developed within MATRIX. This framework (MATRIX deliverable D5.2, Nadim et al., 2013) indeed provides a useful and valuable scheme within which to identify the characteristics of interactions between a given area's hazard and risk environment, and an appropriate identification of interaction scenarios is a fundamental step in this process.

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The temporal dimension in multi-risk assessment: Effects of antecedent conditions and simultaneous events on the functional vulnerability of critical infrastructures.

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Introduction

The MATRIX project aimed to develop methodologies to assess and compare some of the different natural risks that society has to face. Hence, in order to address multi-risks, one has to take into account the different interactions that might exist between the risks. These interactions, at the hazard and the vulnerability levels, might happen with different delays. It is, therefore, necessary to consider the temporal aspect of such interactions to properly assess multi-risk. The time dependencies might involve the following:

- The repetition of events over time.
- The concomitance of simultaneous-yet-independent events.
- The succession of dependent phenomena (cascading events).

The study of the time-dependency of vulnerability was the objective of work package 4 of the MATRIX project.

Repetition of the same hazard events over time

The effects of the repetition of a type of event have been studied by following a seismic example. The effects of fatigue due to the repetition of seismic shocks (the first mentioned above) within a physical vulnerability assessment have been analysed through two mechanical methodologies. The first approach, proposed by BRGM (Reveillere et al., 2012), developed damage-state dependent fragility functions (Figure1), while the second approach, performed by AMRA (Iervolino et al., 2014), analysed the multiple shock capacity reduction for non-evolutionary structural system (Figure 2).

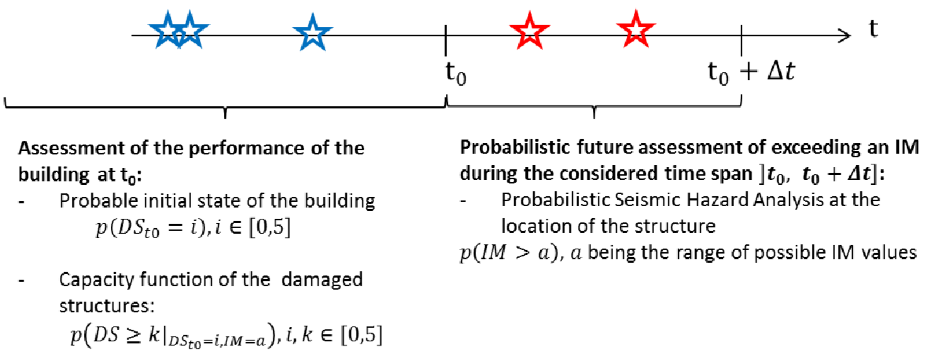

Figure 1: Scheme of the time-dependent risk assessment methodology at a time t0.

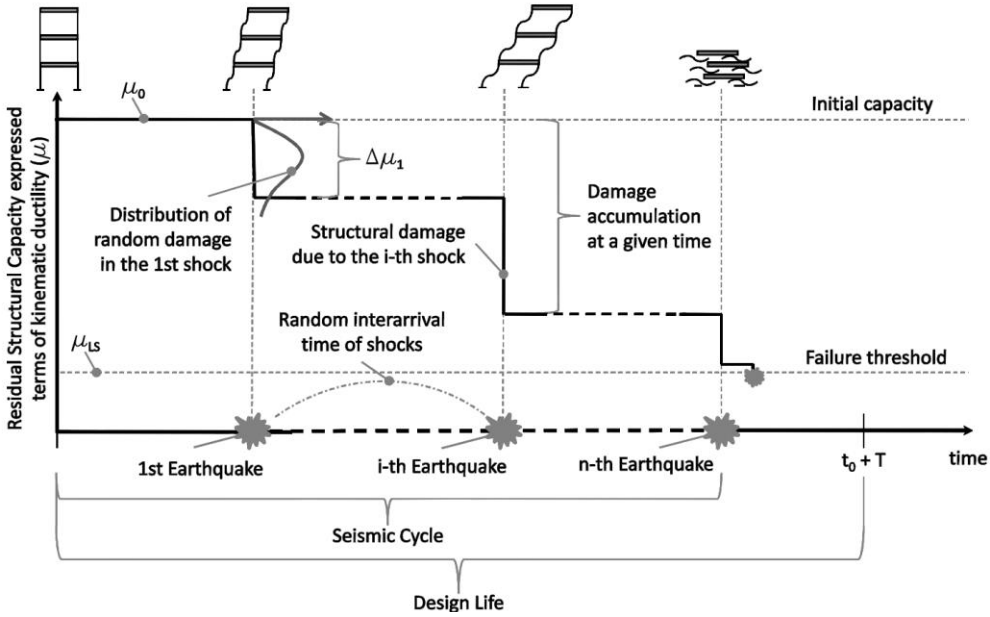

Figure 2: Cumulated damage evolution in the life-cycle.

Concomitance of independent events and cascading scenario

Another study within this work package developed a methodology to take into account the two other types of temporal dependency in societal impact studies. It has been applied to cascading events for illustrative purposes, but it could also be employed for concomitant, yet independent events. The major concern of the study was the integration of two different types of hazards into the evaluation of emergency system functionality during a crisis. The two hazards considered are earthquakes and induced landslides: the first one heavily damages the built environment, whereas the other only impacts upon the road network. The functionality of the road network as a function of these events is modelled using the I2Sim[4]

[4] http://www.i2sim.ca/

platform developed at the University of British Columbia. This tool simulates the interdependencies between infrastructures and among them (Marti et al., 2008).

The first step was the definition of a deterministic disaster scenario using several simulation tools to present a realistic earthquake and landslides scenario for the study area, which was Guadeloupe, Basse-Terre. The hazard cascading scenario consisted of a M6.3 earthquake striking Basse-Terre Island, and triggering landslides in the mountainous areas where previous rainfall events have made the area prone to mass movement (Figure 3). Damage due to the earthquake has been estimated for 5 considered systems (buildings, healthcare system, electrical network, water supply network and transportation, Figure 4). In our scenario, landslides mainly affect transportation networks, resulting in the closure of some roads. This physical damage was then introduced into the lifelines simulation tool (I2Sim), to convert the impacts on the physical integrity of the built environment (number of collapsed buildings, number of victims) into functional consequences (quantity of water and power available in the different cities, accommodation capacities, hospital treatment capacity and capacity of the transportation network to carry injured people to operational hospitals).

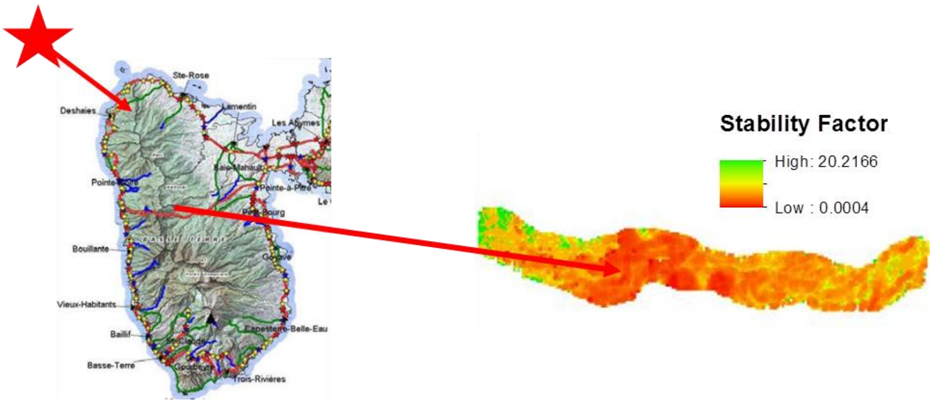

Figure 3: Hazard cascading scenario: an earthquake (star, left) strikes and triggers landslides (resulting slope stability map, right) in the vicinity of the important RD23 road. The stability factors relate to the potential for landslides along a slope, with values lower than 1 indicating a significant landslide hazard.

Systemic vulnerability: inter and intra dependencies between systems

Using the I2Sim tool, the functionality of each element is therefore the combination of the physical (direct damage), as well as functional (indirect) damage. Analyses were performed for different strategies of resource allocations, with one of the final results being the impact of the induced landslides upon the health care treatment capacity of the island. It was found that some systems were very resilient, while others were more vulnerable during disaster situations.

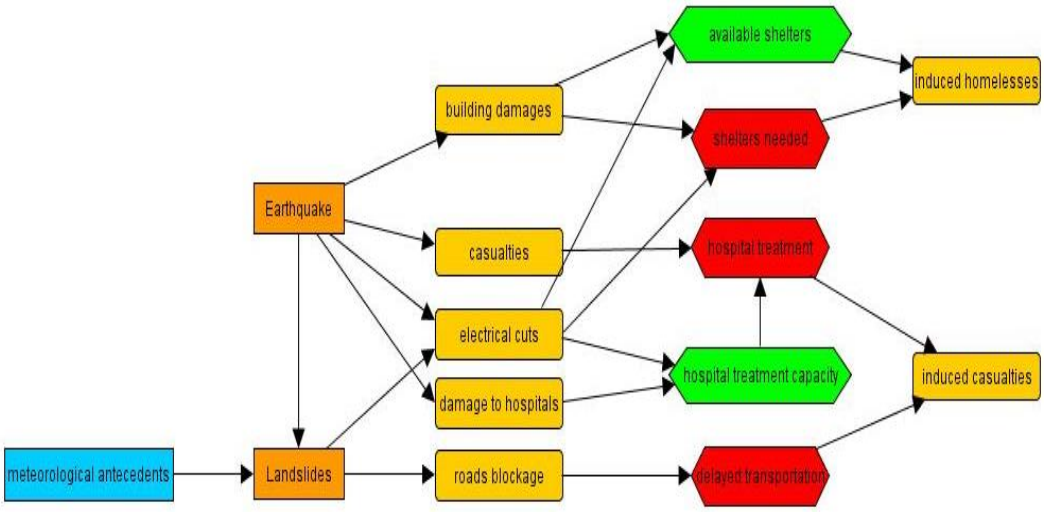

Figure 4: Interactions between hazards at the different levels (physical and functional vulnerability) as examined in the scenario described in this work.

By examining all of the simulation results, several conclusions can be made for the particular earthquake scenario simulated. It was found that the transportation system in Guadeloupe proved to be a major weak point during disaster response. The only route connecting the east and west sides of the Basse-Terre Island, the RD23 road (see Figure 3) is vulnerable to landslides. The simulations proved that, combined with the increased levels of congestion, the evacuation speed would decrease dramatically with virtually no remedy available. Due to the characteristics of the island: i.e., a closed system with mountains in the centre, both the road network and the health care system have a low level of redundancy.

General remarks

Lifelines play a vital role, even under normal conditions. Therefore, during a crisis, the dependency on critical infrastructures is likely to be exacerbated. Indeed, systems have to be functional to provide rapid emergency responses. However, the different systems are interdependent and even if not directly damaged, they can have their functionality seriously reduced and even stopped due to damaged elements of other systems. Thus, it is necessary to take functional vulnerability into account in order to have a comprehensive multi-risk approach and to improve the robustness of assessments of the impact of natural hazards on society.

For example, the impacts of individual hazards, taken separately, might not significantly affect societies or alter system functionality, but might reduce redundancy, and therefore could increase the functional vulnerability of the system to another hazard. This work undertaken within the MATRIX project therefore aimed to analyse the effects of cascading events on interdependent systems and on the capacities of the health care system to treat the victims under damaged-lifeline conditions. Further details may be found in MATRIX deliverable D7.4, Monfort and Lecacheux (2013).

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MATRIX Framework for multi-risk assessment

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Introduction

Many regions of the world are exposed to and affected by several types of natural hazard. The assessment and mitigation of the risk posed by multiple natural and man-made threats at a given location requires a multi-risk analysis approach that is able to account for the possible interactions among the threats, including possible cascade events. Performing quantitative multi-risk analysis using the methodologies available today presents many challenges (e.g., Kappes et al., 2012, Marzocchi et al., 2012). The risks associated with different types of natural hazards, such as volcanic eruptions, landslides, floods, and earthquakes, are often estimated using different procedures and the produced results are not comparable. Furthermore, the events themselves could be highly correlated (e.g., floods and debris flows could be triggered by an extreme storm event), or one type of threat could be the result of another (e.g., a massive landslide that is triggered by an earthquake, an example of a cascade effect).

It is obvious that a mathematically rigorous approach to multi-risk assessment that addresses all the challenges named above, as well as the uncertainties in all steps of the analysis, will be complicated and require resources and expertise. On the other hand, in many situations, the decision-maker in charge of risk management can identify the optimum alternative among the possible options without undertaking a detailed, rigorous multi-risk analysis. Therefore, the framework recommended herein is based on a multi-level approach where the decision-maker and/or the risk analyst will not need to use a more sophisticated model than what is required for the problem at hand, or what would be reasonable to use given the available information.

The recommended three-level framework for multi-risk assessment

The recommended multi-risk assessment framework is a multi-level process which assumes that the end-user (decision-maker or risk analyst) has identified the relevant threats and has carried out an assessment of the risk(s) (again at the level of sophistication required for the problem at hand) associated with each individual hazard. Figure 1 shows the general steps of our multi-risk assessment framework. The overall multi-risk assessment process comprises the following stages: (1) risk assessment for single hazards, (2) level 1: qualitative multi-risk analysis, (3) level 2: semi-quantitative multi-risk analysis, and (4) level 3: quantitative multi-risk analysis. The details are described below.

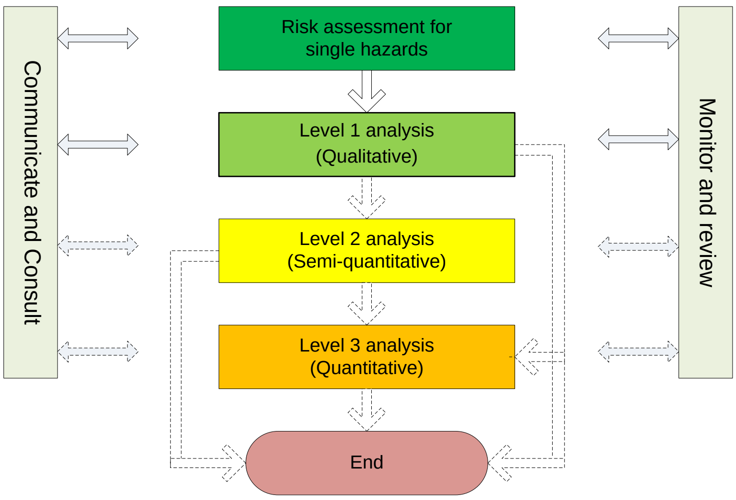

Figure 1: Schematic view of the steps followed in the proposed multi-risk assessment framework.

Level 1 Analysis

Level 1 analysis comprises a flow chart type list of questions that guides the end-user as to whether or not a multi-type assessment approach is required. These questions explicitly account for cascading hazards and dynamic vulnerability within the context of conjoint or successive hazards. Each question is supplied with an exhaustive list of answers that the user can choose from. This process is shown schematically in Figure 2.

If the Level 1 results strongly suggest that a multi-type assessment is required, then the end-user moves on to Level 2 to make a first-pass assessment of the effects of dynamic hazard and time-dependent vulnerability (see Figure 3). If cascading events are potentially a concern, the user goes directly to the Level 3 analysis.

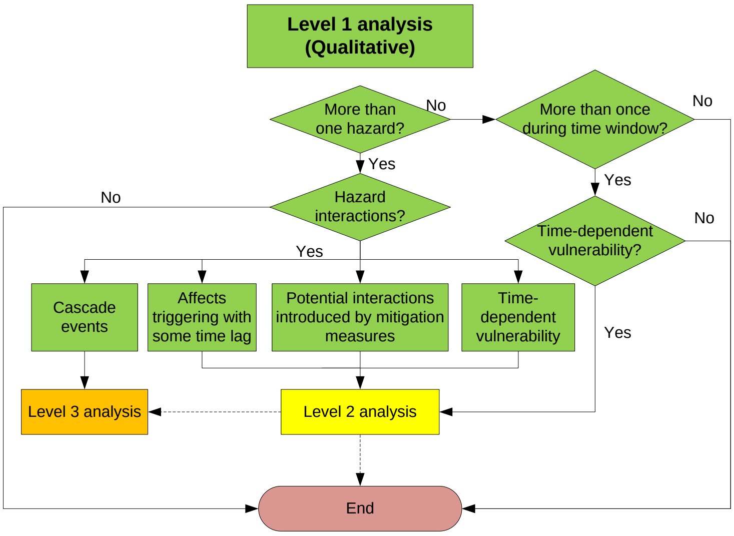

Figure 2: The steps involved in the Level 1 multi-risk analysis.

Level 2 Analysis

In the Level 2 analysis, the interactions among hazards and dynamic vulnerability are assessed approximately using semi-quantitative methods. The steps involved in the Level 2 analysis are shown in Figure 3a.

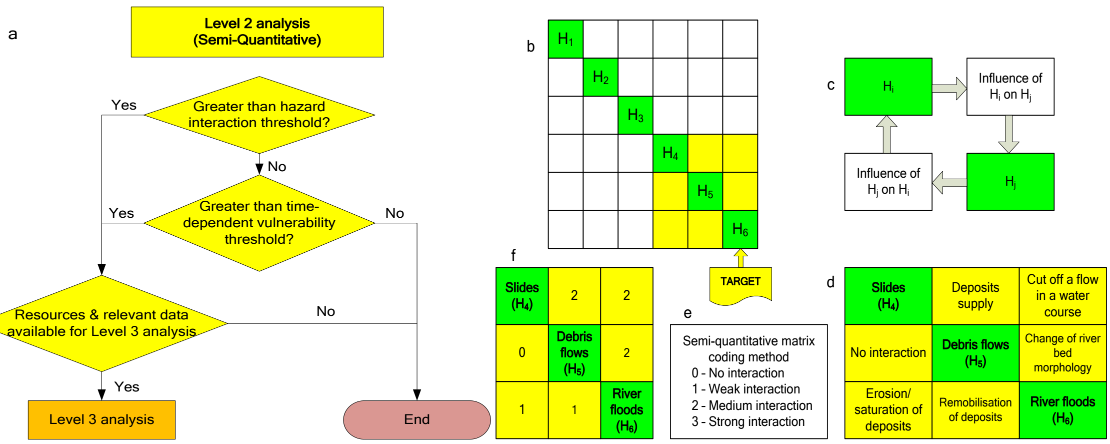

Figure 3: Level 2 multi-risk analysis. (a) The steps involved in the process. (b) The matrix approach followed. (c) The types of interactions that may arise. (d) Description of the mutual influences. (e) The "scoring" system. (f) The matrix with the resulting scores.

To consider hazard interactions and time-dependent vulnerability, the suggested method in the Level 2 multi-risk analyses is a matrix approach based on system theory. Figure 3b-f shows an example to explain this approach (Modified after de Simeoni et al., 1999 and

Kappes et al., 2010). First, a matrix is developed by means of the choice of a pair of hazards, considered as the basic components of the system (Figure 3b). It will be followed by a clockwise scheme of interaction (Figure 3c), with the description of the mutual influence between different hazards (Figure 3d). After the descriptions contained in the matrix, they are assigned numerical codes varying between 0 (No interaction) and 3 (Strong interaction) with intervals of 1, as a function of their degree of the interaction intensity (Figure 3e). Once all the hazards in the matrix are filled (Figure 3f), it is possible to verify the degree of the impact of each hazard on the others and the effect from other hazards. In order to avoid the excessive weighting of a single hazard, the hazard interaction index H_I, which is the sum of the codes for all the off-diagonal terms, is evaluated and compared to a threshold value.

The maximum possible value for the total sum of causes and effects is:

$$H_{I,\,max} = 2 \cdot 3 \cdot n \cdot (n-1) = 6 \cdot n \cdot (n-1) \tag{1}$$

where n is the number of hazards and H_I is the hazard interaction index.

Given the uncertainties and possible excessive or moderate weighting of single hazards, a threshold hazard interaction index H_I equal to 50% of $H_{I,max}$ is recommended for considering a detailed Level 3 analysis. If the hazard interaction index is less than this threshold, Level 3 analysis is not recommended because the additional accuracy gained by the detailed analyses is most likely within the uncertainty bounds of the simplified multi-risk estimates. Otherwise, if the hazard interaction index is greater than the threshold value, a detailed Level 3 analysis is recommended.

Level 3 Analysis

In the Level 3 analysis, the interactions among hazards and dynamic vulnerability are assessed quantitatively with as high accuracy as the available data allow.

A new quantitative multi-risk assessment model based on Bayesian networks (BaNMuR, outlined in MATRIX deliverable D5.2, Nadim and Liu, 2013) is introduced to both estimate the probability of a triggering/cascade effect and to model the time-dependent vulnerability of a system exposed to multi-hazard. A conceptual Bayesian network multi-risk model may be built as shown in Figure 4. To determine the whole risk from several threats, the network takes into account possible hazards and vulnerability interactions. This would include events that are:

(1) *Independent*, but threatening the same elements at risk with or without chronological coincidence (the column marked in orange in Figure 4), or

(2) *Dependent* on one another or caused by the same triggering event or hazard; this is mainly the case for cascading or domino events (i.e., the column marked in green in Figure. 4).

Figure 4: Bayesian network for quantitative multi-risk assessment.

Final Comments

The framework presented in this chapter provides, at the very least, a starting point from which a decision-maker, risk-analyst etc., can proceed from their initial single-type assessment to a more comprehensive (if necessary) analysis. In a later report in this document (Fleming et al., 2013, "The MATRIX framework applied to the test cases of Naples, Guadeloupe and Cologne"), aspects of the framework described here will be applied to the MATRIX test cases, namely Naples, Italy, French West Indies, and Cologne, Germany.

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MATRIX Common IT sYstem (MATRIX CITY) Generic multi-hazard and multi-risk framework - the concept of Virtual City - IT considerations

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Summary

Dynamic risk processes have yet to be clearly understood and properly integrated into probabilistic risk assessments. While much attention has been given to this issue in recent times, most studies remain limited to specific multi-risk scenarios. Here we present the MATRIX Common IT sYstem (MATRIX-CITY), developed within the scope of work package 7 of MATRIX (details are presented in MATRIX deliverable D7.2, Mignan, 2013). MATRIX-CITY is a first step towards a more general use of multi-risk tools in decision-making, and encompasses 3 major advances in the implementation of a multi-risk framework:

1. The development of a generic probabilistic framework based on the sequential Monte Carlo method to implement coinciding events and triggered chains of events, as well as time-dependent vulnerability and exposure (Mignan et al., accepted),
2. The proposition of guidelines for the implementation of multi-risk, using the concept of the "Virtual City" to test basic multi-risk concepts in a controlled, yet realistic, environment (Mignan et al., accepted),
3. A better understanding of the IT requirements for the widespread use of multi-risk tools, based on the lessons learned from the development of an IT platform prototype (the "original MATRIX-CITY", Mignan, 2013) and from interactions with stakeholders.

A generic multi-hazard and multi-risk framework: A "blue print" for extreme event assessment

A sequential Monte Carlo method was proposed to generate a large number of risk scenarios (i.e., the generation of hazardous events and the computation of associated losses). The analysis of these simulated risk scenarios then allowed us to assess losses in a probabilistic way and to recognize more or less probable risk paths, including extremes or low-probability high-consequences chains of events. We finally found that "black swans", which refer to unpredictable outliers, can only be captured by adding more knowledge about potential interaction processes to the computation process. However, this can only be achieved over time by following a “brick-by-brick” approach given the considerable effort that is required.

To quantify hazard interactions, we introduced the concept of the hazard correlation matrix (Figure 1a). We considered three categories of interactions: event repeat (e.g., $A_i \rightarrow A_i$; C $\rightarrow$ C), intra-hazard interaction (e.g., $A_i \rightarrow A_j$) and inter-hazard interaction (e.g., $A_i \rightarrow B_j$). The effect could be positive (i.e., probability increase) or negative (i.e., probability decrease), and temporary or long lasting. Time-dependent vulnerability and exposure are not described here, but are taken into account within the framework at a later stage of the calculations. To evaluate how multi-risk participates in the emergence of extremes, we additionally introduced the concept of the risk migration matrix and showed that risk migration and risk amplification are the two main causes for the occurrence of extremes (Figure 1b).

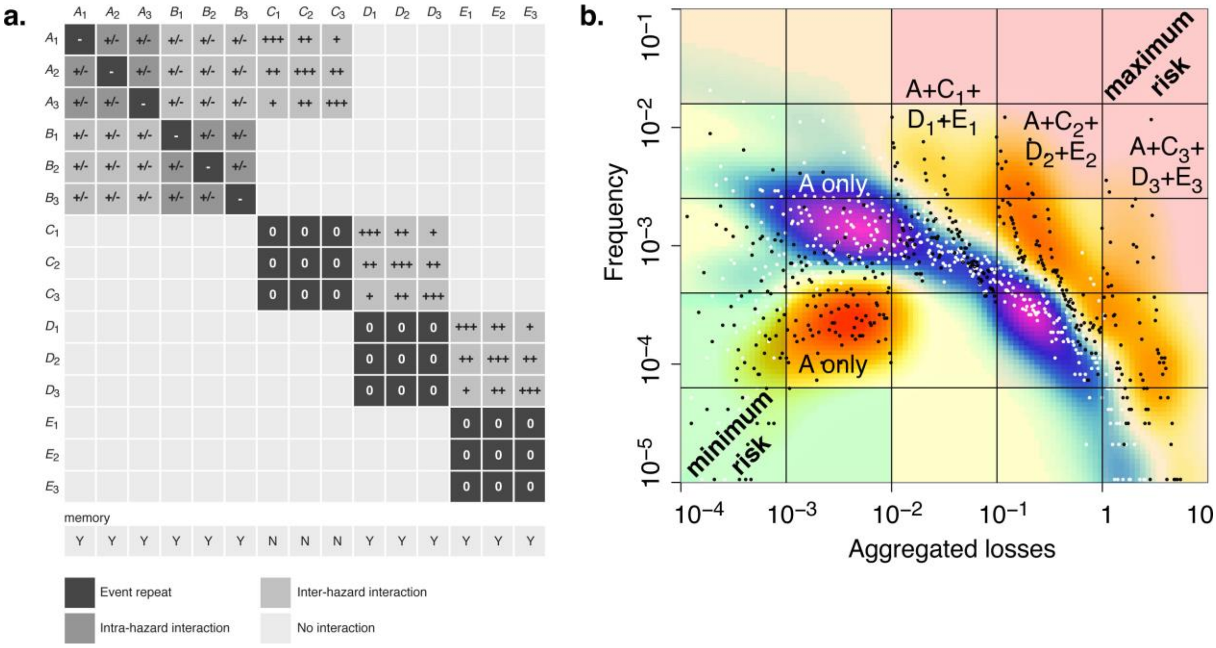

Figure 1: Main results from the proposed generic multi-risk framework. **a.** The concept of the hazard correlation matrix. Trigger events are represented in rows i and target/triggered events in columns j. Each cell indicates the 1-to-1 conditional probability of occurrence Pr(j|i). The n-to-1 conditional probability is considered by incorporating a memory element to the correlation matrix. The identifiers A, B, C, D and E represent different types of perils. **b.** The risk migration matrix, a multi-risk metric that shows how risk changes as a function of frequency and aggregated losses when new information is added to the system (here adding cascading effects A $\rightarrow$ C $\rightarrow$ D $\rightarrow$ E as defined in **a.**). An increase of risk is represented in red and a decrease in blue. The points represent the individual risk scenarios, where black indicates those where interactions are considered and white where they are not. Source: Mignan et al. (accepted). Figure 1b is also available from the Appendix of Komendantova et al. (2014).

The Virtual City concept: Guidelines for shifting from abstract processes to realistic processes

The multi-risk framework was developed and tested based on generic data and processes generated following the heuristic method. This strategy, which involves the use of intuitive judgment and simple rules, allows for the solving of problems that are otherwise difficult to consider. Our approach follows the existing recommendations on extreme event assessment, which involves the use of inductive generalizations and "scientific imagination" to include known examples of extremes, as well as potential "surprise" events within the same framework. However, abstract concepts, such as the definition of generic perils (e.g., A to E, Figure 1), remain difficult to comprehend and we therefore proposed some guidelines to help risk modellers and decision-makers apply this approach to realistic cases. For this purpose, we developed the concept of the Virtual City (Figure 2). Within this concept or tool, the perils A, B, C, D and E are no longer simply abstract concepts, but are replaced, for instance, by earthquakes, volcanic eruptions, tsunamis, fluvial floods and storms. Hazard, exposure and vulnerability data, as well as details about possible interacting processes, are based on real examples obtained from the scientific literature.

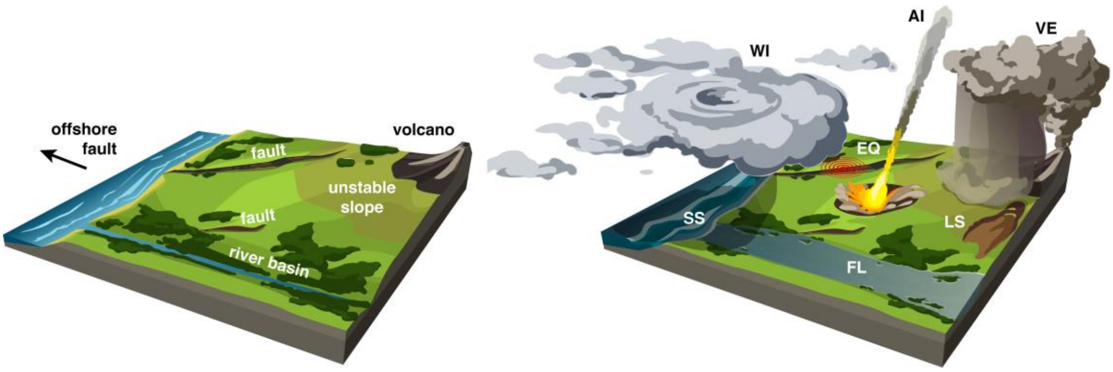

Figure 2: (left) The virtual region in which the Virtual City is located. (right) The considered perils include: earthquakes (EQ), volcanic eruptions (VE), landslides (LS), fluvial floods (FL), wind events (WI), sea submersion (SS, e.g., storm surge or tsunami) and asteroid impacts (AI). Also included, but not shown, are NaTech (Natural Technological) events, i.e., technological accidents triggered by a natural event. Source: Mignan et al. (in preparation). A previous, simpler, version is shown in Komendantova et al. (2014).

IT considerations: Planning the widespread use of multi-hazard and multi-risk tools by decision makers

A prototype version of an IT platform for multi-risk loss estimations was developed during the first part of the project, the so-called MATRIX Common IT sYstem - or MATRIX-CITY

(Mignan, 2013). While based on state-of-the-art software engineering and a Python-based code, it was rapidly observed that multi-risk software would need to have all the functionalities of existing risk tools, on top of the innovative multi-risk framework described previously. Such a task would require significant resources and a commitment of modellers used to other types of risk modelling tools (including various procedures and formats). At this present stage, we recommend the exporting of the method developed for this IT tool to existing risk tools, which would facilitate its implementation and potentially encourage the widespread use of the proposed approach, as explained in Figure 3.

Concluding comments

The present work should be seen as a proof-of-concept, as we did not intend to fully resolve the complex problem of low probability-high consequence events. We only considered a selected number of possible interactions, where naturally adding more perils and interactions would yield more complex risk patterns. We thus recommend a brick-by-brick approach to the modelling of multi-risk, to progressively reduce epistemic uncertainties. A more realistic modelling of low-probability high-consequences events would also require the consideration of additional aspects, such as uncertainties, domino effects in socio-economic networks and long-term processes, such as climate change, infrastructure ageing and exposure changes. While the concepts developed in the present study outline the theoretical benefits of multi-risk assessment, identifying their real-world practicality will require the application of the proposed framework to real test sites.

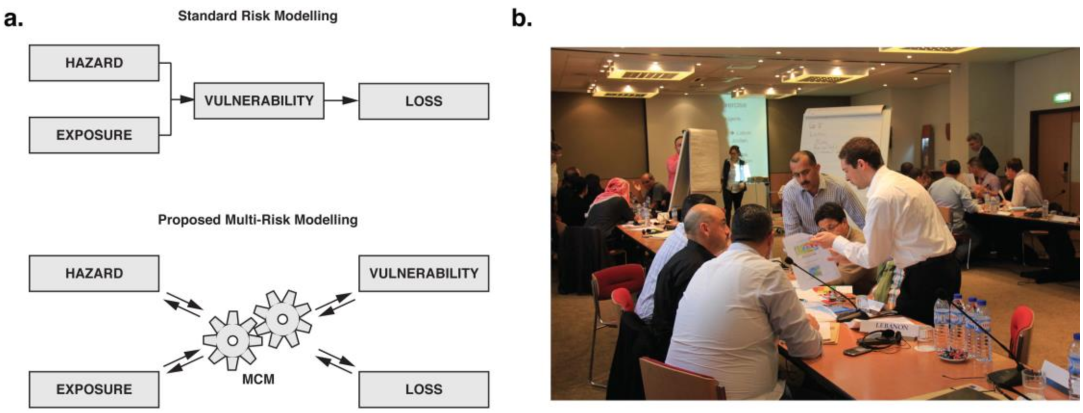

Figure 3: A paradigm shift in risk assessment? **a.** The structural differences between standard risk modelling and the newly proposed multi-risk approach. MCM refers to the sequential Monte Carlo Method. Such an approach could be exported to existing risk tools. Source: Mignan et al. (under revision); **b.** Discussion with stakeholders at the PPRD[5] South 2012 Lisbon workshop on multi-risk.

[5] http://www.euromedcp.eu/index.php

The needs of decision makers must be taken into account to facilitate the communication and use of multi-risk approaches (see also Komendantova et al., 2014).

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Multi-risk and multi-hazard decision support models and the needs of stakeholders from practice

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Introduction

Existing risk assessment methods integrate large volumes of data and sophisticated analyses, as well as different approaches to risk quantification. However, the key question is why do losses from natural disasters continue to grow if our scientific knowledge on multi-risk is increasing? (White et al., 2001). As Kappes et al. (2012) stated in their review on multi-hazard risk assessment, to be able to understand this question, we need to also examine the frameworks employed in the field of risk management, as well as the interactions between science and practice in terms of knowledge transfer and the applicability of results. Our work deals with the questions of communication and the transfer of scientific knowledge on multi-risk and its underlying drivers to stakeholders within the decision-making process. A two-way communication process has allowed us to not only collect feedback from stakeholders (i.e., civil protection offices) across Europe on the usability of the multi-risk decision–support tools that have the potential to benefit decision-makers and to provide them with information on mitigation measures, but also to integrate their feedback into improving the tools themselves.

The theoretical background of our work involves the concept of risk governance, which takes into account cultural and political factors when implementing risk mitigation measures and emphasizes the role of participation and communication. The risk governance concept is concerned with such issues as how information is perceived, collected and communicated, and, based on these factors, how management decisions are made (IRGC, 2005). Participatory modelling is an important part of risk governance and allows us to take into consideration not only facts, but also values by collecting feedback from stakeholders (Forester, 1999). The process of interacting with stakeholders leads to an enhanced understanding of the views, criteria, preferences and trade-offs employed in decision-making (Antunes et al., 2006). Also, as social science scholars argue, because the development of scientific tools is also a social process, it is essential to involve relevant stakeholders who will be using the tools in the design process through the collection and integration of their feedback (Tesh, 1990).

Two complementary decision-making tools developed within the context of the MATRIX project are discussed here:

(1) A generic framework developed by ETH Zurich and which is the subject of another report in this deliverable (MATRIX deliverable D7.2, Mignan, 2013, Mignan, 2014, this report), and
(2) An evaluation methodology based on the concept of the risk matrix that incorporates expert knowledge through stakeholder interactions into multi-hazard scenario development, developed by the Karlsruhe Institute of Technology (KIT) (Wenzel, 2012).

Feedback for decision-making tools

This research was motivated by the gap in the scientific literature about feedback with respect to the usability of decision-support tools. While the use of feedback for the development of decision-support tools for environmental issues has been reported (Constanza and Ruth, 1998), as well as there being multi-risk decision–support tools that have the option of collecting feedback (T6, 2007), there is no evidence or analysis of the feedback from stakeholders from practice on the usability of multi-risk decision-support tools. During our work, we not only collected such feedback from civil protection officers, but we also used this information to improve the developed decision-making tools, directly integrating stakeholders' perceptions into the model by attributing different weights to loss parameters according to preferences from stakeholders. The information was gained during two workshops, namely a MATRIX stakeholders' meeting in Bonn (July, 2012) and a workshop on urban multi-hazard risk assessment in Lisbon[6] (October, 2012), and from a

[6] Multi-hazard Risk Assessment in Urban Environment, 18-19 October 2012, Lisbon, Portugal, PPRD South program

questionnaire distributed prior to the first workshop. The selection of the stakeholders forms a representative sample, given the fact that our stakeholders´ consultation process covered most European countries, with a majority of them representing National Platforms, as well as the UNISDR.

A presentation of the generic multi-risk framework (tool #1) in Lisbon involved a half-day exercise, where one of the tasks required investigating the different hazards presented in the used examples, based on data such as hazard maps and to give some score to their severity and frequency within the concept of the risk matrix - hence combining the tool #1 core modelling concept with a visualization and ranking of multi-risk similar to tool #2. In fact, this represented an upgrade of tool #1, based on feedback obtained during the Bonn workshop. An exercise involving tool #2 was presented at the Bonn workshop, in which stakeholder input was needed to identify the weights with which the impact of particular components of the model are specified in a participatory fashion (i.e., what is the relative importance of the different loss parameters in the risk ranking?). Thus, the primary difficulty in gathering stakeholder input involved creating a "value model" that would support stakeholders in assessing problems and expressing their views more explicitly.

The general results show that for the usage of multi-risk decision-support tools, two areas are most problematic. These are (1) the absence of clear definitions and (2) the lack of information on the added value of multi-risk assessment. Multi-risk is not systematically addressed among the EU countries for all hazards, but is only singularly integrated into risk assessment approaches. Some examples include the superposition of existing single hazard risk prevention plans for all hazards, for example, combining flood and landslide hazards and flood risks with wind effects, the application of which is within the context of risk assessment of critical infrastructure, in particular the combination of meteorological and technological risks. Generally, multi-risk analysis is barely or not at all integrated into decision-making processes, and only around half of stakeholders were aware of methodologies and tools to assess multi-risk.

The reaction of stakeholders to the multi-risk assessment and decision-making tools presented at the both workshops was optimistic. Several stakeholders invited the developers of these tools to give presentations and to conduct training on the tools at their home institutions. The majority of stakeholders would consider the use of the generic multi-risk framework (tool #1) and the decision-making tool (tool #2) after their testing phase. However, the usability of the tools in practice is complicated by such factors as the required large

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http://www.euromedcp.eu/index.php

volume of input parameters, which involves cumbersome data gathering to consider multiple hazards and risks in a given region, and that their possible application is limited to only a narrow number of experts as high-level expertise is required to assess the dynamic multi-hazard and multi-risk processes, taking into account the complexity of the models and the required parameters.

The consultation process with stakeholders also showed significant variation in perceptions between stakeholders in academia and in practice. While both academicians and practitioners agreed that the decision-support tools are useful for understanding losses and their contributions in a risk scenario, differences arise between how practitioners viewed the usefulness of the tools when it comes to prioritizing risk and developing risk management strategies. Similarly, practitioners found the tools less useful than academics when it comes to preparing for disasters and allocating resources.

Closing comments

We have collected recommendations on two possible areas involving the application of decision-support tools. The first is in the more narrow sense of convincing stakeholders involved in the decision-making process of the usefulness of the multi-hazard approach. The second deals with the broader view of disseminating these results to the general public, hence confronting public acceptance issues. Some stakeholders expressed the opinion that politicians could use such models as training to see what the consequences of a multi-hazard situation could be. Another general recommendation was that the decision-support tools could be used for educational purposes.

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The MATRIX framework applied to the test cases of Naples, Guadeloupe and Cologne

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Introduction

One of the objectives of the MATRIX project was the development of a conceptual framework that could be applied to multi-hazard and multi-risk environments. The developed framework (MATRIX deliverable D5.2, Nadim et al., 2013, Liu and Nadim, 2013) involves several levels of analysis of increasing sophistication, an overview of which is provided in another reference report in this document[7]. It is therefore the aim of this chapter to present some results of a simplified application of this framework to the MATRIX test cases, namely Naples, Italy, Guadeloupe, French West Indies, and Cologne, Germany. All three test cases represent multi-hazard and risk environments, although with differing degrees and complexities of hazard and risk interactions. As outlined in the overview of the framework, one of the aims was to develop a system whereby a decision-maker or end-user could identify how much effort is actually required (also dependent upon the available resources) by answering a series of questions, and then deciding whether a complete, quantitative multi-risk analysis is necessary for the case at hand.

The MATRIX test cases

In order to verify the concepts and tools developed within MATRIX, it is necessary to apply them to real world situations where conjoint and cascading events and interactions between

[7] Nadim et al., 2013 “MATRIX framework for multirisk assessment”,

different hazards and risks need to be considered. It is for this reason, and matching the expertise of the consortium, that the MATRIX test cases were chosen. All three are under threat from multiple hazards (see MATRIX deliverable D3.3, Garcia-Aristizabal et al., 2013a, and Garcia-Aristizabal et al., 2013 "Identifying and structuring scenarios of cascade events in the MATRIX project", this document). Naples (MATRIX deliverable D7.3, Garcia-Aristizabal et al., 2013b) and Guadeloupe (MATRIX deliverable D7.4, Monfort and Lecacheux, 2013) are the most threatened (and complex) examples, with both endangered by volcanic eruptions, earthquakes, as well as hurricanes (Guadeloupe), landslides (Naples and Guadeloupe) and forest fires (Naples). Each case is also susceptible to cascading events, in particular rain- and earthquake-induced landslides and volcano-earthquake interactions. Cologne (MATRIX deliverable D7.5, Fleming et al., 2014) on the other hand is not as exposed to such a range of hazards, nonetheless it must still contend with threats from earthquakes, floods and windstorms (Grünthal et al., 2006), with the possibility of earthquake-induced damage to its dyke system increasing the flood risk to the city.

The MATRIX multi-risk framework

As the framework is outlined in another chapter of this document (Nadim et al., 2014), we will only present the barest details here. In summary, it consists of four levels:

- Single hazard(s) risk assessment (Figure 1 of Nadim et al., 2014).
- Level 1 – Qualitative analysis – decides if a multi-type assessment is required (Figure 2 of Nadim et al., 2014).
- Level 2 – Semi-quantitative analysis – identifies the various interactions between hazards (Figure 3 of Nadim et al., 2014).
- Level 3 – Quantitative analysis – the interactions between hazards, time-dependent vulnerability and the accompanying uncertainties are estimated.

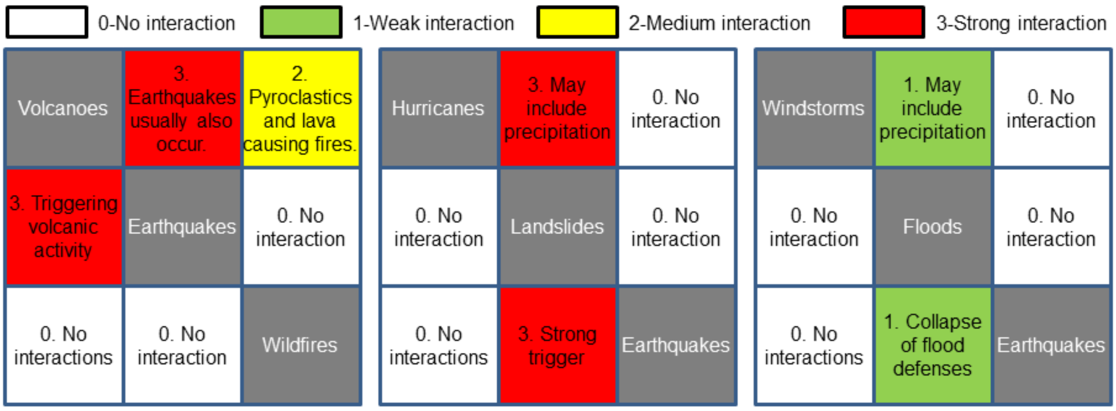
As commented upon earlier, by considering a series of questions, a decision maker or stakeholder can decide if it is necessary to proceed to a higher level. Considering Level 1, the answers for each test case being presented in Table 1, we note immediately that for each example, we must proceed from the initial "More than one hazard?" question to dealing with the various interactions, with the need for at least a Level 2 analysis. However, even if this were not the case, i.e., only one hazard of concern, then there is also the possibility of events of the same kind repeating during a given time period, which may be taken as the time required to carry out the necessary repairs/recovery from the original event (e.g., a series of storms separated by short periods of time). We also note that for all three cases, we would probably need to proceed to a quantitative Level 3 analysis, based on the fact that cascade events may arise. However, the fact that cascade events in Naples and Guadeloupe are more likely than in Cologne cannot, at this stage of an assessment (or comparison), be resolved. In addition, the cascade example for Cologne presented, i.e., an earthquake damaging flood defences, hence increasing flood risk, would also fit within the context of conjoint events. Therefore, it would appear that even the most "quiet" territories may be exposed to several hazards, with interactions potentially always present (for example, Na-Tech - Natural Technological - interactions are in many industrialised districts a major concern, although they are not dealt with in detail in MATRIX). Hence, one may expect the situation where only a Level 1 assessment is required would be fairly rare.

	Naples	**Guadeloupe**	**Cologne**
More than 1 hazard (YES)	Earthquakes, volcanoes, tsunamis, storms, landslides, forest fires, floods.	Earthquakes, volcanoes, tsunamis, storms (hurricanes), landslides, floods (rains, storm, surges).	Earthquakes, flooding (river), windstorms.
Hazard interactions (YES)			
Possible cascades:[8]	Volcano-earthquake interactions Earthquake – landslides Volcanoes – wildfires Heavy precipitation (flood) – landslides	Volcano-earthquake interactions Volcano/earthquake-tsunamis Earthquake – landslides Heavy precipitation (floods) – landslides	Earthquake damaging a loaded dyke, causing flooding (conjoint event).
Affects triggering with some time delay	Increased landslide risk after heavy rainfalls, e.g., an earthquake soon after heavy rains, when the soils are saturated and thus more susceptible.	Increased landslide risk after heavy rainfalls.	Increased flood risk arising from unrepaired dykes following an earthquake
Potential interactions due to mitigation measures	This has not been considered within this work. While increasing a house's height could reduce loss due to flooding, it may increase loss due to earthquake.	Not considered in this work. Some retrofitting actions against cyclones or floods may increase seismic vulnerability if proper attention is not given to earthquake design issues	Location of dykes may shift the flood risk spatially.
Time-dependent vulnerability	Earthquake-Earthquake interactions; Earthquake-Landslide interactions	Time-dependent vulnerability in buildings is considered in this work; however, landslide potential varies during the year owing to the changing levels of water saturation.	The main issue would be the vulnerability of the defences to seismic loading, depending upon the water levels.

Table 1: The answers to the questions posed as part of Step 1 of the framework (Figure 1).

[8] See Deliverable D3.3 "Scenarios of cascade events", Garcia-Aristizabal et al. (2013a)

Considering the Level 2 assessment, the aim is to describe the various relationships between the assorted hazards. This is done by following a matrix approach (modified after de Simeoni et al., 1999 and Kappes et al., 2010), the results for the three test cases being presented in Figure 1 (again, please refer to Figure 3 of Nadim et al., 2014, this document). To read these figures, consider first that along the diagonal, the hazards of concern are listed. Then, moving in a clockwise manner, the level of interaction (scored between 0 and 3 with intervals of 1, where 3 indicates a strong interaction and 0 indicates none) and the nature of such interactions between each hazard pair are identified.



(a) Naples (b) Guadeloupe (c) Cologne

Figure 1: The hazard interaction matrix means of identifying the type and magnitude of the various interactions possible for the MATRIX test cases (0 – no interaction, 3 – strong interaction). Note, only some examples for Naples and Guadeloupe are included.

For Naples and Guadeloupe (Figure 1a and 1b), for the purpose of this work, we simply refer to three hazards, although obviously a larger matrix would be needed to be employed for a thorough study. We note the strong (3) interactions between some hazards, e.g., earthquakes and volcanoes for Naples, landslides and earthquakes for Guadeloupe, as well as hazards where no interaction would arise (e.g., hurricanes and earthquakes). Considering Cologne (Figure 1c), we identify few interactions between hazards, i.e., windstorms potentially bringing heavy rain, although for Cologne, more localised heavy precipitation causes little widespread flooding, and an earthquake damaging flood defences. However, it is also recognized that if we considered this at the risk level, then a windstorm may damage a building, increasing its susceptibility to a later earthquake, while considering the reverse (an initial earthquake followed by a windstorm) would most likely be more serious. Based on the numbers presented in each square, a so-called hazard interaction index may be inferred (found by adding all results row by row, representing causes, then column by column, representing effects), the size of which relative to some criteria (e.g., a predefined percentage of the maximum possible index for a given site) may decide whether or not to proceed to the more resource intensive Level 3 analysis. For example, Naples has a score of 16 and Guadeloupe 12, while Cologne has a value of only 4, indicating as expected the much great importance of such interactions for the first two cases.

Finally, an attempt to consider a quantitative Level 3 analysis was carried out for Naples, considering volcano-earthquake interactions at the hazard and vulnerability levels (see MATRIX deliverable D3.4, Garcia-Aristizabal et al., 2013c). For the hazard level, the contribution to seismic hazard by volcanic earthquakes during periods of volcanic unrest was assessed. Likewise, the combined effects of ash loads deposited over roofs and seismic loading were considered in order to estimate their effects on the risk quantification. It was found that because of the characteristics of the volcanic seismic swarms (shallow and generally small events), their contribution to seismic hazard is strongly localized around the epicentre zone of the events and quickly vanishes with distance. Conversely, the combined effects of seismic and volcanic ash loads increases the average risk by an order of 3% to 6% (with respect to calculations that don't take into consideration the effects of volcanic ash). Furthermore, a scenario-based analysis considering specific ash-load scenarios was also undertaken, with more specific amplification effects observed. Such scenario-based analyses can provide important information for short-term assessments.

Final comments

The multi-hazard and risk framework developed within MATRIX provides a useful and valuable scheme within which to identify the characteristics of interactions between a given area's hazard and risk environment. Although not all hazards for Naples and Guadeloupe are considered in the level 2 assessment, one can still see that this framework shows the much stronger need for the more complex analysis for Naples and Guadeloupe than for Cologne.

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Multi-risk assessment and governance: research into practice

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Introduction

In risk assessment research and policy, there is currently much debate on multi-type hazard and risk assessment and the definition and use of realistic scenarios. This debate has been evoked, not least, by several specific disasters in recent years that have resulted in extremely high numbers of fatalities and massive damage to properties and infrastructure. Recent examples are the Super Typhoon Haiyan, which hit the Philippines in November 2013, causing floods and landslides, and the Tohoku earthquake that struck Japan in March 2011, with the resulting devastating tsunami and nuclear accident.

The research undertaken in MATRIX Work package 6 “Decision support for mitigation and adaptation in a multi-hazard environment” aimed at *providing guidance on how to maximize the benefits arising from, and overcome the barriers to, the implementation of a multi-hazard and risk assessment approach within current risk management regimes.*

This reference report focuses on the synthesising the identified benefits and barriers to multi-hazard mitigation and adaption[9]. It is addressed to practitioners within the public/private sector working in communities exposed to multiple risks as well as to those active at the science-policy interface, thus including researchers, policy and decision makers in risk and emergency management.

[9] Deliverable D6.4 “Synthesis” Scolobig et al. (2013)

Research design

The research design was grounded on documentary analyses and extensive empirical work involving policy makers, private sector actors, and researchers in risk and emergency management. The work was informed by thirty-six semi-structured interviews, three workshops (Figure 1) with over seventy practitioners in total attending, feedback from questionnaires and focus groups discussions. Most of the fieldwork was conducted in two of the MATRIX test sites: Naples (Southern Italy) and Guadeloupe (French West Indies). Lessons learnt from five historical multi-hazard disasters have been also included, as well as examples reported from practitioners representing eleven countries (Italy, France, Norway, Germany, Hungary, Bulgaria, Sweden, United Kingdom, Iceland, Croatia, Austria). This lead to practical and evidence-based recommendations that are informed by a well-researched understanding of the process through which new knowledge about multi-hazard and risk assessment can be taken advantage of by practitioners.

Figure 1: A workshop with practitioners organised in Naples, Italy.

From multi-risk assessment to multi-risk governance

Within current single-risk-centred governance systems (which have evolved in parallel with the single-risk-centred risk assessment processes), practitioners hardly ever have the opportunity to discuss multi-risk issues, including triggered events, cascade effects and the rapid increase in vulnerability resulting from successive hazards. However, as revealed by the workshop results, risk and emergency managers clearly see the benefits of including a multi-risk approach in their everyday activities, especially in the urban planning sector, but also in emergency management and risk mitigation (see the chapter in this document by Komendantova et al.).

Benefits of a multi-risk viewpoint

As one example of how a multi-risk viewpoint would be of value, practitioners believe that decisions on building restrictions for urban planning would benefit greatly from the results of multi-risk assessment. A multi-risk approach is considered particularly useful also for gaining a holistic view of all of the possible risks that may affect a territory. For example, such an approach can show that focusing only on the impacts of one hazard could result in raising the vulnerability of the area to another type of hazard. For example volcanic ash can have an additive effect on seismic loads. Another example of this is in the older buildings of Kobe, Japan, which were built with relatively heavy roofs. This helped to mitigate against the frequent typhoons, but enhanced their vulnerability to rarer earthquakes.

Other benefits that are considered to be particularly crucial by practitioners include: the cost reductions and improvements in the efficiency of proposed risk mitigation actions; the development of new partnerships between agencies working on different types of risks; an awareness of the potential for expected losses being exceeded (i.e., the total risk is possibly greater than the sum of the individual parts), as well as the lives and property saved and better protected by the use of a multi- vs. single-risk approach. However, further research is still needed in order to better understand the extent of some of these benefits, as well as the need to consider aspects of the mitigation problem, such as the different time scales involved between the events themselves, response, initial recovery and ongoing mitigation. Our results also reveal that practitioners and researchers have in mind different agendas for future research on multi-risk assessment. Therefore, a transparent process to reach a compromise on the required priorities is needed.

Barriers

Barriers to an effective implementation of multi-risk assessment can be found in both the science and practice domains. For example, considering scientific contributions to risk assessment research, the process has evolved differently in the fields dealing with geological versus meteorological hazards, with the different scientific development paths representing a major barrier to understanding and communicating between different "risk communities". Accompanying this is the lack of open access to databases and research results, which is particularly worrying for risk managers. Overarching these problems are the matters of the lack of interagency cooperation and communication, which are particularly difficult for risks that are managed by authorities acting at different levels (e.g., in Naples, national bodies are responsible for volcanic risk, while river basin authorities deal with flood risk). The lack of capacities at the local level and unsatisfactory public-private partnerships are also major barriers that need to be confronted.

Catalysts for the effective implementation of multi-risk assessment

As a result of our interactions and discussions with stakeholders, some priority actions have been identified:

- Encourage knowledge exchange and dialogue between the risk communities dealing with geological and meteorological hazards;
- Identify new options for mitigation, - e.g., multi-risk insurance schemes, new forms of public-private responsibility sharing for households exposed to multi-risks;
- Develop territorial platforms for data and knowledge exchange between researchers and practitioners;
- Create an inter-agency environment, where the different departments at the national and/or regional governmental level, can exchange information, develop complementary protocols, and serve to provide consistent information and responses to the relevant stakeholders;
- Create commissions for discussion at the local/municipal level ("local multi-risk commissions") in order to gain a common understanding of what multi-risk assessment actually is, what kind of cooperative actions can be undertaken to implement it, what are the priorities for future research etc.. Members of these commissions should be decision and policy makers, researchers and local natural hazard advisors, the latter acting as the liaising bodies between local communities and practitioners.

Additional information and references

Work package 6 of the MATRIX project produced four deliverables based upon the conceptual and empirical work of an interdisciplinary team of researchers, integrating expertise from the physical, environmental and social sciences. The interested reader is referred to them.

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More information is available from the MATRIX website http://matrix.gpi.kit.edu/index.php.

Appendix: List of the deliverables resulting from the MATRIX projects

The following table lists all of the deliverables produced during the MATRIX project. These may be obtained from the MATRIX website (for the public document) or by directly contacting the project coordinator.

Regarding the dissemination level, if a document is not PU, then the consortium may need to be contacted and, at the author's discretion, the document will then be made available.

PU - Public
PP - Restricted to other programme participants (including the Commission Services)
RE - Restricted to a group specified by the consortium (including the Commission Services)
CO - Confidential, only for members of the consortium (including the Commission Services).

Number	Name	Lead partner	Dissem. level
D1.1	Kick off meeting report	GFZ	PU
D1.2	1st period intermediate reports	BRGM	PP
D1.3	2nd period intermediate and final reports	GFZ	PP
D1.4	1st period scientific audit	AMRA	RE
D1.5	2nd period and final scientific audit	GFZ	RE
D2.1	Single-type risk analysis procedures: Report on single-type risk analysis procedures in the framework of synoptical risk comparisons	GFZ	RE
D2.2	Uncertainty quantification: Report on uncertainty quantification and comparison for single-type risk analyses	BGRM	RE
D2.3	Harmonization strategy: Report on the optimal harmonization of single-type assessment methodologies for achieving risk comparability.	GFZ	RE
D3.1	Review of existing procedures: Review of the existing procedures for multi-hazard assessment	AMRA	PP
D3.2	Dictionary of terminology: Dictionary of terminology adopted.	AMRA	PP
D3.3	Scenarios of cascade events: Report on the description of the possible scenarios of cascade events.	AMRA	PP
D3.4	Probabilistic framework: Report describing the proposed probabilistic framework for multi-risk assessment.	AMRA	RE

Number	Name	Lead partner	Dissem. level
D3.5	Software for multi-hazard assessment: Software for multi-risk assessment.	BRGM	RE
D4.1	Fragility functions: Impact of repeated events with various intensities on the fragility functions for a given building typology at local scale.	BRGM	CO
D4.2	Fragility of pre-damaged elements: Realisation of fragility functions of elements pre-damaged by other past events and demonstration on a scenario.	BRGM	CO
D4.3	Functional vulnerability: Report on the functional vulnerability assessment of a system prone to multiple hazards.	BRGM	PP
D4.4	Social and economic vulnerability: Report on the social and economic vulnerability to multiple hazards.	IIASA	PP
D5.1	State-of-the-art in multi-risk assessment: Review of the state-of-the-art in multi-risk assessment.	AMRA	PP
D5.2	Framework for multi-risk assessment: Framework for consistent multi-risk assessment.	NGI	RE
D5.3	Tangible and intangible losses: Quantification of tangible and intangible losses in multi-risk assessment.	IIASA	RE
D5.4	Fault trees and event trees: Development of fault trees and event trees for environmental risks.	TU-Delft	CO
D5.5	Uncertainties in multi-risk assessment: Treatment of uncertainties in multi-risk assessment.	NGI	CO
D6.1	Decision-analytic frameworks for multi-hazard mitigation and adaption: Review of the literature on decision analytic methods, and identify those best suited to multi-hazard cases through the application in a virtual city context.	KIT	PU
D6.2	Individual barriers to multi-hazard analysis: Identify the cognitive and cultural barriers to effective decision-making for individuals, and present experimental results used to test their application to multi-hazard cases.	IIASA	RE
D6.3	Social and institutional barriers to effective multi-hazard decision-making: Report on case study analysis, including empirical work with stakeholders, to identify the social and institutional constraints and opportunities to effective multi-hazard mitigation and adaptation.	IIASA	RE
D6.4	Synthesis: Synthesis: Benefits and barriers to multi-hazard mitigation and adaptation, with policy recommendations for decision-support.	IIASA	PP
D7.1	MATRIX common IT platform: Report on the MATRIX common IT platform	ETHZ	CO
D7.2	Implementation of the Virtual City: Implementation and analysis of the Virtual City	ETHZ	RE
D7.3	Naples test case: Report on Naples test case.	AMRA	RE
D7.4	French West Indies test case: case: Report on French West Indies test case	BRGM	RE
D7.5	Cologne test case: Report on Cologne test case.	GFZ	RE

Number	Name	Lead partner	Dissem. level
D8.1	Project web portal: Project web portal and data repository system online.	KIT	PU
D8.2	Communication strategy: Communication strategy and promotional material, brochures.	KIT	PU
D8.3	Guidelines for reference reports: Guidelines for MATRIX reference reports	KIT	RE
D8.4	MATRIX results I and reference reports	KIT	PU
D8.5	MATRIX results II and reference reports	KIT	PU
D8.6	Design of semantic MediaWiki	KIT	RE
D8.7	MATRIX SMW platform: MATRIX SMW platform up and running with ontology-based content.	KIT	PU
D8.8	Contacts to National Platforms I: Contacts with National Platforms and HFA Focal Points including disaster management communities, EC Civil Protection, CoE Major Hazards Agreement, Preventionweb established.	DKKV	PU
D8.9	Contacts to National Platforms II	DKKV	PU
D8.10	Contacts to National Platforms III	DKKV	PU
D8.11	Contacts to National Platforms IV	DKKV	PU
D8.12	Contacts to National Platforms V	DKKV	PU
D8.13	DRM profiles: DRM profiles of selected EU states available	DKKV	PU
D8.14	MATRIX results to DMC	DKKV	PU
D8.15	Platforms and MATRIX community: Performance evaluation of interaction between platforms and MATRIX community.	DKKV	RE
D8.16	Materials to the public: Communication materials to the public.	AMRA	PU
D8.17	Course design and material: Course design and training course material.	AMRA	PU
D8.18	Virtual laboratory: Concept and materials for virtual laboratory.	AMRA	PU
D8.19	Vision paper: Vision paper on multi-risk assessment strategies and its implementation in national and EU-wide mitigation strategies.	KIT	PU