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Quantifying the Impact of Critical Infrastructure Failure due to Extreme Weather Events

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ABSTRACT: The recent extreme weather events in Europe and around the world have raised issues about the organization and management of critical infrastructure. There is uncertainty and a lack of information on how infrastructure should be managed when subject to these extreme events. The existence of chaos and uncertainty in these situations can result in disruptions to transport, power outages and in the most extreme instances, loss of life. The 7th Framework *RAIN* (Risk Analysis of Infrastructure Networks in response to extreme weather) project is addressing these issues, involving partners from Ireland, Belgium, Germany, Finland, Italy, Netherlands, Slovenia and Spain. The objective of the *RAIN* project is to provide an operational analysis framework to minimize the impact of major weather events in the EU.

This paper summarizes the work that will be performed in one of the work packages of the *RAIN* project. This work package will examine the impact of critical infrastructure failure on society, security issues and the economy. Based on a risk analysis framework, a means of quantifying the level of risk will be established, firstly due to single land transport mode failures, and secondly for selected multi-mode-interdependent failure scenarios (e.g., failure of power stations result in failure of electrical train lines). In this study, methods will be developed to create an advanced risk assessment procedure, using a probabilistic based approach, to derive a measurable indicator of risk. The risk procedure will be benchmarked against case studies conducted on critical transport and operational tactical connections.

The project outputs will contribute to the process of knowledge management used in the protection of Critical Infrastructure and will provide a basis for the development of decision support systems.

1. INTRODUCTION

In recent years, a variety of extreme weather events, including droughts, rain induced landslides, river floods, winter storms, wildfire, and hurricanes, have threatened and damaged different regions across Europe and worldwide. Some of these events have had a devastating impact on critical infrastructure systems and have raised challenges for the organization and management of critical infrastructures. Uncertainty and lack of information on infrastructure behaviour in extreme weather events play central roles in these challenges. Disruptions to transport, power outages and in the most extreme instances, loss of life are just a few examples of the impacts. For example, in 2002, a flood caused by over a week of continuous heavy rain resulted in dozens of deaths and billions of Euro in damage in Germany, the Czech Republic, Austria and Slovakia (Figures 1 and 2). The effects on infrastructure consisted of electricity failures, failed telecommunication links, damage to approximately 250 roads and 256 bridge structures, disruption to the gas service due to damaged pipelines and contamination of clean water with flood water.

Figure 1: Flood damage in Karlin, Prague, the Czech Republic [1]

Figure 2: Flood damage in Dresden, Germany [2]

Reducing uncertainty and gaining a better understanding of how critical infrastructures and their operators should adjust their behaviour to weather events will help ensure the security of vital utilities. Within the context of an extreme event there is a need for an interaction between several entities such as; emergency planners, utility operators, first responders, engineers and, most importantly, the citizens living in the area of the extreme event. Consequently ways to improve the outcomes from such an interactive system cannot be found in isolation by any one discipline.

The 7th Framework project, *Risk Analysis of Infrastructure Networks in response to extreme weather*, (*RAIN*), will address these issues, by bringing together experts from transportation, energy, risk assessment, climate prediction, social sciences, civil engineering and telecommunications with the goal of predicting how extreme weather events will impact upon critical European infrastructure networks collectively.

The *RAIN* project aims to provide an operational analysis framework to minimize the impact of major weather events on the EU. A holistic risk mitigation approach will be used to establish the key components of existing critical infrastructure network and to assess the sensitivity of these components to extreme weather. The sensitivity of European infrastructure to widespread disruption due to extreme weather events will then be assessed to reduce the impact of possible future events.

The main objective of this project is to quantify the complex interaction of existing infrastructure systems and their interrelated damage potential in the event of specific extreme weather events. This will improve the robustness of European Networks in order to avoid disproportionate damage or disruption due to extreme events.

The *RAIN* research activities are organized around six technical work packages (WP). The second package, WP2, focuses on hazard identification. Critical land, energy and telecommunication structures are the main focus of third and fourth work packages, respectively. Development of the Risk Analysis framework, identifying measurable risks and benefits, and developing mitigation strategies are covered in WP5, WP6 and WP7 respectively. WP1 and WP8 complete the work plan by covering the management and dissemination activities as indicated in Figure 3. The diagram also serves to show the interaction and interdependencies between WP's.

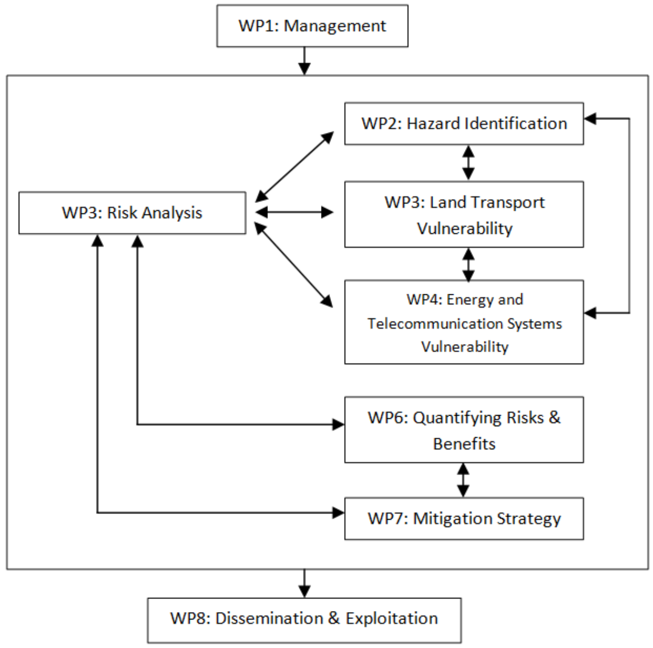

Figure 3: Work Plan Strategy & Methodological Diagram

The authors' main contribution to this project is to quantify the risks and impacts of critical infrastructure failure within WP6 activities. This work package aims to assess the societal, security and economic impacts of critical land, energy and telecommunications infrastructure failures, for single and multi-mode failure events. In this work package, a means of quantifying the level of risk will be established based on a risk analysis mapping protocol. In this framework, an advanced risk assessment procedure is being developed to derive a measurable indicator of risk. The developed risk procedure will be benchmarked against two case studies: i) the Loviisa nuclear reactor in Finland and, ii) the Fell river basin in the Alpine region.

In the final step, based on the impacts of the failures, the quantifiable benefits of providing resilient infrastructure will be identified from a societal, security and economic point of view.

2. RISK ASSESSMENT FRAMEWORK

This section presents a summary of the proposed framework for risk analysis of interconnected infrastructure systems for WP6. In general, risk is defined as a set of scenarios (S_i), each of which has a probability of occurrence (P_i) and a consequence (X_i) (Kaplan and Garrick, 1981). The first step in risk assessment is system definition in terms of its physical components and the related operational organization to make the system function (Bea et al., 2009; Roe and Schulman, 2008). Interacting and interdependent components forming a system should be defined in this step.

In each system the critical infrastructures will be defined. Critical infrastructures can be defined as assets or subsystems that are essential for the functioning of the system from a societal, economic and security point of view. In the scope of this study, critical infrastructures are limited to land, energy and telecommunication systems. In the next step, interactions between critical infrastructures will be defined, i.e., independence, dependence and interdependence (Roe, 2010).

The functioning of the system can be affected by various extreme weather events, such as storms, heavy rainfalls, coastal or river floods and landslides. These influences could lead to a change in the system's state from normal functionality to disruption or failure. Disruption can be defined as temporary and/or partial failure of the system which is often referred to as the Serviceability Limit State (SLS) and it mostly relates to interruption and delay of a system's processes. The consequences of such a disruption state may be delay and economic damage, which can be restored within a reasonable time. The failure state, also known as the ultimate limit state (ULS), is one in which an object permanently ceases to function through failure or collapse. This state constitutes a direct threat to safety and the consequences potentially involve fatalities and economic damage. Hazards, failure mechanisms and scenarios are required to be identified and described for each system.

Scenarios defining the interconnections between systems are also needed to be defined in this step.

Following the general definition of risk scenarios, possible failure scenarios will be quantified and will be characterized by their probability of failure (P_f) and the associated consequences (C_f). With the results of the former steps the risk can then be evaluated. In this step, the decision is made whether the risk is acceptable or not. In order to manage the risk an additional step is considered which is dependent on the outcome of the risk evaluation phase. It allows decisions to be taken to reduce the risk by monitoring, inspection or maintenance. Figure 4 illustrates all the steps required for risk management.

The objective of the developed risk analysis framework is to assess the P_f and C_f for a whole range of possible event scenarios. This allows the estimation and presentation of the risk level, depending on the availability of statistical information.

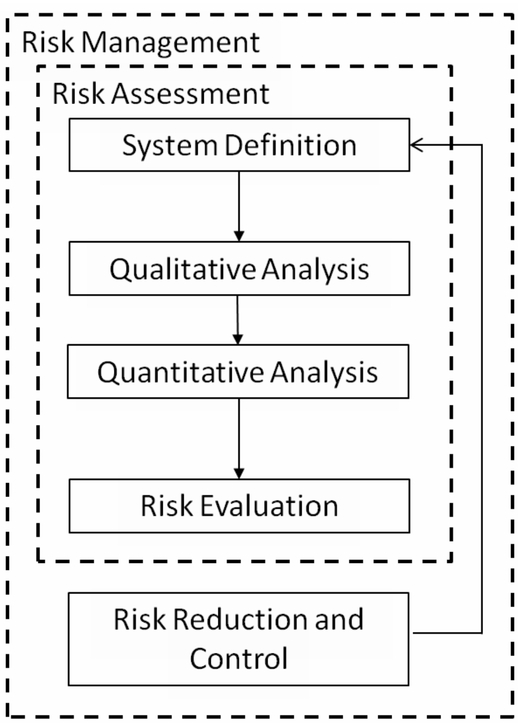

Figure 4: Risk Management Procedure

Following the general definition of risk, a Bayesian Network (BN) is a suitable approach to analyse a set of scenarios. BN is a probabilistic graphical model that represents a set of random variables and their conditional dependencies via a directed acyclic graph (DAG) or arrow. In this diagram, nodes represent random variables and arrows represent conditional dependencies. In this approach, all the relevant interactions in the system will be assessed and the relationships between various sub-systems will be plotted and visualized. This step will describe how the failure or disruption of one sub-system could lead to a change of state (failure, disruption) of another. As part of this qualitative analysis, the type of interaction also needs to be assessed. In the next step the conditional probability of occurrence of a certain state in a sub-system is quantified, given the state of another system which will be described by means of conditional state probabilities. Within the scope of this study, only the failure state (ULS) will be considered. As such the goal in this step is to quantify conditional failure probabilities. Finally the expected damage will be found by summing the probabilities multiplied by the consequences over all scenarios. The risk curve can be found by the probability of exceedance of a certain damage value, i.e., cumulative distribution curve. In order to manage the risk, different strategies will be assessed in an iterative procedure. It will be possible to see how risk level changes with different management policies and the reduction in failure probabilities or damage due to different strategies.

3. CASE STUDIES

3.1. Finish Nuclear Station

The first case study is critical transport and operational tactical connections of the Loviisa nuclear reactor as a result of sudden flooding and rising seawaters at the Gulf of Finland (Figure 5). A severe gale in the Northern Baltic Sea took place on January 7^{th}, 2005. A violent storm formed over the British Isles and moved from East to Central Finland. Several countries were affected by the violent storm including the United Kingdom, Norway, Denmark, Sweden and the Baltic countries. The highest winds occurred south of Finland and the biggest problem was the rise in sea level, which was as much as +197cm in Hamina. Waves reached heights of up to 8 metres and there was a significant sea level rise in the Gulf of Finland by the evening of 8th January.

Following the first early warning signals from the Finnish Institute of Marine Research (FIMR) to the Ministry of the Interior, the situation awareness of the Finnish emergency management agencies started to build on various assessments and predictions from the Finnish Meteorological Institute (FMI)'s and the FIMR's forecast machinery.

Water closed roads throughout the coastal region and traffic was cut off in many places in the Helsinki region. According to estimates, the storm caused €20 million in costs to the insurance company Sampo alone. Sampo estimates that in Finland its customers suffered damage worth €7 million.

Figure 5: Finnish Nuclear Station

3.2. Malborghetto-Valbruna municipality – Alpine region

The second case study is in the region of Friuli Venezia Giulia (Northern Italy) located in an Alpine area on the border with Austria and Slovenia, with 1036 inhabitants – Figure 6). This area is located in the Valcanale valley at the confluence of the Fella river and the streams of Rio Malborghetto and Rio Uque. On 29th of August 2003, a flash flood hit Malborghetto-Valbruna. The debris flow reached a peak of 4 m in the centre of one of the hamlets of the municipality (the village of Ugovizza). The water transported sediments, stones, shrubbery and trees into the village and caused two casualties and extensive material damage. Approximately 600 residents were evacuated and the damage amounted to €190 million. Clearing away the mud from the streets took almost one month. Damage to the basic services (water, electrical power, road connections and telecommunication) led to problems for the local population, and rescue services alike. The first responders in the emergency phase were volunteers from Austria and Slovenia, since the road connection on the Italian side of the valley was blocked. The regional civil protection only reached the municipality two days later. Within the municipal system the drainage and the electric lines had to be completely restored, while the aqueduct was blocked for several days. The recovery phase raised issues related to equity in the distribution of compensation payments, and disagreements among local people about the reconstruction process.

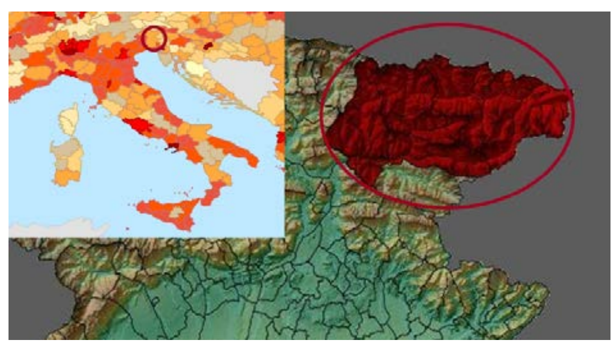

Figure 6: Alpine Region Case study

4. EXPECTED RESULTS AND OUTPUTS

The expected outcome of the work involved in work package WP6 of the RAIN project will give decision-makers an improved understanding of climate change risks in Europe and the uncertainty associated with its assessment. It will bring the best available evidence together using a consistent framework that describes the sensitivity, vulnerability and potential risks related to climate change. This will be one of the first European assessments of climate risks and goes further than previous reviews by drawing together different strands of evidence, comparing risks and providing a preliminary evaluation of the consequences of climate from social, economic and security perspectives.

5. ACKNOWLEDGMENT

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