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A multidisciplinary approach for risk analysis of infrastructure networks in response to extreme weather

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Abstract

In recent years, it is becoming more frequent the occurrence of extreme weather events across Europe, such as rain induced landslides, river floods, winter storms and hurricanes. These hazards result in deterioration or fail of critical elements, and in the consequent disruption or disablement of the traffic networks. Therefore, developing tools and guidelines are mandatory to enhance safety and reliability of critical infrastructure networks, and address European policy in the areas of safety and security, inter-modality and emergency response planning. With this goal, the European research project RAIN (Risk Analysis of Infrastructure Networks in response to extreme weather) presents a multidisciplinary approach, involving aspects as diverse as climatology, transportation, or sociology. The RAIN vision is to provide an operational analysis framework that identifies critical infrastructure components impacted by extreme weather events and minimise the impact of these events on the EU infrastructure network. The project focusses on land transport networks, and the energy and telecommunication systems to identify cascading and inter-related effects. Technical and logistic solutions are developed to minimise the impact of these extreme events, which include novel early warning systems, decision support tools and engineering solutions to ensure rapid reinstatement of the network. This paper presents an overview of the RAIN project including results and methods that can be applied globally to determine the impacts of increased extreme weather events.

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Keywords: extreme weather events; critical infrstructure; risk analyisis; European project

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1. Introduction

Minimizing the impact of major weather events upon the EU has become a priority for the European planners in order to avoid disproportionate damage or disruption. This implies to quantify the complex interaction of existing infrastructure systems and their interrelated damage potential in such situations. Moreover, a proper interaction between entities such as emergency planners, utility operators, first responders, engineers and, most importantly, the citizens living in the affected area, is essential and requires a multidisciplinary coordination.

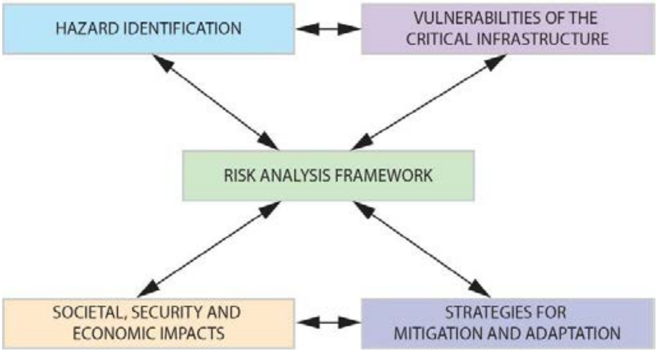


Fig. 1. Diagram of the RAIN project strategy.

The project Risk Analysis of Infrastructure Networks in response to extreme weather, RAIN, will provide an operational analysis framework that identifies critical infrastructure components impacted by extreme weather events and minimise the impact of these events on the EU infrastructure network. The multidisciplinary approach of RAIN project involving experts from transportation, energy, risk assessment, climate prediction, social sciences, civil engineering and telecommunications, guarantees a holistic response plan to transcend borders.

The general framework of this project can be split into five interrelated stages, as Figure 1 indicates.

The first stage implies the hazard identification, that is, identifying the most potential harmful hazards and their intensity thresholds to be considered as “extreme cases”, taking into account regional differences in vulnerability and climate. Afterwards, the frequency of weather hazards throughout Europe for both the present and future climate, until the year 2100, is assessed, by applying methods such as CORDEX (regional level) and CMIP5 (global level).

The second stage is focussed on the analysis of the vulnerabilities of the critical land transport, energy and telecommunication infrastructure. To identify the critical land transport infrastructure, i.e. road and rail transport, it is required a review of critical land transport infrastructure failures and the current means of protecting them. This will allow the understanding of the failures of this infrastructure leading to societal vulnerability and insecurity. Parallel, the critical energy and telecommunication infrastructures are analysed.

Given that the critical transport, energy and telecom infrastructures are highly interconnected and form “systems of systems” that tend to be vulnerable during extreme hydro-meteorological events, the existing modelling approaches, with fault trees and event trees, are not suitable in the extreme situations analysed. For that reason, developing a risk analysis framework for single events and cascading effects of single or multiple hazard events has to be addressed. The cascading effects consider the interdependency identified in critical infrastructure. Several techniques need to be combined including influence diagrams, Bayesian networks, event trees, mapping, GIS, and analysis of human and organizational factors.

The risk analysis framework will permit the examination of the impact of critical infrastructure failure on society, security issues and the economy. The risk procedure will be benchmarked against case studies conducted on critical transport and operational tactical connections (O’Connor et al. (2014); O’Brien et al. (2015)).

Finally, some technical, logistical and response strategies are developed. Recommendations on standards and techniques for mitigation and adaptation to the potential impacts of extreme weather will result in an improvement of the resilience of the existing infrastructure networks by increasing the infrastructure robustness and addressing European policy in the areas of safety and security, inter-modality and emergency response planning.

The paper is organized as follows; Section 2 presents the identification of the hazards to be analysed within RAIN project and explains the process to obtain their probability of occurrence in the present and future scenarios. Section 3 deals with the vulnerability of the land transport, energy and telecommunications systems by means of the analysis of the critical infrastructure; A description of the risk analysis framework for single events and cascading effects of single or multiple hazard events is given in Section 4; Section 5 presents a discussion of the societal, security and economic impacts and quantifiable benefits of providing more resilient infrastructure; and Section 6 provides the process to identify strategies for mitigation and adaptation to the future extreme weather events. Finally, in Section 7 some conclusions are drawn.

This paper presents a general overview of the RAIN project, based on the document Description of Work of the mentioned project.

2. Hazard identification

The first stage of the project is the identification of the most severe weather hazards considering regional climatological differences and the definition of their associated critical thresholds. A deep review of prior and on-going studies has been carried out, leading to a preliminary assessment of their potential impacts.

After compiling the list of past events of critical infrastructure failures caused by severe weather, the intensity threshold levels for the phenomena are determined by estimating the sensitivity of the infrastructure systems in collaboration with their managers. With this aim, interviews with stakeholders in the transport, energy and telecom sectors are conducted and quantitative information on the impact of e.g. falling trees, snowfall on railways or high-voltage power lines are collected. As a result, a list of 14 severe weather hazards has been identified as the most potentially dangerous event in Europe. This list includes heavy rainfall, windstorms, coastal floods, river floods, landslides, lightning, tornadoes, hail, convective windstorms, snowfall and snow storms, icing, snow loading, forest fires and freezing rain.

The next step is to estimate the present-climate frequency of occurrence of extreme events using reanalysis data sets (e.g. ERA-Interim), model simulation ensembles of the current climate (hind-casts) and observational datasets (Klok and Klein Tank (2009)) Proxy parameters are analysed for single and cumulative winter extreme episodes, computing their distributions, while taking into account large-scale patterns such as the North Atlantic and Arctic Oscillations (AO, NAO). Finally, physical models of the hydraulic and geotechnical failure mechanisms of flood defenses are used to calculate the failure probability via Monte Carlo simulation from load- and resistance distributions where possible.

The developed proxy parameters are applied to General Circulation Model (GCM) simulations of the future climate and regional models, including the newest emission scenarios RCP 4.5, RCP 6 and RCP 8.5 for the period until the year 2100 (Gregow et al. (2012)). For instance, the future trend of coastal and river flood risks is addressed by combining national empirical databases with new insights on rainfall-runoff models based on the latest insights in load and resistance distributions of flood defenses. In these models, the risk of precipitation is transformed to the risk of flooding by Monte Carlo simulations and first order techniques.

The main output of this first stage is the pan-European gridded data sets of the probability of occurrence of hazardous phenomena in the present and future climate.

3. Vulnerabilities of the critical infrastructure

Societal vulnerability is a part of a disaster risk assessment and crucial information is necessary for supplementing hazard and mitigation assessments. Identification and estimation of various vulnerabilities of societies, economies, institutional structure and environmental resource bases are the basic information necessary for improving risk reduction and preparedness to natural hazards. The social vulnerability concepts and social vulnerability components (security, economic, social) incorporate the “physical” impact of an event on the natural and built environment where people are located and the ability for key institutions to respond and manage the event effectively to cause minimal disruption to exposed communities. Economic factors exert a profound influence upon social vulnerability. This level of vulnerability is highly dependent upon the economic status of individuals, communities and nations. The social component is characterized by at-risk individuals or communities who alter the degree of susceptibility and sensitivity to hazard impact. It includes for example demographic characteristics such as age, gender, family structure, health and disability, occupation and employment, as well as access to political power (see Kuhlicke et al. (2011)).

RAIN project focusses on the affection of the extreme weather events upon the land transport infrastructure elements, road and rail transport (see Nogal et al. (2015)), and the energy and telecommunication systems, as they are the cornerstone of a well-functioning society. The studio of the vulnerability of these systems is carried out by analysing critical infrastructure.

In the case of the land transport network, the critical infrastructure is identified by means of sectoral and cross--cutting criteria, which includes aspects such as the probability of occurrence of an emergency event, the natural environmental damage and the potential loss of public confidence, among other indicators to measure the vulnerability of the network. In literature numerous initiatives are found to measure and assess social vulnerability but there is still no consistent set of metrics used to assess vulnerability to extreme weather events and natural hazards and these initiatives usually lack a systematic and transparent approach.

Regarding the Energy and Telecommunication (ETC) infrastructure, the identification requires a more complex approach as their connections and interdependencies cause different structure of failure to those generated by the transport systems (see Yusta et al. (2011)). For this reason, each element in ETC is studied in a risk assessment approach. Besides, the connections between those elements and the interdependencies between critical infrastructures are analysed, at a European level, in terms of potential risk and their dependencies.

4. Risk analysis framework

In the presented context, risk assessment is assumed as a methodology to determine the nature and extent of risk by analyzing potential hazards and evaluating existing conditions of vulnerability that could pose a potential threat or harm to people, livelihoods and the environment on which they depend. Risk assessment encompasses the identification, quantification, risk analysis (qualitative, semi-quantitative, and quantitative) and evaluation of risks associated with a given system. Overall, the risk assessment aims to support rational decision-making regarding risk-bearing activities (Apostolakis (2004)).

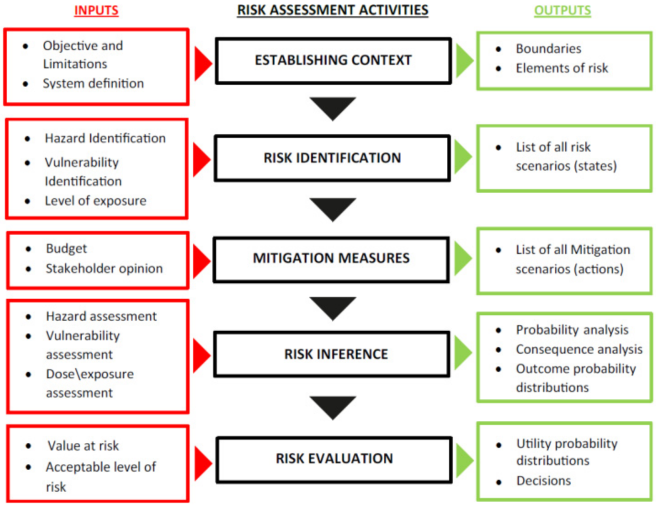


Fig. 2. Diagrammatic representation of the risk assessment framework.

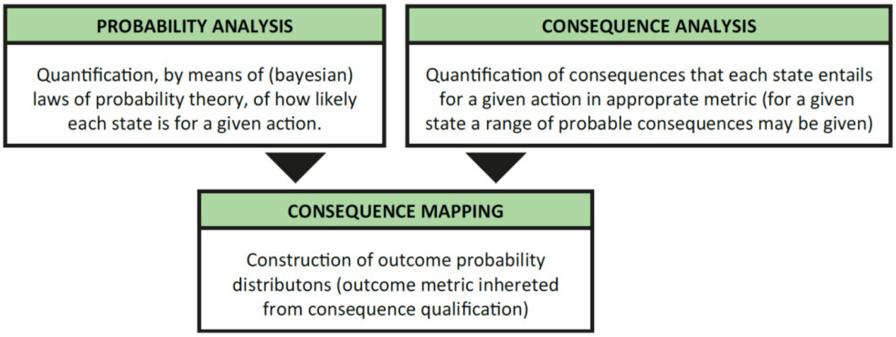


Fig. 3. Detail of the risk inference framework.

Neglecting or underestimating interdependencies between the failures or disruptions of the critical infrastructure systems can cause designers, experts, managers and decision makers to underestimate the overall inter-infrastructural risks. It is therefore necessary to further develop approaches for risk assessment and management that consider the interconnected nature of critical infrastructure systems. With this aim, a risk assessment framework is developed, using a Bayesian Network approach to quantify both single-mode and ultimately multi-mode risks and the impacts of extreme weather events on interconnected critical infrastructure systems.

Based on an established context, the analysed system is defined in terms of its elements and what constitutes normal operation to serve as a baseline reference point (see Figure 2). After identifying the possible risks and the source of hazard, the scenarios of risk are established together with the consequences and vulnerability elements. Mitigation measures are subsequently introduced for each vulnerable element studied. At the risk inference stage (see Figure 3), the likelihood of the different scenarios considered and their corresponding levels of damage are assessed based on the mitigation actions. Finally, in the risk evaluation (see Figure 4) the results are evaluated and interpreted to guide the risk manager or infrastructure owner on strategies to be adopted to reduce risk to an acceptable level.

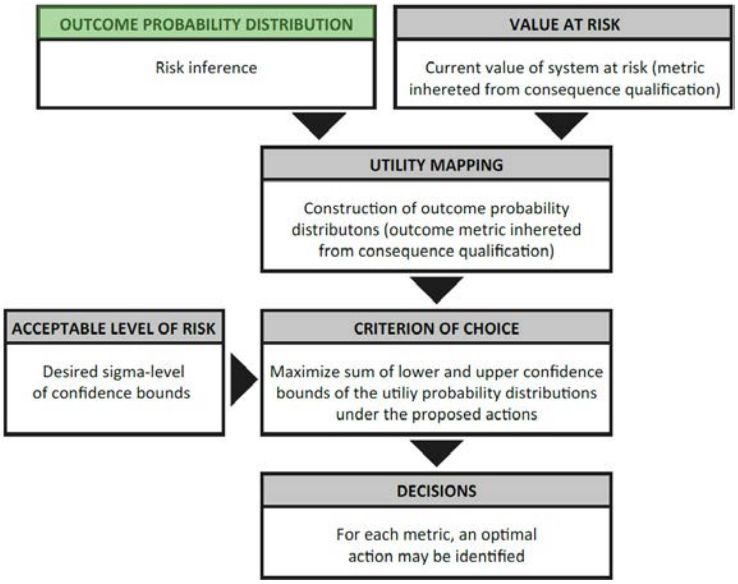


Fig. 4. Detail of the risk evaluation framework.

5. Societal, security and economic impacts

The quantification of the benefits of providing resilient infrastructure supports the assessment of the societal, security and economic impacts of the identified critical land, energy and telecommunications infrastructure failures due to single and multi-mode failure events.

With this aim, the analysis is carried out in a layered manner, i.e., firstly, the single mode failure risks and their corresponding societal and security impacts are analysed. The risk procedure is benchmarked against several case studies conducted on the critical transport and operational tactical connections. The focus of the benchmarking is on early warning response and consequence management. Afterwards, the analysis of the multi-mode interdependent risks (e.g failure of power stations result in failure of electrical train lines) and failures are addressed.

The estimation of the economic impacts of improving the security and safety of infrastructure is conducted using traditional economic assessment tools such as cost benefit analysis. An Objective Ranking Tool (ORT) is used for ranking failure criteria in order of importance, resulting in a methodology that allows the identification of how single factors can improve security (see Van Gelder and Erp (2015)).

The proposed ORT allows the evaluation and classification in order of importance of key factors affecting each aspect of risks due to failure of critical infrastructure. Each key factor is evaluated according their respective contribution to the each risk (societal, security or economic), and weighted by a panel of experts.

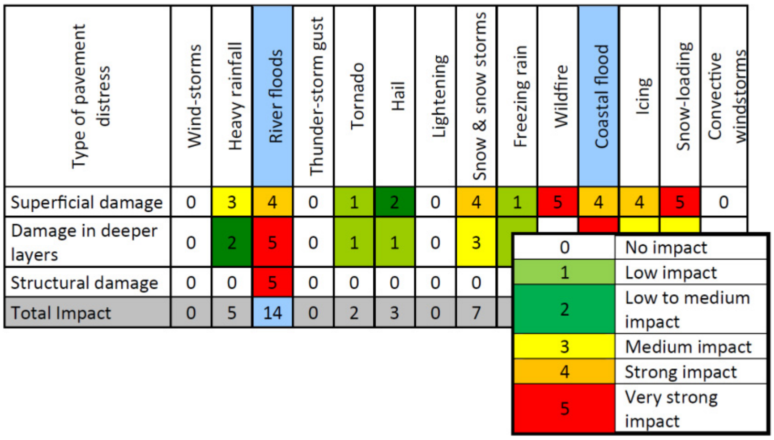
A methodology to estimate the economic benefits of a multifaceted approach to improve security of infrastructure will be developed, based on the previous findings and the collaboration of the stakeholders.

6. Strategies for mitigation and adaptation

This last stage of the RAIN project strategy focuses on measures that can be adopted to improve the resilience of the existing infrastructure network. The proposed enhancement strategy to increase infrastructure robustness considers both physical adaptations to the network in conjunction with changes to the management strategy.

Based on the evaluation of the modes of failure that impact on critical infrastructure nodes given by the risk analysis framework, and the cascading effects and risk profiles identified, engineering solutions are developed that increase redundancy and minimise the potential for cascading effects. These solutions can be classified into (a) remediation strategies, (b) harmonization of early warning systems, and (c) operational and development strategies.

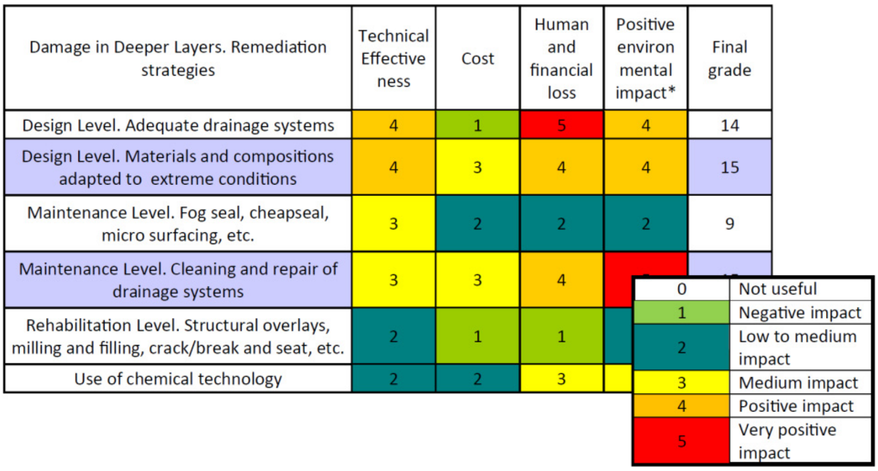
The remediation strategies that have the most significant impact on reducing the risk profile of infrastructure are presented by means of technical impact matrices. Figures 5 and 6 show an example of the technical impact matrix and the technical remediation matrix associated with failure of pavements due to extreme weather events.



Type of pavement distress	Wind-storms	Heavy rainfall	River floods	Thunder-storm gust	Tornado	Hail	Lightening	Snow & snow storms	Freezing rain	Wildfire	Coastal flood	Icing	Snow-loading	Convective windstorms
Superficial damage	0	3	4	0	1	2	0	4	1	5	4	4	5	0
Damage in deeper layers	0	2	5	0	1	1	0	3						
Structural damage	0	0	5	0	0	0	0	0						
Total Impact	0	5	14	0	2	3	0	7						

0	No impact
1	Low impact
2	Low to medium impact
3	Medium impact
4	Strong impact
5	Very strong impact

Fig. 5. Example of technical impact matrix associated to critical elements of the traffic network.



Damage in Deeper Layers. Remediation strategies	Technical Effectiveness	Cost	Human and financial loss	Positive environmental impact*	Final grade
Design Level. Adequate drainage systems	4	1	5	4	14
Design Level. Materials and compositions adapted to extreme conditions	4	3	4	4	15
Maintenance Level. Fog seal, cheapseal, micro surfacing, etc.	3	2	2	2	9
Maintenance Level. Cleaning and repair of drainage systems	3	3	4		
Rehabilitation Level. Structural overlays, milling and filling, crack/break and seat, etc.	2	1	1		
Use of chemical technology	2	2	3		

0	Not useful
1	Negative impact
2	Low to medium impact
3	Medium impact
4	Positive impact
5	Very positive impact

Fig. 6. Example of technical remediation matrix showing the strategies that have the most significant impact on reducing the risk profile of a given infrastructure.

Regarding the harmonization of the early warning systems integrated into the infrastructure network, their impact is estimated in conjunction with the potential failure modes, taking into account the early warning systems currently available for discrete forms of infrastructure and their inter-connectivity. The potential for a network wide asset management tool that extends across multiple infrastructure types and is sensitive to fluctuations in weather patterns will be assessed, paying a special attention on the usability by crisis decision makers of versatile early warning signals of extreme weather hazards.

Finally, operational and development strategies that reduce the potential for extreme weather to affect the existing infrastructure system will be analysed and enhanced, by means of a predictive and preventative approach that aims to improve the robustness of those critical infrastructure where operational/maintenance strategies should be focussed on.

7. Conclusions

This paper has presented a detailed explanation of RAIN project, which will result in an improvement of the understanding of how critical infrastructure and their operators should adjust their behaviour to extreme weather events, guaranteeing the security of vital utilities.

The proposed approach is based on 5 pillars, namely, estimation of the probability of suffering extreme weather events in the future; assessment of the vulnerabilities of inter-related systems by means of the identification of critical infrastructure; analysis of risk probabilities; study of the societal, security and economic consequences; and development of mitigation and adaptation strategies.

The results of RAIN project will be disseminated amongst all types of stakeholders ranging from industry to system operators, policy makers and research institutes. The main objective is to ensure the widespread dissemination of the knowledge and results generated by the project, including lessons learned from and exploitation to other modes. To this end, dissemination activities, such as workshops oriented to stakeholders, and communication activities targeted the general public, such as distribution of news and material to the media, are carried out. A detailed description of these activities can be found in http://rain-project.eu/.

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