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# Probabilistic Analysis of Potential Impact of Extreme Weather Events on Infrastructures

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ABSTRACT: 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 many different regions across Europe and worldwide. These events can have devastating impact on critical infrastructure systems. The 7th Framework RAIN project will address these issues, involving partners from Ireland, Belgium, Germany, Finland, Italy, Netherlands, Slovenia and Spain. In this project, the impact of critical infrastructure failure on society, on security issues and on the economy will be examined. Based on the impacts of the failures, quantifiable benefits (from a societal, security and economic standpoint) of providing resilient infrastructure will be identified. In this project, a means of quantifying the level of risk will be established, first due to single land transport mode failures, and second due to selected multi-mode-interdependent failure scenarios (e.g. failure of power stations result in failure of electrical train lines). This paper introduces the RAIN project and its goal of developing a methodology to create an advanced risk assessment procedure, including a probabilistic based approach, to derive a measurable indicator of risk.

KEY WORDS: Operational Analysis Framework, Infrastructure, Resilience, Risk Analysis, Mitigation Strategies, Societal Vulnerability/Security, Economic & Social Markers

## 1 INTRODUCTION

The recent extreme weather events in Europe and around the world have thrown the organisation and management of critical infrastructures into chaos. This chaos is a product of uncertainty and a lack of information on how the infrastructures we take for granted in our daily lives, will manage with 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. For example, in Germany and the Czech Republic, the worst affected areas in Europe flood in August 2002, the effects on infrastructure consisted of electricity failures, disconnected telecommunication links, damage to approximately 250 roads and 256 bridge structures (Figure1), disruption to the Gas service due to damaged pipelines and contamination of clean water with flood water (Figure 2).

Figure 2-damaged bridges during European Flood in 2002 [1,2]

Removing uncertainty and gaining a better understanding of how our critical infrastructures will cope and adapt to weather events will help ensure the security of vital utilities. Within the context of an extreme event one would typically see 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. Given the diversity of those involved in such an event – the answers to improving the outcomes of such events cannot be considered in isolation by any one discipline.

Figure 1: Prague Zoo flooded by the swollen river Vltava [3]

The objective of the Risk Analysis of Infrastructure Networks in response to extreme weather (RAIN) project is to provide an operational analysis framework to minimize the impact of major weather events on the EU land. A holistic risk mitigation approach will be used to establish the key components of existing infrastructure network and assess the sensitivity of these components to extreme weather and consequent socio-political effects. This project aims to predict the sensitivity of European infrastructure to widespread disruption due to extreme weather events to reduce the impact of possible future events.

RAIN aims to quantify the complex interaction of existing infrastructure systems and their interrelated damage potential in the event of specific extreme weather events. One of the main objectives of this project is to improve the robustness of European Networks in order to avoid disproportionate damage or disruption due to extreme events. This involves increasing the level of redundancy in the infrastructure networks at critical nodes, improving the performance of key infrastructure and developing detailed plans for a range of potential emergency scenarios.

The project is the collaboration between fifteen organizations in eight countries (Figure 3): Roughan & O'Donovan Ltd (ROD), Trinity College Dublin (TCD) and Gavin and Dehorty Geosolutions Ltd (GDG) in Ireland, European Sever Storms Laboratory (ESSL) and Freie Universitaet Berlin (FU-Berlin) in Germany, Zilinska Universiteit Delft (UNIZA) in Slovakia, Technische Universiteit Delft (TU-Delft) and Prak Security and Judgment (PSJ) in Netherlands, Dragados SA (DSA), Union Fenosa Distribution SA (UFD) and Applicaciones En Informatica Avanzada SL (AIA) in Spain, Hellenberg International OY (HI) and Finnish Meteorological Institute (Ilmatieteen Laitos, FMI) in Finland, Instituto di Sociologia Internazionale di Gorizia (ISIG) in Italy, Youris.com (Youris) in Belgium.

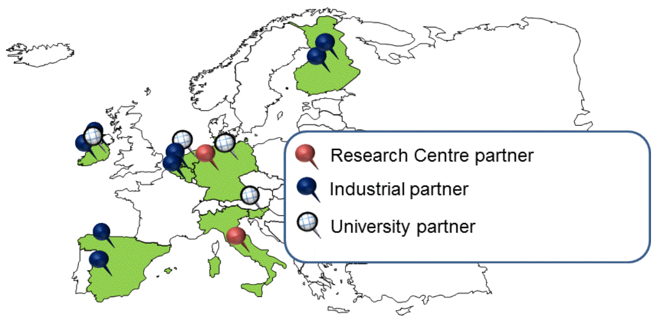


Figure 3: Consortium

The RAIN consortium is carefully chosen group of organizations involved in research in the areas of critical land based infrastructure systems. These organizations contribute toward developing the frameworks and policy that reinforce the safety of the European infrastructure networks. The consortium is multidisciplinary including meteorologists (FMI), climate researchers (ESSL), economists (TCD), energy specialists (UFD), infrastructure risk analysts (TU-Delft), specialist engineering designers and planners (ROD and GDG). Furthermore, the advisory group has been developed to ensure the more widespread applicability of the results to industry by establishing a direct liaison with infrastructure owners and managers. For example within the advisory board, the utilities EDF and RWE will contribute toward power grid operability, while FEHRL, PRORAIL, and DeutscheBahn will contribute toward transport system management.

The consortium therefore has an appropriate distribution of different level partners to make up a credible partnership for R&D in Cost-effective improvement of the resilience of EU infrastructure in response to extreme weather events.

The members of the consortium gather high level expertise on all aspects of critical infrastructure protection and/or weather assessment to study three main research threads in the project:

- Weather and climate modelling with respect to critical infrastructure
- Critical infrastructure

Risk analysis tools for critical infrastructure

## 2 WEATHER AND CLIMATE MODELLING WITH RESPECT TO CRITICAL INFRASTRUCTURE

Previous projects that addressed the sensitivity of transport systems to extreme weather, in particular the FP7 projects EWENT (East-West European Network) and WEATHER (Weather Extremes: Impacts on Transport Systems and Hazards for European), form the starting points for the Hazard Identification work. Questions on time-perspectives of weather information are partly answered in EWENT project, providing the frequencies of extreme weather in different parts of Europe and probabilities of adverse weather affecting transport in Europe [4-6].

Estimating the present occurrence frequency of the small but intense thunderstorm-related events, such as damaging lightning, local extreme winds, large hail, lightning and tornadoes, is challenging because they are too small and short-lived to be resolved by measurement networks of the National Meteorological Services [7]. Nevertheless, improved data is becoming available, especially within the European Severe Weather Database, which is being developed and maintained by ESSL. An additional difficulty is that the small size and short duration of the events also prevents them from being explicitly simulated even by state-of-the-art climate models. As of now no study has produced a regionalized projection of the future trend of such events across Europe.

The critical weather events are usually considered as sudden but for the protection of infrastructure and the security of citizens there are also events that develop over a longer time scale. Obtaining these "critical weather chains" will be a new approach but one which is already familiar to FMI. However, the trends in such "chains" have not yet been analysed. When completed in RAIN, there will be new means of providing warnings of singular catastrophes, multiple severe catastrophes and a variety of cascading events both in the early warning and climate watch scale. The critical winter weather episodes that FMI will focus on are related to synoptical situations causing abundant snowfall, heavy snow loads, icing and freezing rain. The increase in the fire risk is identified by warm spells, drought and wind. All of these aspects are critical in assessing, for example, the impact on hydrology and drinking water - if snow melts suddenly then the question arises as to how much contamination will be generated from the agricultural fields and the roads? Similarly, how early will the fire risk start? - this depends on the lack of snow in winter and drought in the winter and spring. New methodologies for drinking water alerts can be developed in RAIN when the snow and drought aspects are both included in the methodology.

In climate change projections these “critical weather event chains” related to critical weather episodes, or the timing of these event chains, have also not yet been considered. Determining these chains, on both temporally and spatially, will result in a significant scientific break-through and obtain the urgently needed climate change impact projections for both the protection of infrastructure and the security of citizens.

In terms of the predictability of severe weather, RAIN will, for the first time, address several different types of severe weather, and through a combination of research and literature reviews, will establish an overview of the typical levels of confidence available at various lead times before severe weather strikes and address implications for the design of early warning systems.

## 3 CRITICAL INFRASTRUCTURE

The understanding and definition of the term ‘resilience’ has different interpretations and a universal conception and measuring of it is therefore a very unlikely result of any research project. However, for the purpose of this work, the UN/ISDR definition is used as a starting point, as it highlights the crucial factors to be taken into account when resilience is at stake. It is defined as the “capacity of a system, community or society potentially exposed to hazards to adapt, by resisting or changing in order to reach and maintain an acceptable level of functioning and structure. This is determined by the degree to which the social system is capable of organising itself to increase this capacity for learning from past disasters for better future protection and to improve risk reduction measures” [8].

To determine vulnerability it is necessary to adopt a more complex perspective to address resilience. In this perspective, the understanding of the effects of actual policies (i.e. by means of institutional analysis) is put in place to enhance resilience of infrastructural (and related social) systems offer a practical and effective way to start addressing this complex mechanism.

It is therefore crucial to explore financial, institutional and social aspects behind the enhancement of resilience of transport and energy/telecommunication infrastructures exposed to the impact of extreme weather hazards.

Critical Infrastructures Protection is something that sometimes overlaps national territories and goes beyond territorial delimitation. For their connecting roles, critical infrastructures are better framed in regional or trans-regional perspectives than purely national ones. Thus, the EU promoted a specific program to help member states to implement common strategies for critical infrastructure protection, without aiming at substituting or duplicating the prerogatives of each member state.

From an early stage in the project, critical infrastructure will be identified based on performance level, impact of disruption and exposure to significant hazards to provide an inventory of target typologies, which will form the basis of the key input required for later stages of the project. The project will assess and utilise the newly developed concept of European Critical Infrastructure [9], an area that has not received significant attention. Several different performances will be explored, in relation to the regulations in Europe and their unification, as currently, different laws and standards are applicable across the European Union. Problem specific methods and standards will be defined and developed, which will represent a main advance towards harmonization in hazard and risk assessment on a European basis.

Network usage gives information about the impact that an element will have in the system. Moreover, network usage forecast provides information about how close to the operational limits the network is working. When the network is working in a safe condition, the system is robust and can cater for some anomalies or fluctuations. However, when the system is working close to the operational limit, small anomalies or disturbances may produce a collapse in the whole network. Consequently it is essential to be able to provide information about the network usage as it presently exists and as it will exist in the future.

It is also critical to know the probability of failure of each element in the network under different weather conditions. This will provide information about the likelihood of element and system failure.

Combining network usage and equipment failure probability, RAIN will provide information about the likelihood of element failure and the resulting impact. Together, these two forecasting capabilities provides working tools to study the resilience (or vulnerability) of critical infrastructure under extreme conditions. Performing what- if simulations will enable the conditions which affect the network to be examined.

RAIN forecasting capabilities are based on the assumption of modulating the problem, not just the result. RAIN will study 'symbols' - these symbols are elements that modify the forecasted variable. In an electric demand forecast, for example, symbols may be the laborality calendar, temperature, domestic profile, industrial category, nubosity, etc.

Modelling the problem in a symbolic approach, RAIN is not only able to provide future estimations, but also provide other high-valued capabilities, such as;

*Trusting margins* - the trusting margin is based on the expected error in the forecasting module. This error is based on the possible variations in each symbol. The error on each symbol is modelled, providing a maximum and minimum value for each estimation.

*What-if simulations* - Apart from typical forecasting, a symbolic forecast may provide simulations for different scenarios. For example, a system is able to provide network usage estimations for cold, warm and hot temperature years, for rainy months, combinations of weather effects, etc.

*Aggregations* - A symbolic forecasting can provide estimations for each element or any aggregation which is the cumulative estimation per area, region, country, climatic zone, etc. This will provide a very useful tool in assessing pan-European security.

The forecasting module will provide a powerful tool to help operators to study their critical infrastructure under several extreme situations. The forecasting module will help operators examine under which situations the different networks may collapse, the probability that some element fails under normal or exceptional situations, the weakest points in the network and the more critical elements, from a social or financial point of view, between other elements. The RAIN forecasting module will be of high-value for operators, helping them to understand the potential risks on the network and how the system will behave under both an external situation (weather) or an internal situation (element state or network usage).

The project outputs will contribute to the process of knowledge management development used in the protection of Critical Infrastructure and will provide the basis for the development of decision support systems - from the view of maximum effectiveness of the first response on the violation of critical infrastructure functionality caused by extreme weather events.

## 4 RISK ANALYSIS TOOLS FOR CRITICAL INFRASTRUCTURE

A number of methodologies, applications and software tools have been developed, worldwide, for critical infrastructure protection and a detailed summary can be found in [8]. Modelling techniques include decision making procedures, multi-agent systems, system dynamics, rating matrices, relational databases and network theory. These are supplemented by computational methods such as time step simulation, Monte Carlo simulation, decision trees, GIS, risk management techniques and event monitoring or real time recording.

In these methods, road, highway and rail infrastructure are given the least attention, approximately in only 10% of cases, with IT and Telecoms covered in about 21% of cases with 11% related to human activities queries and response checking [9]. Approximately one quarter of the methodologies and applications have limited availability or are restricted and so there is limited exchange of information occurring between the Governments/policy makers and researchers and of the commercial packages available, most are used in the energy sector. Only approximately 12% of the modelling techniques employed have been focused on implementation of policies and regulations.

The majority of the critical infrastructure protection plans have been based on a risk management framework, with rating matrices being the most widely used modelling technique. Network theory and system dynamics, which consider internal feedback loops and time delays that affect the behaviour of the entire system, and network modelling are the least utilised techniques.

In identifying risks, there are a number of techniques used, however a variety of strategies are used to quantify the risk, with no singular method being dominant. For example, vulnerability assessment of infrastructural nodes in relation to seismic and flood hazard is carried out mainly through empirical evidence and historical records of failure. While this is acceptable in areas of relatively high risk with frequent damaging events, is not directly transferable to high density/ low probability events, which might have devastating consequences to regions and assets with low risk perception.

Previously, the Morlet continuous wavelet transform has been used to analyse the temporal and spatial fluctuation of environmetric (hydro meteorological) cycles and can be applied to response variables (such as the annual water discharges time series). In recent years, many authors have presented results of hydrological variability using such wavelets [11-13], therefore wavelets can be considered as a current state of art. However, the application of wavelet results to stress testing has not been investigated before and represents a novel approach to stress testing infrastructure.

Updated existing and new modelling concepts (wavelets, morphological analysis, network analysis, & Objective Ranking Tool (ORT) methods as described below) will be applied to critical infrastructure risk and resilience assessment procedures. Success in assessing the effect of such events in a timely and realistic manner requires the development of new vulnerability models which look at effect propagation of highly destructive localised events to interconnected networks. The project will deliver simple analytical vulnerability models for transport infrastructure, with a particular focus on linear infrastructure systems such as road and rail networks. The specific infrastructure components will be evaluated and used to rank the susceptibility of the network to damage (using a ranking index). This index will categorise the infrastructure into various subsets which can then be combined with potential failure modes (i.e. caused by extreme weather events). The output will identify hot-spot vulnerability in the form of critical parameters affecting performance under extreme events and quantifying their predicted range of operability during these events.

A logic tree approach will be used to define damage modes and extents and derive fragility functions. Such modelling is associated with several levels of uncertainties, both epistemic and aleatoric, which will be quantified and propagated throughout all stages of the explicit risk analysis. Wavelets can be considered as one of the most suitable and powerful approaches to model the temporal and spatial variability fully and can be applied directly to the source or response variables (hazard or effect). Integrating wavelet results within a risk based network infrastructure model will pose a big challenge but will lead to a methodology in which the output of wavelets, or the interdependence between the variables can be used as input for critical weather events which may not have been experienced in the past.

Non-quantified inference models representing those aspects of the results of the project, which cannot be (meaningfully) rendered as quantitative models will be developed and employed to simulate the 'what if' wildcard scenarios. These morphological models, which simulate genuine uncertainty, are computer-based, and the recipients of the project's results receive software in order to run them. The development of these interactive morphological inference models of the total problem space and the bounded solution space, including structured, interactive scenario and strategy models, will be a new departure from critical infrastructure assessment, which has previously been utilised in defence and military applications. Both single hazard and multi hazard risk GIS models will be generated, with the aim of producing a harmonised GIS model of individual risk methodologies, contributing to greater economy, efficiency and decision making across the infrastructure network. Probabilistic approaches will be used to develop realistic event scenarios through full simulation of the event, thus maximising the efficiency of the inputs into the harmonised risk methodologies. An ORT will be adopted to rank and prioritise the outcomes of the results.

Furthermore, the impact of extreme weather is assessed not only based upon physical vulnerability of the infrastructure, but also the interaction of humans relying on these infrastructures connected as networks. A hierarchy framework will be developed to accommodate the spatio-temporal variability to undergo multi-risk stress test scenarios, including people dynamics. With the introduction of complex network analysis we can investigate the topologies and hierarchical structures of infrastructure interdependencies. In this sense we can envisage infrastructure networks as a multilayer system. In network analysis standard approaches have focused on the study of a single non-interacting network, while a comprehensive synthetic paradigm, which takes infrastructure multilayer networks into account, is still missing, thus building on existing approaches currently adopted.

RAIN will leverage recent results in the development of platforms for sharing environmental information between relevant stakeholders in the risk assessment domain using cloud processes. The project will enable better interoperability and sharing of environmental data, results of simulation models, real-time data, as well as services by deploying platforms to relevant stakeholders. This will enhance information sharing which is limited at present.

Based on the principles of similarity judgment, RAIN will develop a web based tool to facilitate the computation process, i.e., of prioritizing the need to act when judging hazards and their impact to infrastructures. This web based tool will be used during several stages of the project to provide the different working packages with the ability to classify and rank different outcomes. To ensure a proper usage of the outcomes of RAIN a dedicated training program and further education course will be implemented.

The web based tool will be made available for companies and governments working in the area of the transport and telecommunications infrastructure. This will help the respective companies and governments to identify the consequences of extreme weather events for their own situations.

## 5 METHODOLOGY AND ASSOCIATED WORK PLAN

The research activities are organised around six technical work packages (WP), each organised around a core topic necessary for the complete description of the problem dynamic. One of these, WP2, focuses on hazard identification, while the second and third work packages, WP3 and WP4 respectively, focus on the elements of critical infrastructure addressed in RAIN. Development of the Risk Analysis framework, identifying measurable risks and benefits, and developing mitigation strategies are covered in WP5, WP6 and WP7 respectively. Management and dissemination activities complete the work plan, as indicated in Figure 4. The diagram also serves to show the interaction and interdependencies between WP's.

Authors' main contribution to this project is to develop methods to create an advanced risk assessment procedure, including a probabilistic based approach, to derive a measurable indicator of risk for single and multi mode failure risks, in the 6th work package. The economic benefit of multifaceted approach to improve security of infrastructure then will be produced.

In this work package, a means of quantifying the level of risk will be established, based on the mapping protocol of risk analysis framework developed in WP 5, first due to single land transport mode failures, and second due to selected multi-mode-interdependent failure scenarios (e.g failure of power stations result in failure of electrical train lines). The impacts will be assessed in each case.

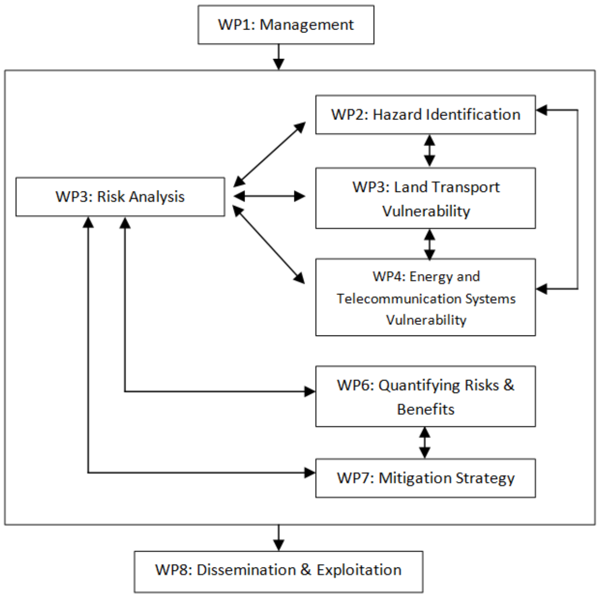


Figure 4: Work Plan Strategy & Methodological Diagram

The WP 6 will result in three deliverablese and two milstones which will be provided in the form of technicl papers detailing the probabilistic approaches, and the variables proposed to quantify single and multi mode risks and their societal, security and economic impacts and also a report on benefit of critical infrastructure protection, providing the building of the methodologies an findings of the workpackage to assess the multifacted economic benefts of critical infrastructure resilience.

## 6 ACKNOWLEDGMENT

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