FP7 2013 Cooperation Work Programme
Theme 10: Security (10.2 Security of Infrastructure & Utilities)

RAIN PROJECT

Risk Analysis of Infrastructure Networks in Response to Extreme Weather

Final Report
Part A: Publishable Summary

Primary Author	Alan O'Connor/Trinity College Dublin (TCD)
Submission Date	28/07/2017

This project has received funding from the European Union's Seventh Programme for research, technological development and demonstration under grant agreement No 608166

Project Information

Project Duration: 01/05/2014 - 30/04/2017

Project Coordinator: Professor Alan O'Connor

Trinity College Dublin

alan.oconnor@tcd.ie

Work Programme: 2013 Cooperation Theme 10:

Security (10.2 Security of Infrastructure and Utilities).

Call Topic: FP7-SEC-2013.2.1-2 Impact of Extreme Weather on Critical Infrastructure.

Project Website: www.rain-project.eu

Partners:

Participant No.	Participant Organisation Name	Participant Short Name	Country
1 (Coordinator)	The Provost, Fellows, Foundation Scholars & The Other Members of Board of the College of the Holy & undivided Trinity of Queen Elizabeth Near Dublin	TCD	Ireland
2	European Sever Storms Laboratory	ESSL	Germany
3	Zilinska Univerzita V Ziline	UNIZA	Slovakia
4	Technische Universiteit Delft	TU-Delft	Netherlands
5	Gavin and Doherty Geosolutions Ltd.	GDG	Ireland
6	Dragados SA	DSA	Spain
7	Freie Universitaet Berlin	FU-Berlin	Germany
8	Roughan & O' Donovan Ltd.	ROD	Ireland
9	Hellenberg International OY	HI	Finland
10	Istituto di Sociologia Internazionale di Gorizia I.S.I.G	ISIG	Italy
11	PSJ	PSJ	Netherlands
12	Ilmatieteen Laitos	FMI	Finland
13	Youris.com	Youris	Belgium
14	Independent Power Transmission Operator	IPTO	Greece
15	Aplicaciones En Informatica Avanzada SL	AIA	Spain

Document Information

Version	Date	Description	Primary Author
Template	03/03/2017	For Partner Contribution	Alan O'Connor
Rev01	08/06/2017	Draft for Final Review Meeting	Alan O'Connor /TCD & the RAIN Consortium
Rev02	28/07/2017	Final Draft following Final Review Meeting	Alan O'Connor /TCD & the RAIN Consortium

TABLE OF CONTENTS

1.0 Publishable Summary 1

1.1 EXECUTIVE SUMMARY 1

1.2 A SUMMARY DESCRIPTION OF THE PROJECT CONTEXT AND THE MAIN OBJECTIVES 2

1.3 DESCRIPTION OF THE MAIN S & T RESULTS/FOREGROUNDS 5

1.3.1. WP2 – Hazard Identification 5
1.3.2. WP3 – Land Transport Vulnerability 10
1.3.3. WP4 – Energy & Telecommunications System Vulnerability 14
1.3.4. WP5 – Risk Based Decision Making Framework 17
1.3.5. WP6 – Quantifying Risks and Benefits 24
1.3.6. WP7 – Mitigation Strategies 27
1.3.7. WP8 – Dissemination & Exploitation 29

1.4 POTENTIAL IMPACT AND MAIN DISSEMINATION ACTIVITIES AND EXPLOITATION RESULTS 31

1.4.1. WP2 - Hazard Identification 31
1.4.2. WP3 - Land Transport Vulnerability 32
1.4.3. WP4 - Energy & Telecommunications System Vulnerability 33
1.4.4. WP5 - Risk Based Decision Making Framework 34
1.4.5. WP6 - Quantifying Risks and Benefits 34
1.4.6. WP7 - Mitigation Strategies 35
1.4.7. WP8 - Dissemination & Exploitation 35

1.5 THE ADDRESS OF THE PROJECT PUBLIC WEBSITE AND RELEVANT CONTACT DETAILS 39

1.0 PUBLISHABLE SUMMARY

1.1 Executive Summary

In recent years, a variety of extreme weather events (EWE's), including droughts, rain-induced landslides, floods, winter storms, wildfires, and hurricanes have threatened and damaged many different regions across Europe and beyond. These events have in some cases had a devastating impact on critical infrastructure (CI) systems. The RAIN (Risk Analysis of Infrastructure Networks in response to extreme weather) project, www.rain-project.eu, has examined these EWE's with a multidisciplinary team of engineers, sociologists, meteorologists & climatologists, CI owners/operators and security experts.

This report presents a synopsis of the work performed in the project. Taking each Work Package in turn it presents the main S&T results and foregrounds developed by the project consortium as well as detailing the potential impacts of the work and the main exploitable results.

The nature of extreme weather impacts on CI was explored, with severe weather intensity thresholds being established. A review of state-of-the-art early warning systems presented the predictive skill of these systems. The probability of occurrence of the extreme events in the present was modelled using a number of novel methods and projections of changes of severe weather probability in the future (up to 2100) were created using regional climate models. The RAIN *Gridded Datasets* represent an extremely important resource which is made freely available via an online repository (https://data.4tu.nl/repository/collection:ab70dbf9-ac4f-40a7-9859-9552d38fdccd).

Methodologies for assessing the vulnerability of land transport (road & rail) and energy and telecommunications infrastructure were developed and are presented in this report. Information on protection of these CI's in the context of EWE's are major outputs of the project. Case studies are detailed highlighting important considerations and lessons learned. Finally, and significantly, methods for assessing societal vulnerability have been developed within the project and are detailed in this report and in the associated project deliverables.

A major innovation of the RAIN project had been the development of a Risk-Based decision making framework for single events and cascading effects of single or multiple hazard events. This framework has been implemented in a web based tool which is described in detail in this report (and in associated deliverables). The tool, which is available for use online via the project website, provides infrastructure owners/managers with the opportunity to consider a variety of EWE's and to assess their impact on land based transportation and E&TC infrastructure from the perspective of risk. Significantly, the tool facilitates investigation of risk reduction via selection of alternative mitigation strategies. Thereby enabling risk-based decision making in the context of EWE's.

Details of extensive dissemination activities are summarised in the report. In addition to production of a Video News Release (VNR) featured on Euronews; hosting a number of stakeholder workshops and Delphi panels; publishing online interviews and engaging with sister projects, the consortium have attended a large number of National and International Conferences to publicise the project and have published a large number of articles in conferences and International peer reviewed journals.

Ultimately, the outputs of the RAIN project aid decision-making in the long-term, securing new robust infrastructure development and protection of existing infrastructure against changing climates and increasingly unpredictable weather patterns.

1.2 A summary description of the project context and the main objectives

Recent extreme weather events (EWE's) in Europe and around the world have thrown the organisation and management of critical infrastructures (CI) 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, disruption to the gas service due to damaged pipelines and contamination of clean water with flood water.

Removing uncertainty and gaining a better understanding of how our CI 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.

The principal objective of the RAIN (Risk Analysis of Infrastructure Networks in response to extreme weather) project, www.rain-project.eu, is to provide an operational analysis framework to minimize the impact of major weather events on land based transportation and energy and telecommunication (E&TC) CI in the EU. A holistic risk-based decision making framework is developed to establish the key components of these infrastructure networks and to assess their sensitivity to EWE as well as to facilitate identification of the impact of alternative mitigation measures.

RAIN aims to quantify the complex interaction of existing infrastructure systems and their interrelated damage potential in the event of specific EWE's. As a result it is intended to improve the robustness of European CI Networks in order to avoid disproportionate damage or disruption due to EWE's. This involves increasing the level of redundancy in the infrastructure networks at critical nodes, improving the performance of key infrastructures and developing detailed plans for a range of potential emergency scenarios.

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

The RAIN consortium is a carefully chosen group of organizations involved in the all aspects of assessing and protecting CI systems and determining the impacts of their failures from economic, societal and security perspectives. The consortium is multidisciplinary by necessity, including meteorologists (FMI, FU-Berlin), climate researchers (ESSL), economists (TCD), energy specialists

(IPTO & AIA), CI owners/operators (DSA), infrastructure risk analysts (TU-Delft &TCD), specialist engineering designers and planners (ROD and GDG), security and strategic response experts (UNIZA, PSJ, HI), social scientists (ISIG) and dissemination experts (YOURIS). Furthermore, an advisory group was developed to ensure widespread applicability of the results to industry by establishing a direct liaison with CI owners, managers and insurers.

The project was arranged according to six technical work packages (WPs 2 - 7), Figure 1.

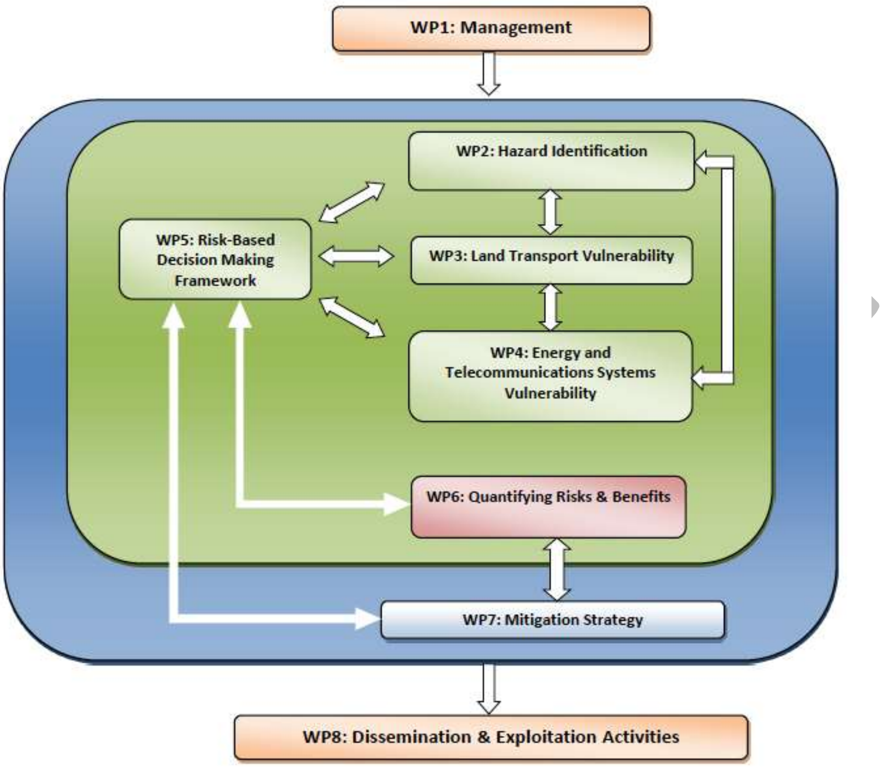


Figure 1 – RAIN WP Structure

WP2 entitled 'Hazard Identification', had three main objectives. Firstly, to identify the extreme weather events to be analysed in detail in RAIN, including defining appropriate intensity thresholds, taking into account regional differences in vulnerability and climate. Secondly, to assess the present state-of-the-art forecast systems for extreme weather and their characteristics, and to address and estimate their predictive skill. Thirdly, to assess the frequency of weather hazards throughout Europe for both the present and future climate; by applying state-of-the-art methods to regional (CORDEX) and global (CMIP5) climate model data until the year 2100.

WP3 entitled 'Land Transport Vulnerability', focused on identifying critical land transport (i.e. road and rail) infrastructure and on reviewing critical land transport infrastructure failures (via case studies), the current means of protecting them were presented and a methodology to determine societal vulnerability (using social/economic markers etc.) was developed. WP4 'Energy and Telecommunications (E&TC) System Vulnerability ' adopts similar aims from the perspective of an alternative CI system.

WP5 entitled 'Risk Based Decision Making Framework' develops RAIN's general risk-based decision framework for single and multiple hazard events, which is able to take into account the (collateral) impacts of cascading effects. The framework serves as a template to integrate and harmonize all content-owning WPs in the project. Within WP5 the framework is implemented in a web based tool. The tool, which is available for use online via the RAIN website, provides infrastructure owners/managers with the opportunity to consider a variety of EWE's and to assess their impact on land based transportation and E&TC infrastructure from the perspective of risk. Significantly, the tool facilitates investigation or risk reduction via selection of alternative mitigation strategies. Thereby enabling risk-based decision making in the context of EWE's.

WP6 entitled 'Quantifying Risks and Benefits' has as its objectives: to assess the societal, security and economic impacts of critical infrastructure failures examined in WP3 and WP4 (i.e. land transport and E & TC infrastructures), based on single and multi-mode failures and based upon the impacts of the failures, to identify the quantifiable benefits (from a societal, security and economic standpoint) of providing resilient infrastructure. In this context the WP presents two case studies which are based on past events which differ in terms of geographic location, geographic scale and hazard source events. Case study 1 is centred on a 2003 event in the Friuli Venezia Giulia Region (FVG) of North Eastern Italy while case study 2 focuses on a 2005 storm surge event in the Uusimaa region of Southern Finland.

The final technical WP, WP7 entitled 'Mitigation Strategies' WP7 focuses on detailing technical engineering solutions which increase the resilience of the considered CI's to the effect of EWE's.

WP8 'Dissemination and Exploitation' had as its aim to promote the visibility of the project and to disseminate its results amongst all types of stakeholders ranging from industry to system operators, policy makers, insurers and reinsurers and research institutes. The main objective was to ensure the widespread dissemination of the knowledge and results generated by project to the relevant stakeholders inside and outside the consortium, including lessons learned from and exploitation to other modes. Numerous dissemination materials were produced during the project to raise awareness of the project outputs amongst stakeholders. These have included a video news release (VNR) features on Euronews, newsletters, online Interviews & articles and workshop reports. A dissemination conference was also held at the end of the project, where the main research findings and outputs were presented to a variety of CI stakeholders (i.e. CI owners/operators, policy makers and governmental departments, researchers and practitioners). The event was extremely successful and copies of the presentations are currently available online. All of the dissemination materials produced in the project are currently available on the project website: www.rain-project.eu. A significant aspect of WP8 was the production of an Exploitation Strategy by the RAIN project partners. The strategy, which focuses on exploitation of the RAIN risk based decision making framework foresees inputs from all of the partners, according to their areas of expertise, in providing an important service to those tasked with considering/mitigating the impacts of extreme weather events on critical infrastructures.

1.3 Description of the main S & T results/foregrounds

The main results of the project have been broken down into the various technical work packages, as follows:

1.3.1. WP2 – Hazard Identification

The work in this WP2 Hazard Identification was divided into four tasks. First, the nature of extreme weather impacts on CI was explored, while relevant severe weather intensity thresholds for use in later analyses were established. Second, a review of state-of-the-art early warning systems was carried out along with an assessment of the predictive skill of these systems. Subsequently, the probability of occurrence of the extreme events in the present was modelled using a number of novel methods. Finally, projections of changes of severe weather probability in the future were created using regional climate models.

Within WP2, the following individual hazards were studied: Winter weather (e.g. snowfalls, blizzards, snow load, and freezing rain); wildfires; river floods and coastal floods; thunderstorm-related phenomena (e.g. large hail, severe wind gusts, tornadoes and lightning); wind storms and heavy precipitation. In the following, a summary of the work performed in WP2 is presented.

To define the severe weather hazards, considering regional climatological differences and the definition of appropriate thresholds, an exploration of the effects of extreme weather impacts was carried out. The first aim was to learn how extreme weather affects the considered critical infrastructure systems within the scope of the RAIN project, i.e. rail transport, road transport, telecommunications and power transmission. The second aim was to identify thresholds of severe weather intensity to be used in the later climate modelling work.

As a first step, the extreme weather hazards that would be analysed in detail were specified. For each of these hazards, thresholds were developed or identified, Table 1. This was done by carrying out new research, as well as by literature reviews. Subsequently, interaction was sought with critical infrastructure operators and emergency services in order to identify the ways in which extreme weather impacts their operations. This was done by carrying out interviews by all partners with relevant stakeholders, and by organizing a workshop, which featured these stakeholders.

Severe winter weather phenomena (snowfalls, blizzards, snow load, and freezing rain) as well as wildfires (forest fires) were analysed and their potential impacts on critical infrastructure (CI) were assessed. For these phenomena, new impact indicators were developed. It was found that the impacts and consequences related to exceeding a particular threshold vary across Europe, and depend on the resilience of the systems. This holds in particular for the transport infrastructure. The impacts of winter weather extremes were among the phenomena about which the CI operators are mostly concerned. Especially the more frequent winter events, heavy snow and snowstorms, were considered most relevant, because they can cause wide disruptions in transportation: e.g. roads and rail tracks may be temporarily out of use, the rate of road accidents may increase, and snow removal logistics need to be considered. Snow loading and accumulated ice on power lines or trees may cause operational failure or power outages. Wildfires may impact especially rail and road transportation as they can lead to disruptions in traffic flow. Also fire can destroy or damage public or private property and cause telecommunication failures.

Table 1 - Thresholds of extreme weather events.

Phenomenon	Threshold 1	Threshold 2
Windstorm	50 - year event	-
Heavy rainfall	10 - year event	-
River flood	100 - year event	-
Coastal flood	100 - year event	-
Tornado	any tornado	-
Lightning	any lightning	-
Large hail	hail diameter ≥ 2 cm	≥ 5 cm
Thunderstorm wind	25 m/s (90 km/h)	32 m/s (115 km/h)
Crown snow load	≥ 20 kg/m2	≥ 60 kg/m2
Heavy snowfall	6 cm / 24 h	25 cm / 24 h
Blizzard (snow storm)	≥ 10 cm snow in 24 h, wind gust ≥ 17 m/s, and temperature ≤ 0 °C	
Freezing rain	5 mm / 24 h	25 mm / 24 h
Wildfire	Fire Weather Index > 20	Fire Weather Index > 45

The skill-of-prediction of severe weather with current state-of-the-art forecasting systems was assessed. Warning systems and intensity thresholds used by the Weather Services (based on questionnaire results) were examined. It was found that most Weather Services do issue warnings for many of the hazards, but the national warning criteria (thresholds) vary to a large degree. Many have a three-level warning system based on the severity of expected impacts. Warnings for snow loading, tornadoes are not typically issued. The majority of Weather Services use a 24h lead time when issuing warnings for heavy snowfall and many have tailored warning products for CI customers with several days' lead time. General forecasts up to 10 days and ahead do not usually include any products of extreme weather events. Forecast skill related to severe winter phenomena has improved substantially in the short and medium range in the last two decades because of model resolution improvements and computer power enhancements. Most of the forest fire warnings given by Weather Services cover a time scale of 1-2 days and a couple of them issue also early warnings, but due to a low number of answers no conclusions can be made based on this. In addition, only eight countries deliver forest fire warnings to the EUMETNET METEOALARM system. Only a few studies exist about the skill of forest fire indices in Europe. Warnings about forest fires have strong additional value in the short range (up to 72 h). By way of example, Figure 2 provides information (taken from RAIN Deliverable 2.3), detailing the skill of warnings issued by European weather services.

Forecasting ranges according to WMO: / Hazard type:	0–2 h, Nowcasting	2 – 12 h, Very Short Range Fore-casting	12 – 72 h, Short Range Fore-casting	72 – 240 h, Medium-Range Forecasting	10 – 30 d, Extended Range Fore-casting	1 – 3 m, 3 Month Outlook, Long Range Forecasting	3 m – 2 y, Seasonal Outlook (departure from climate values)
Windstorms	+	+	+	o	-	-	-
Heavy precipitation	+	+	+	o	-	-	-
Coastal floods	-	-	+	+	-	-	-
River floods	-	+	+	+	-	-	-
Heavy snowfall and blizzard	+	+	+	o	-	-	-
Wildfires/ forest fires	?	?	+	?	-	-	-
Hail	o	o	o	-	-	-	-
Thunderstorm gusts	+	+	o	?	-	-	-
Tornadoes	o	-	-	-	-	-	-

Legend: - Product Not Available or Useless, o Little Use for Some Applications, + Useful, strong additional value compared to Mean Climate Information, ? Unknown

Figure 2 – Skill of Issued Warning Products by European Weather Services

The predictability of heavy precipitation and windstorms with state-of-the-art forecasting systems was also considered. For the assessment a literature research was conducted. Based on the literature research a review on the conditions leading to extreme precipitation in the Mediterranean region was compiled and published. The availability of forecasts in different European countries was also compared. In addition, a method was developed to examine the ability of an ensemble weather prediction system to forecast the occurrence probability and the path of windstorms. It was shown that the European ECMWF ensemble prediction underestimates the uncertainty associated with these variables and is overconfident.

Additionally multiple national and regional state-of-the-art risk monitoring and early-to-medium-range warning systems dealing with river and coastal flood hazards were analysed. It found that river flood warnings are commonly disseminated and used in Europe. The performance of early warning systems is good; they provides valuable warnings, while being constantly improved thanks to advances in meteorological forecasting and observation systems. However, the availability, range and dissemination of coastal flood warnings in Europe is modest compared to river floods and other meteorological hazards.

Analysis of the probability of extreme weather hazards in the present climate using climate models and observational data sets was conducted. The probabilities of the severe winter phenomena and wildfires were studies in the present climate (1981-2010) using observation and reanalysis data and applying the newly defined threshold indices for each phenomenon. The connection between blizzards to large-scale circulation was studied by comparing the risk between winters with positive and negative North Atlantic Oscillation (NAO) index during 1981-2010. The risk of forest fires in the present climate using the Canadian Fire Weather Index (FWI) and ERA-Interim data was examined. In the current climate the risk for severe snowfall (>5mm/24 h) is highest in Northern and Eastern Europe (10-20 days/year) and in mountainous areas (over 20 days/year). Although heavy snow fall events (> 25 cm) occur in general only over the higher European mountains, large areas in Northern and South-Eastern Europe might be also impacted. Blizzards occur most often in Norway, coastal part of Scandinavia and in the Alps. During the positive NAO phase they occur around Iceland and in Norway and potentially in the Alps and at the south-western coast of Finland. Crown snow loading in trees (>20kg/m^{-2}) occurs mostly in the Scandes and the Alps while the risk is moderate in Scandinavia and South-Eastern Europe. Events with heavy snow load (>60 kg m^{-2}) have not occurred elsewhere than in the Alps and the Scandes during the studied period. The spatial and temporal variation of freezing rain over Europe has been defined applying a new freezing rain typing algorithm developed in the RAIN project. The climatology of freezing rain events is characterized by high annual probabilities (>30%) in Eastern and South-Eastern Europe and over the southern coast of Norway, the risk is modest elsewhere. The very severe freezing rain events (>25 mm/24 h) are scattered and rare. Maps of annual probabilities of the severe winter phenomena can be found in Rain Deliverable D2.5 – *Present and Future Probability of Meteorological and Hydrological Hazards in Europe* and are published via the RAIN *Gridded Datasets* (https://data.4tu.nl/repository/collection:ab70dbf9-ac4f-40a7-9859-9552d38fdccd).

Wildfires are dependant on hot and dry weather. In the current climate the fire risk is highest in Southern Europe, with daily probability values over 10%, from where it gradually decreases towards Northern Europe (1% daily probability). The highest risk of extreme fires (FWI>45) is in the Mediterranean area.

The changes in the occurrence of hazardous winter weather phenomena and wildfire risks by 2100 were assessed using a set of six Regional Climate Models (RCMs) at 50 km spatial resolution and 6-hour time resolution for two scenarios, RCP 4.5 and RCP 8.5, produced in EURO-CORDEX. The scale of changes was calculated for two time horizons, 2021-2050 and 2071-2100 compared to the control period 1971-2000. Due to climate change it was determined that heavy snowfall, blizzards and snow load will become less likely over much of Europe. Dense snowfall (>6 cm/24 h) is expected to decrease by 25-50 pp (percentage points) by 2100. Very heavy snowfall events were so rare (>25 mm/24 h) that no clear signal could be seen in the annual probabilities. Crown snow load events are projected to become less frequent over most of Europe except in northern and north-eastern part of Europe where an increase of 10-25 pp is expected by 2100. The occurrence of freezing rain will shift northwards and intensify in Fennoscandia and Northern Russia, presenting a significant increase (10-15 pp) by 2100, in Central Europe the probability will decrease (up to 10pp). Conditions suitable for wildfires and forest fires will become more frequent especially in the Southern Europe, due to longer dry periods. The risk is smaller in Northern Europe.

The thresholds needed for the detection of infrastructure threatening heavy precipitation and windstorm events were calculated from observations of the recent past and from model simulations forced with observed greenhouse gas concentrations. The model simulations were validated. The identification tools and severity measures developed in the RAIN project were applied to the observations and the present-day-climate simulations. The frequency and characteristics of infrastructure threatening windstorms and heavy precipitation events in the recent past were assessed.

Large multi-model ensemble data sets were downloaded from the climate data servers. Applying the identification tools developed in RAIN, the frequency of infrastructure threatening windstorms and heavy precipitation events simulated by regional climate models forced with two different greenhouse gas concentration scenarios were analysed. The results were summarized in a report and uploaded onto a publically available data server

Statistical and hydrodynamic modelling of extreme flood events in a pan-European domain, both under present and future climate was performed. Modelling of coastal floods was done along 225,800 km of coastline. River discharges were estimated for almost 2 mln km of rivers, and flood extents for areas adjacent to rivers with catchments bigger than 100 km^2 (498,420 km in total). The following output (raster grids, 100 m resolution) were provided to the repository, for 5 return periods (10/30/100/300/1000 years) under 5 climate scenarios (1971-2000, 2021-2050 RCP4.5, 2021-2050 RCP8.5, 2021-2050 RCP4.5, 2021-2050 RCP8.5):

- River flood extents, without considering flood protection levels;
- River flood extents, with estimated flood protection levels;
- River flood water depths, without considering flood protection levels;
- Coastal flood extents, without considering flood protection levels;
- Coastal flood extents, with estimated flood protection levels (Figure 3);
- Coastal flood water depths, without considering flood protection levels;

Additionally, the following supporting information (vector point data) was produced and added to the repository, for the aforementioned climate scenarios and 10 different return periods (from 2 to 1000 years):

- River discharge by river segment;
- Change in return period of river discharge by river segment;
- Storm surge height by coastal segment;
- Change in return period of storm surge height by coastal segment;
- Extreme sea level by coastal segment;
- Auxiliary data: mean high tide, mean sea level rise by scenario and glacial isostatic adjustment trend.

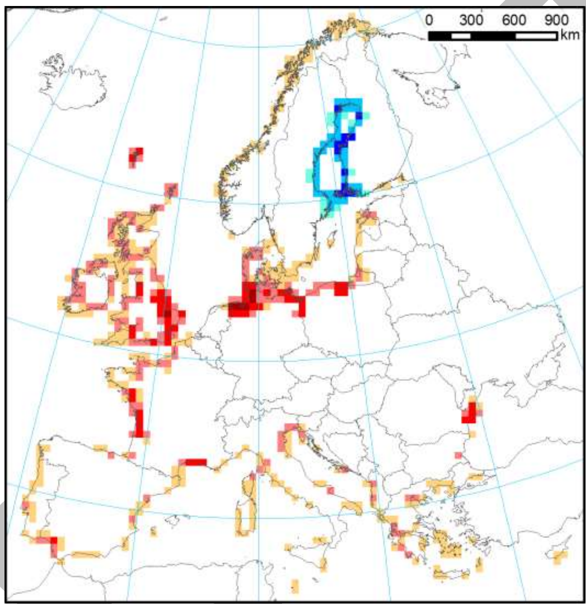


Figure 3 - Changes of area of 100-year coastal flood hazard zones (with estimated current flood protection), aggregated to 50x50 km grid until 2071-2100 under the RCP8.5 climate scenario.

It was found that river floods will become approximately twice as likely in the future compared to current climate, especially the case of central Europe and the UK, unless mitigation efforts are taken. Throughout Europe, the regions at risk from 10-year, 30-year and 100-year return period floods will expand greatly. Germany, Hungary, Poland and France are expected to have the largest absolute increases in flood-prone areas. On the other hand, northern Europe will encounter a decrease in flood-prone areas. Meanwhile, sea level rise will cause an increase in extreme water levels along all European coasts, with particularly big relative effects in the Mediterranean Sea region.

The present and future probability of thunderstorm-related hazards was analysed using a large ensemble of 14 regional climate model predictions, Figure 4. To this aim, a new methodology was developed by which the probability of a thunderstorm hazard was modelled as the product of the probability of occurrence of a thunderstorm and the probability that a hazard will occur given that a storm occurs. The results the analyses indicate that lightning will become much more common across central and northern Europe during the 21st Century, especially in the unmitigated rcp8.5

climate scenario. In addition, the probability of severe thunderstorm-related phenomena such as large hail, tornadoes and severe gusts will increase across much of Europe, and especially across South-Central Europe. Over Southwest Europe, however, the trend is uncertain, primarily because of diverging model runs.

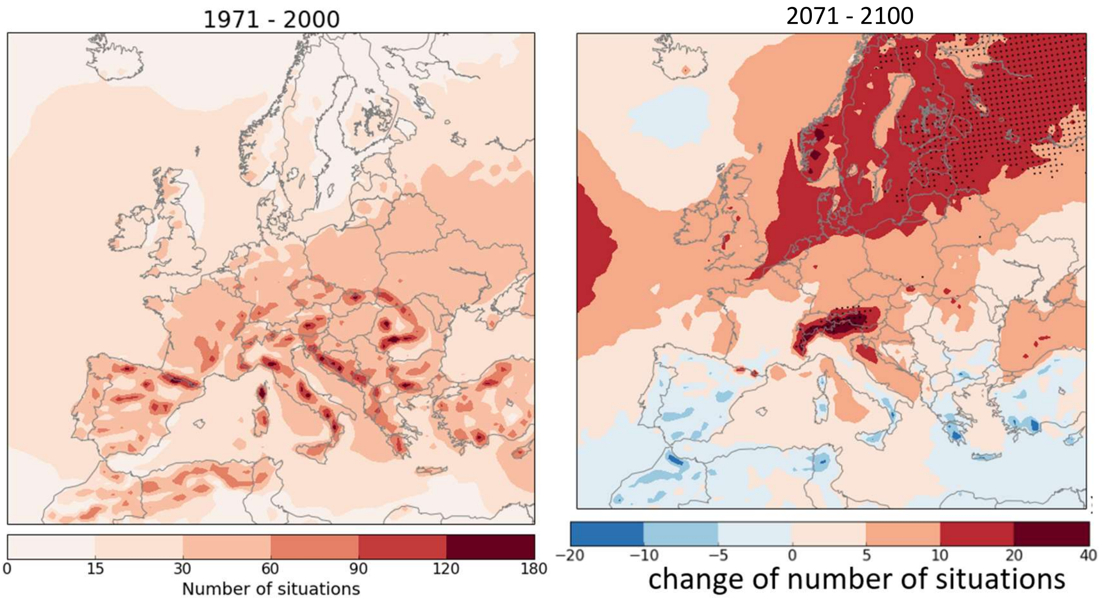


Figure 4– Modelled annual number of 6 hourly periods with lightning (1970-2000; left) and changes according to a consensus of EuroCordex climate models in the RCP8.5 climate scenario in the period 2071-2100.

1.3.2. WP3 – Land Transport Vulnerability

In WP3 the focus was on the identification of critical land transport infrastructure and a review of (i) failures as a result of extreme weather events, (ii) the current means of critical land transport infrastructure protection, and (iii) development of an understanding how failure of this infrastructure leads to societal vulnerability.

The main S & T results are represented by the Methodology for identification of potential critical infrastructure elements in transport infrastructure. The Methodology is organized in two basic parts. The first part focuses on the development of a theoretical framework for identification of potential critical infrastructure elements, defining and analysing typological elements of the road and rail transport from the view of their inclusion into potential elements of the critical infrastructure. Additionally a list of potential elements of critical land transport infrastructure with specific examples is provided. The second part focuses on the threats to potential elements of critical infrastructure in road and railway transport caused by the extreme weather events defined in WP2.

The list of the most probable threats to critical transport infrastructure has been created on the basis of an examination of where, what, and why the threat exists, and what its corresponding impact on the road/railway infrastructure is.

The case study “Impacts of river floods on road and rail critical infrastructure in North-West Slovakia” provides the description of a hypothetical meteorological event, a description of transport infrastructure after the hypothetical event, and the description of the management of the emergency. It highlights that people have to be prepared also for crisis situations that sometimes seem to be unrealistic, but which, because the frequency and intensity of extreme weather events is increasing, imply a serious threat to people, and such danger cannot be underestimated.

The case study “Summer storms 2010 and the winter storm 2011 in Finland” covers two major storms hitting Finland. It was commissioned to examine the civil security mechanism and lessons derived from two major storms in Finland. A common factor in the two storms was their disastrous effect on national land transport infrastructures. The report emphasizes the assessment of the effectiveness of various national response measures. The report concludes that whereas the national level response was not activated and the essential authorities declared that the situational awareness had been sufficient, the local and municipal level authorities faced difficulties to obtain timely and coherent data on the situation and forecasts. Difficulties within the regional rescue departments emerged mainly from insufficient capacity for sharing the data and also because of the incoherence of data crossing their borders. Municipalities took action to improve their preparedness, while citizens found their role in many situations as real time first responders.

Another main S & T result of WP3 is represented by the *Database of Critical Land Transport Infrastructure Protection Methods*. This database includes current methods and best practices that relate to the preparedness and response to the serious impacts of extreme weather on critical land transport infrastructure and their analysis for specific problems. The database is divided into three basic parts: risk identification methods, risk evaluation methods, critical transport infrastructure protection methods. The selection of methods depends on the problems faced, input data, knowledge and experiences of the team. The database provides brief descriptions of real cases of land transport infrastructures where measures against extreme weather events have been taken. This database of methods provides support to the decision making process of crisis managers whose role is, within the prevention, to monitor potential threats, prevent crisis events and in case of emergency to prepare an adequate response and minimize their negative consequences.

The main S&T results relating from the work performed on assessing the Effects on Societal Vulnerability (economics, social impact, financial, security) are represented by the definition of *Indicators of Societal Vulnerability* and in the developed approach to measure vulnerability and specifically societal vulnerability due to the failure of critical land transport infrastructure elements. The identification and selection of indicators for measuring societal vulnerability to the impacts of extreme weather events on critical land transport infrastructure was based on the definition of vulnerability as a function of exposure to extreme weather events, susceptibility to change caused by extreme weather events and capacity to adapt to that change:

Vulnerability Index (VI) = f (Exposure, Susceptibility, Adaptive Capacity)

Indicators have been selected with regard to their relevance, usefulness and measurability, i.e. they are available, adequately documented and regularly monitored.

The approach to societal vulnerability assessment is of multilevel character. The Methodology is divided into two basic parts. The first part “Research of the societal vulnerability concepts and societal vulnerability components” (security, economic, social) deals with theoretical aspects of vulnerability. It includes defining vulnerability, vulnerability concepts, core factors and key dimensions of vulnerability, resilience and survey of some models of risk and vulnerability assessment. The second part “Development of an approach to measure societal vulnerability” includes results of the research in the form of a proposed methodology for measuring societal vulnerability due to extreme weather impacts on critical transport infrastructure. The measure of Societal Vulnerability is expressed through the Vulnerability Index calculated on the basis of selected vulnerability indicators as illustrated in Figure 5.

The Vulnerability is dependent on the specific hazard**.** Hence, a target region can be more vulnerable to a certain kind of threat but much more resistant, i.e. less vulnerable to another kind of threat. Therefore, it is necessary to evaluate vulnerability for each threat or danger separately.

The proposed Vulnerability Index can achieve values from 1 to 5. Increasing values indicate increasing vulnerability. The index and related interpretations serve for evaluation of the current state in a specific region as well as for decision making purposes. In the description of VI values, some recommendations for vulnerability reduction in terms of crisis planning, risk management and preparedness enhancing are provided. With increasing values of VI, the time pressure for immediate reaction (vulnerability reduction) as well as the necessity of a higher level of resources and personnel capacities to cope with extreme weather events is rising. If the given approach is applied on more sectors simultaneously, it is possible to compare them and it allows the identification of more vulnerable areas.

In addition to this approach a specific application for measuring vulnerability and resilience from a user perspective was developed within the Objective Ranking Tool. This specific ORT-application is a tool for self-evaluation by local authorities at different levels and their stakeholders. Within this application it is possible for them to assess their performance and preparedness to different types of extreme weather events. This assessment expresses elements of vulnerability as such but also allows identifying the quality of preparation in terms of resilience. Having seen a clear picture of their strength and weaknesses in the face of extreme weather they can act to improve their resilience.

The possibilities to include the approach of a Delphi-panel and the development of a dedicated Objective Ranking Tool application focusing on vulnerability and resilience was also investigated. The Objective Ranking Tool (ORT) is based on three scientific principles: Similarity Judgment, Analytic Hierarchy Processing and the use of a Delphi-panel. Participants of this Delphi-panel were selected based on previous scientific work within this subject and practical experience. The selection of variables for the evaluation of vulnerability and resilience stems from the further development of the research work within the EU ECOSTRESS project. With the assistance of the ORT-application is was possible to rank i.e. municipalities in a region to their vulnerability and resilience related to extreme weather events. Based on the analyses within the ORT-application it is possible to focus on those criteria which contributes the most to a more resilient situation. The ORT-application is available as a online web-based tool.

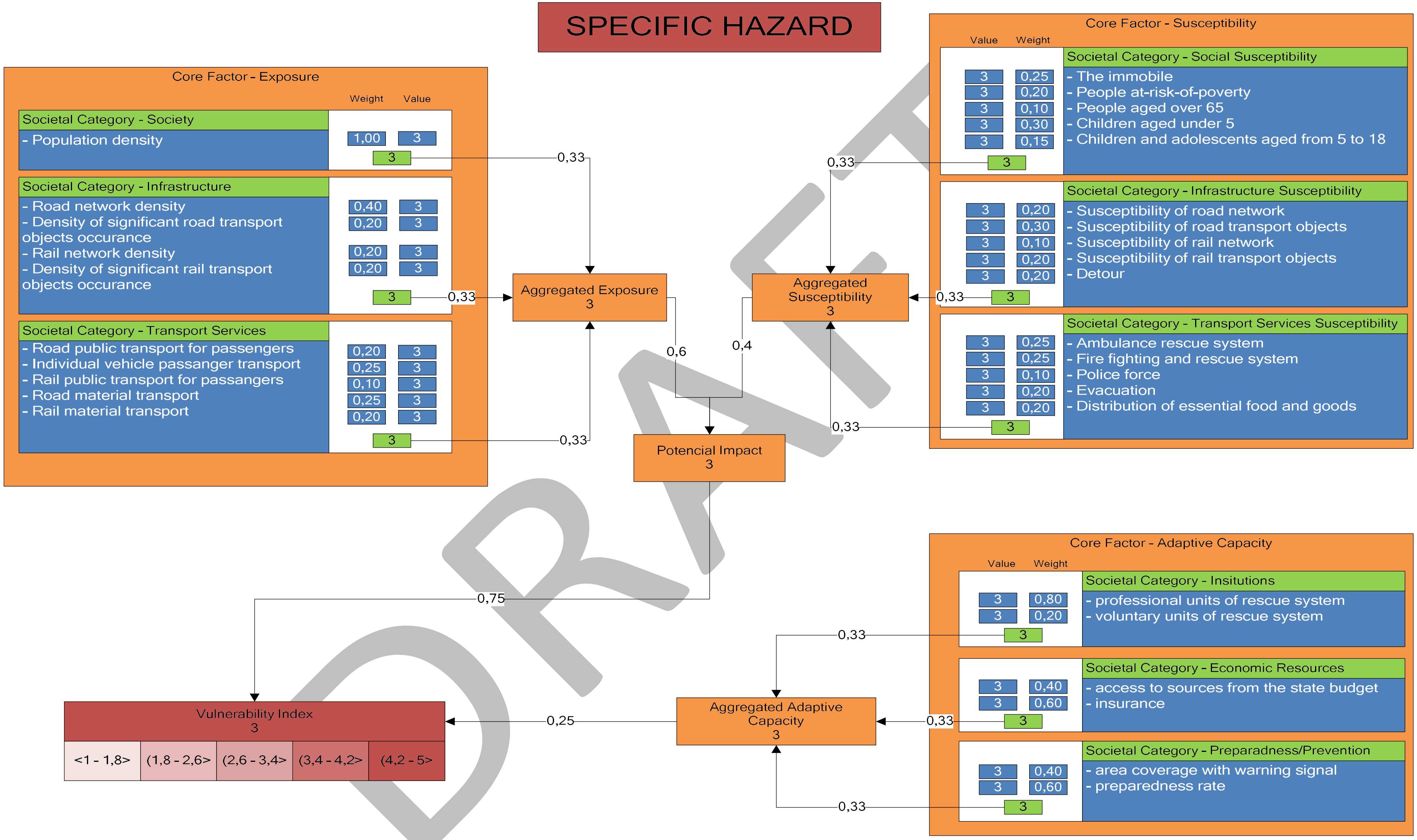


Figure 5 - Detailed depiction of approach for the determination of Societal Vulnerability

1.3.3. WP4 – Energy & Telecommunications System Vulnerability

WP4 deals with two specific critical infrastructures: Electrical networks and Telecommunications networks (E&TC). The logical steps were followed sequentially in each task, from identification and review critical E & TC failures, the current means of protecting them and develop an understanding how failure of this infrastructure leads to societal vulnerability/insecurity (using social/economic markers). The outcomes of this work directly feed the risk based decision-making framework developed in the RAIN project with different inputs regarding the failures modes, the prevention and mitigation strategies, and the relative impact of events.

The main S&T work performed included:

- An overall description of these two Critical Infrastructures (CI): a primer for non-experts, in order to provide an adequate level of understanding for the rest of risk modellers in the RAIN consortium.
- Identification of the CI elements and their (weather related) threats: here focus was on understanding what the threats are, and how they affect both the end-user and the operation.
- Provision of a first scheme of interdependencies with other CI: a qualitative overview analysis of how the failures in electrical grids and telecom networks affect each other, as well as other infrastructures under study in the RAIN project.
- Description of a few selected representative examples of weather-related failures in these infrastructures.

The most significant S&T results of WP4 are:

- **Impact matrices**: for Electrical and for Telecommunication infrastructures, matrices relating the studied meteorological causes with the most critical elements are provided, indicating a measure of the impact, Figure 6.

	Outside Plants	End Offices	Central Offices	Aerial lines	Underground lines	RF/Sat links	Base Stations	MSC	BSC
Lightning	High	Mid	Low	Mid	Low	High	High	Mid	Low
Windstorms	High	Mid	Low	High	Low	High	High	Mid	Low
Ice/snow storms	High	Mid	Low	High	Low	High	High	Mid	Low
Flash floods	High	Mid	Low	Mid	Low	Mid	High	Mid	Low
Extreme cold	Low	Low	Low	Low	Low	Low	Low	Low	Low
Extreme heat	Mid	Low	Low	Low	Low	Mid	Mid	Low	Low
Wild fires	High	Mid	Low	High	Low	High	High	Mid	Low
Sand storms	High	Mid	Low	Mid	Low	High	High	Mid	Low

Figure 6 - Impact Matrix. Summary table of threat assessment per weather threat and telecommunications network element.

- **Protection matrices**: for each of the considered infrastructures, two matrices with the same structure as the impact matrices were generated, one indicating the preventive measures and other with the mitigation measures. The aim of these matrices was to facilitate the construction of this aspect of the risk based decision making framework, Figure 7.

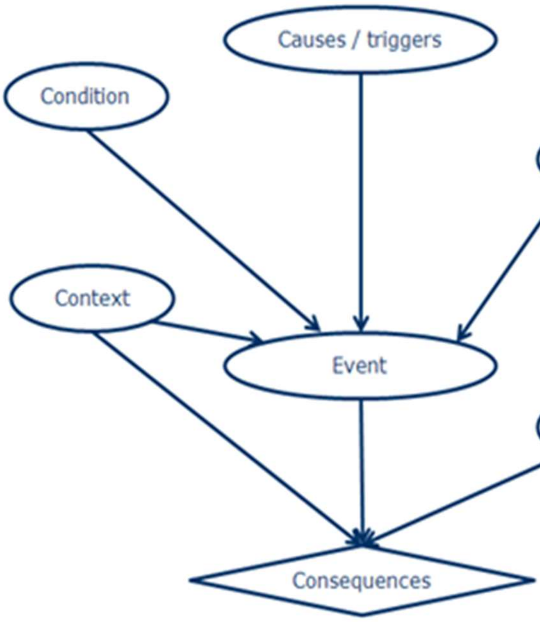


Figure 7 - Role of preventive and mitigation measures in the risk assessment framework

- A scheme of interrelation between Telco and Energy infrastructure failures.
- A survey of the protection methods in both infrastructures, assessing their effectiveness.
- Scripts to run simulations representing different electrical scenarios, development of a database to store results and the provision of scripts for analyzing results, Figure 8.

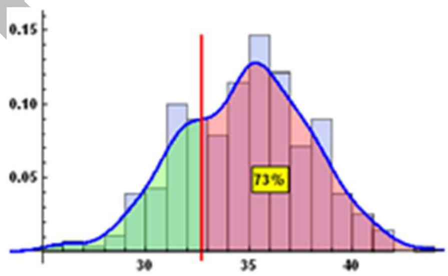


Figure 8 - Probabilistic distribution of power flow through a line, indicating its nominal limit, from Montecarlo simulations.

- Identification of E &TC failures: the most important and frequent failures derived from extreme weather events are listed and analyzed. Special attention was put on the interdependencies between failures in different infrastructures.
- Methods for protecting CI's: A compilation of the practices, techniques, and protocols for protecting (prevention and mitigation) network elements that are critical to the functionality

of power and telecom infrastructures is provided. The methods for protecting are separated in two main subsets: preventive and mitigation, depending on their scope.

- Effects on Societal Vulnerability: the impact analysis is extended from standard markers adding social considerations that go beyond traditional measures of impact (which only take into account loss-of-service concepts). The standard metrics, the ones used in national regulations, were reviewed (coming from engineering or economic criteria) quantifying in physical or monetary units the consequences of outages. Then, the social dimension is explored: separating different type of consumer and the different channels involved, related to the specific human activities affected, Figure 9. The Social Impact Magnitude (Larsson, Björkman, Ekstedt chapter in Hämmerli, Svendsen, & Lopez, (2012)) was also used to assess the societal impact and applied to specific case of the Gudrun/Erwin windstorm 2005, Figure 10.

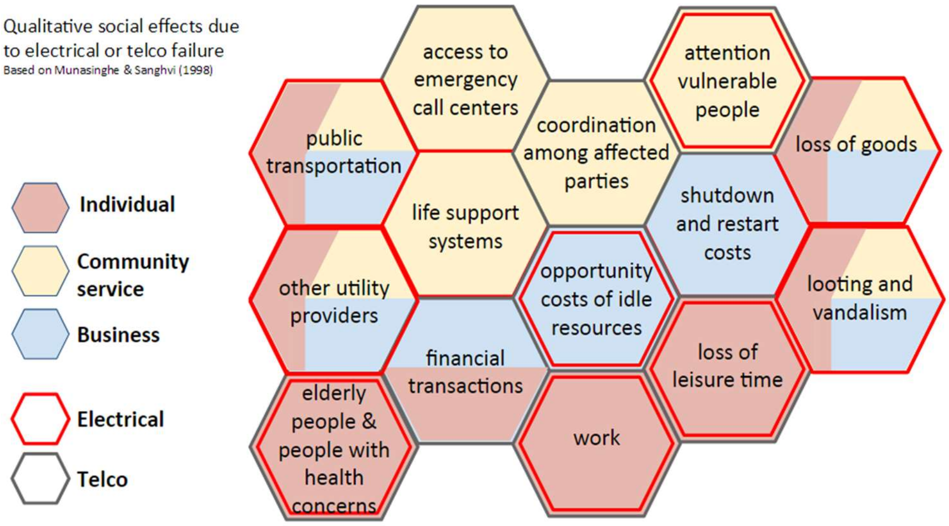
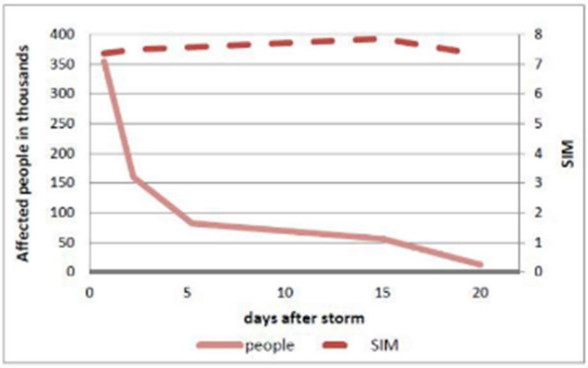


Figure 9 - Affected activities by disruption in the electrical or telecommunications services by type of consumer.



Windstorm Gudrun/Erwin (Sweden, Feb. 2005)

0 ≤ SMI < 3	None or small problems
3≤ SMI < 5	Problematic
5≤ SMI < 7	Severe problems
7≤ SMI	Critical problems

Figure 10 – (Left) Social Impact Magnitude compared to the number of affected people on the Gudrun/Erwin windstorm. (Right) Social Impact Magnitude scale, adapted from (Hämmerli, Svendsen, & Lopez, 2012)

- Network usage forecasting and element incident estimation: Using physical models, a number of simulations were performed in order to estimate the actual distribution of power flows over the network when some elements fail, given some probabilistic distributions for failures and also for preventive and mitigation actions being deployed.

1.3.4. WP5 – Risk Based Decision Making Framework

In WP5 a general risk-based decision framework for single and multiple hazard events was developed which is able to take into account the (collateral) impacts of cascading effects. The framework has served as a template to integrate and harmonize all content-owning WPs, as WPs will be forced to produce (conditional) probability distributions that connect in a meaningful way, following the Bayesian paradigm. For example, severe rainfall impacts the structural integrity of pylons. So, the structural engineer specifies to the rainfall expert which rainfall levels are relevant for pylons. Rainfall experts then produce a tailor made rainfall probability distribution for the structural engineer, which the structural engineer can connect with his pylon structural integrity probability distribution in a meaningful manner. Stated differently, the (conditional) probability distributions are the inference modules that capture the expertise of the content-owning WPs.

The EU policy document Cost-Benefit Analysis of Investment Projects (EU Directorate Guide Regional Policy, 2008) advocates for expected utility maximization. However WP5 demonstrates that expected utility is not valid in decision-making under risk. WP5 has developed a neo-Bernoullian decision theory instead. Expected value maximization leaves out relevant decision theoretical information on worst and best cases. WP5 has demonstrated that the mean of the lower bound, expected value, and upper bound needs to be maximized, rather than the expected value. This may increase the investment willingness into safety barriers up to ten-fold. WP5 has also developed the Probability Sort algorithm in order to estimate Markov Chains in modelling cascading effects in networks, for what otherwise would have been intractable (in)homogeneous transition matrices.

In WP5 a webtool for risk based decision making was developed. This software tool generates the forecasting of the network usage (i.e. stress levels of the power grid, specifically in each transmission line segment) given some geographically distributed consumption and generation profiles. These profiles are obtained taking into account the hour of the day and the weather conditions, among others.

The developed tool provides a visual interface for tuning the configuration parameters of the simulation for a number of possible scenarios. It also displays the results in different formats obtained and provides summary reports.

The software is made of several modules that interact sequentially, namely:

- Meteorological event impact modules, relating extreme weather events critical elements and their failure modes,
- Generation and consumption forecast modules, related to the context,
- Electrical simulation modules,
- Impact evaluation modules.

Figure 11 demonstrates how the nature of the approach, allows assessing the actual amounts of lost load, electrical impact per element of the grid, customers affected, its economical consequences, etc. The left panel shows the summary of the results for the various EWEs analysed. The central panel shows the electrical cases generated through Monte Carlo simulations and its consequences on the electrical substations. Whilst the right top panel shows the electrical consequences on the lines of the grid and on the bottom the probability distribution of costs per sector.

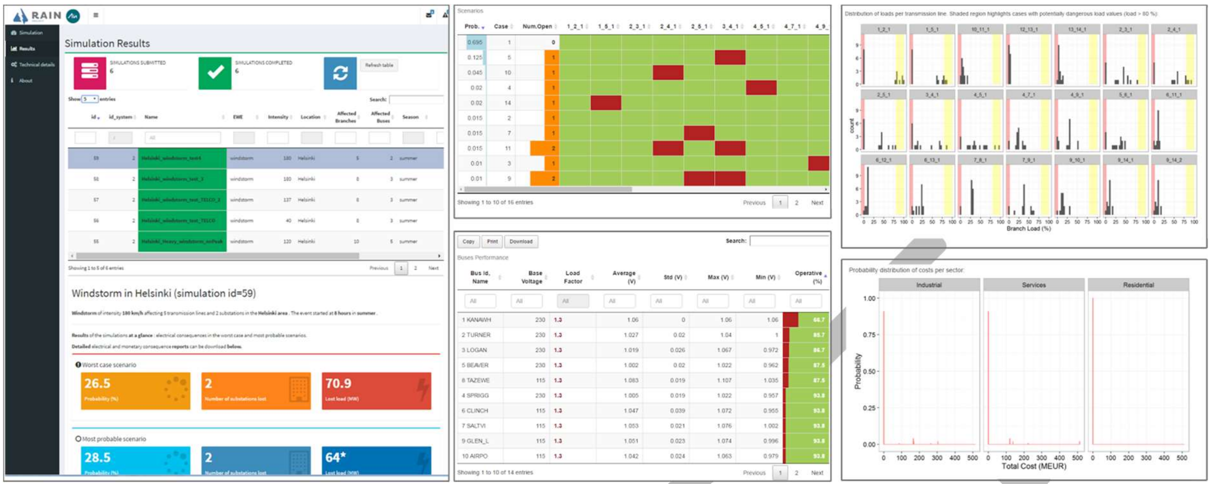


Figure 11 - Examples of the simulation results and analysis in the Load flow computation approach.

The RAIN partners developed and integrated a module to compute the incident probabilities of different network components. This was achieved by identifying, for each component and meteorological threat, the main physical features and variables that determine the probability of failure for different channels (or failure modes) and event intensities, Figure 12.

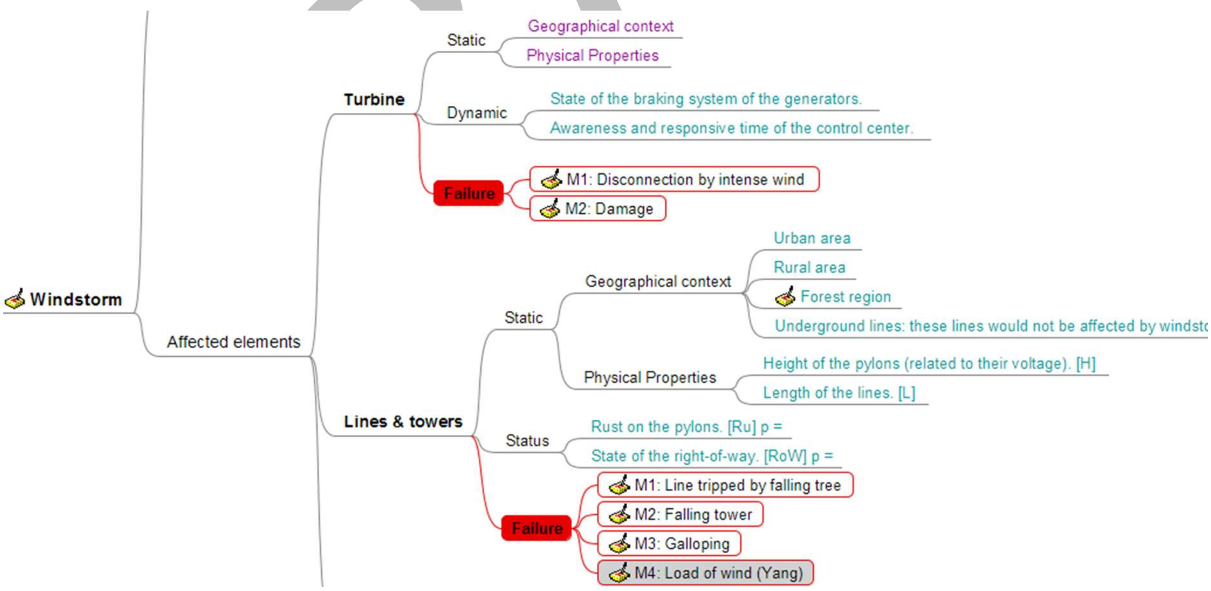
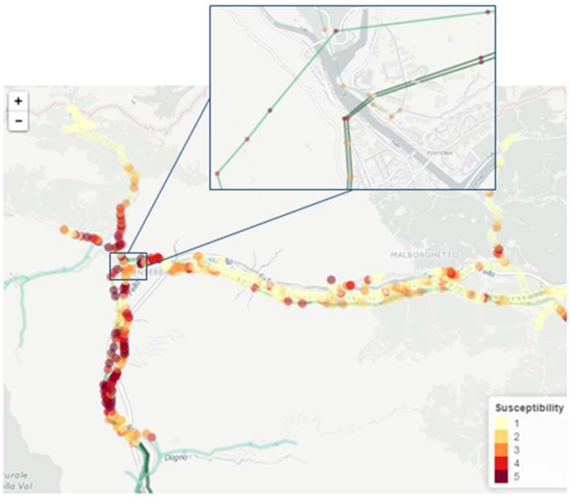


Figure 12 - Example of failure modes analysis for electrical components under windstorms. Physical contextual variables are identified (as the type of area surrounding the power lines) and the different failures modes.

Then, using the weighting methodology developed within the project, the relative importance of each factor is determined by a Delphi panel composed by a group of experts. In some specific cases where fragility curves are available (for instance, damage probability for transmission towers as function of wind speed), the tool has a more precise dependence on the event intensity.

Failure probabilities for each element of the network are defined per EWE joining the information obtained from the Delphi panels, the properties of the EWE studied, and the most probable failure modes per element. For example, in the case of heavy precipitation in a mountainous region, the most probable failure mode for electrical towers is by landslides impacting on them. The different probabilities are joined in a Bayesian approach proposed by WP5 to finally obtain the damage probabilities.

Using the tool the critical components identified can be analysed individually, Figure 13 and Figure 14.



Map:
- Circle: electrical component
- Color: criticality level

Table:
- Compilation of available information

Show 10 entries Search:

	Line Id	Tower Id	Voltage	Type	Susceptibility	Altitude	Slope	X coord	Y coord
11	60117713	747742348	60000	tower	1	594	11.99	13.319597	46.511094
12	60117712	747742358	60000	tower	4	610	15.38	13.317307	46.511539
13	60257696	748572156	132000	tower	5	574	25.37	13.292156	46.467632
14	60117713	748572159	60000	tower	2	557	26.40	13.303801	46.454754
15	60117712	748572169	60000	tower	3	495	11.98	13.295436	46.460432
16	60117712	748572170	60000	tower	1	592	26.48	13.306362	46.453061
17	60117712	748572208	60000	tower	5	574	25.37	13.292804	46.468027
18	60257696	748572218	132000	tower	5	567	23.24	13.292556	46.465554
19	60117713	748572228	60000	tower	4	492	7.30	13.293797	46.462595
20	60117713	748572232	60000	tower	5	567	23.50	13.292764	46.469118

Showing 11 to 20 of 822 entries Previous 1 2 3 4 5 … 83 Next

Figure 13 - Identification of critical components given a specific EWE. Each element is shown on the map (left), listed in the table (right) and their properties are shown for analysis.

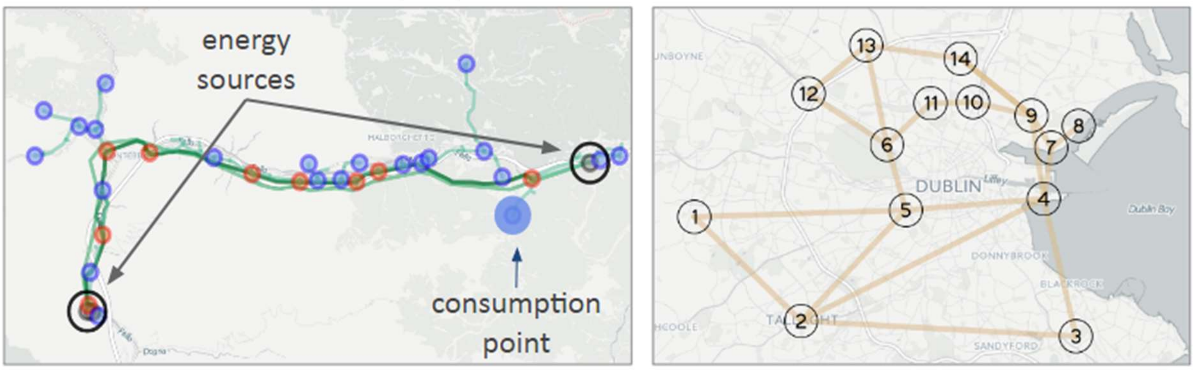
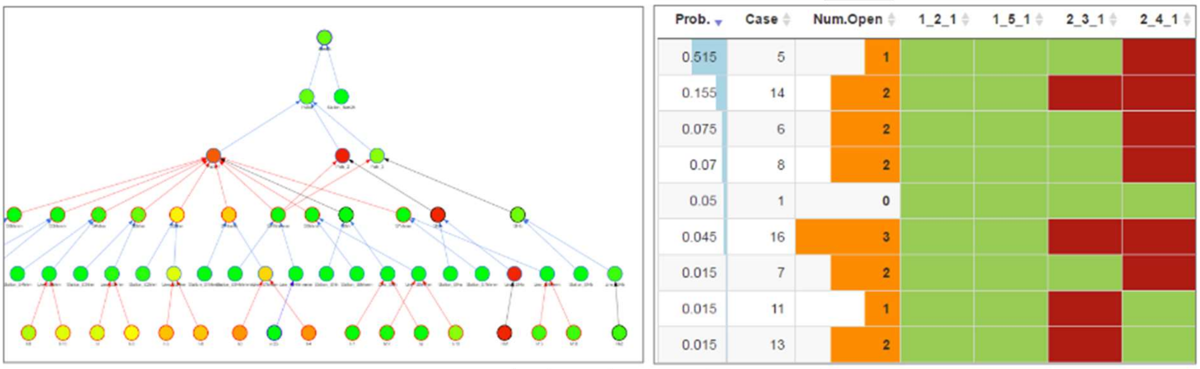


Figure 14 – (Left) electrical grid model used in the connectivity approach. Stations (circles) and transmission lines (lines) are shown as well as the consumption point of the region of interest. (Right) IEEE 14-bus electrical model with geographical context used in the Load flow computation approach.

When these direct failure probabilities of the various elements are obtained, the contingency analysis related to the specific meteorological threat is performed. On the electrical analysis two approaches are followed as a function of the available data:

1. Connectivity analysis: electrical connectivity between energy sources (generators or high-voltage lines) and specific consumption points (electrical stations) is studied. The failure probabilities of each individual element of the electrical grid feeds a Bayesian network, that is used to assess the probability of disconnection, i.e. blackout, in the region of interest.

2. Load flow computation approach: this analysis was developed and it requires sensitive data from energy providers. It is based on performing a load flow analysis on a number of electrical scenarios generated from Monte Carlo simulations considering the failure probabilities of the various elements of the grid.



Prob.	Case	Num.Open	1_2_1	1_5_1	2_3_1	2_4_1
0.515	5	1				
0.155	14	2				
0.075	6	2				
0.07	8	2				
0.05	1	0				
0.045	16	3				
0.015	7	2				
0.015	11	1				
0.015	13	2				

Figure 15 – (Left) Bayesian network used in the connectivity approach to assess the probability of blackout in an electrical station given the failure probabilities of each element considering a specific EWE. Failure probability increases from green to red. (Right) Monte Carlo generated electrical scenarios. Each scenarios includes a number of operative (green) and unavailable (red) lines.

The impact evaluation includes:

- The assessment of the economic consequences of a blackout or lost load and number of consumers affected.
- The analysis of the type of customer affected and its social impact.
- The consideration and analysis of *What-if* scenarios where protection or mitigation engineering measures are applied.
- The comparison of the repairing (direct), blackout (indirect), and investment costs per what-if scenario considered. For this last step, engineering measures for each element of the network are defined per EWE.

As illustrated in Figure 16 and Figure 17.

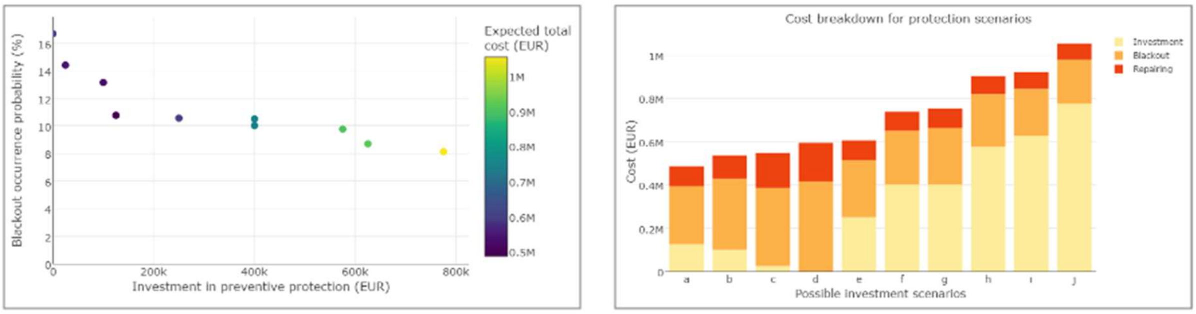


Figure 16 – (Left) Blackout probabilities as function of investment in preventive protection measures. Colorscale shows the expected total cost (considering the new-Bernoullian utility function). (Right) Cost breakdown (investment, direct, and repairing costs) for the 10 best investment scenarios.

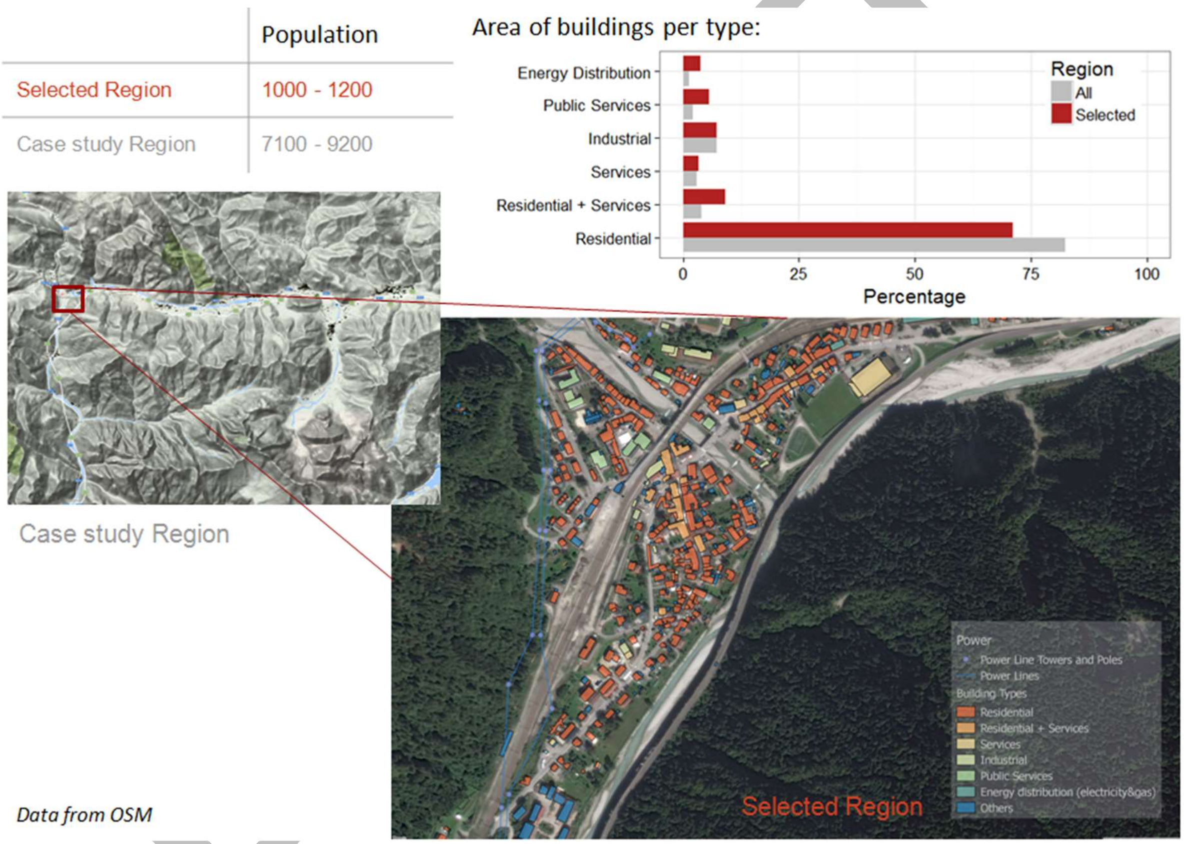


Figure 17 - Identification of social structure in Pontebba region (Alpine case study). Data from Openstreetmap (OSM) allows to identify the type of building in the region of interest and extract the population. This information is used to assess monetary and social impacts.

The original webtool has been extended to include land transportation (roads and railway) in which the project's Bayesian Risk Framework is fully implemented. In particular, the new-Bernoullian utility function for the evaluation of impacts is used in the consequence assessment module. The failure probability analysis for land transportation is implemented following the inputs from the land transportation expert partners.

Demonstration videos are available online (video 1, video 2). The most recent developments include the evaluation of land transportation infrastructures, and weather-related information fed by WP2.

The webtool is accessible online for use and its source code will be released and available at a public repository via the RAIN website. The functionality of the tool is illustrated in Figure 18, Figure 19 and Figure 20.

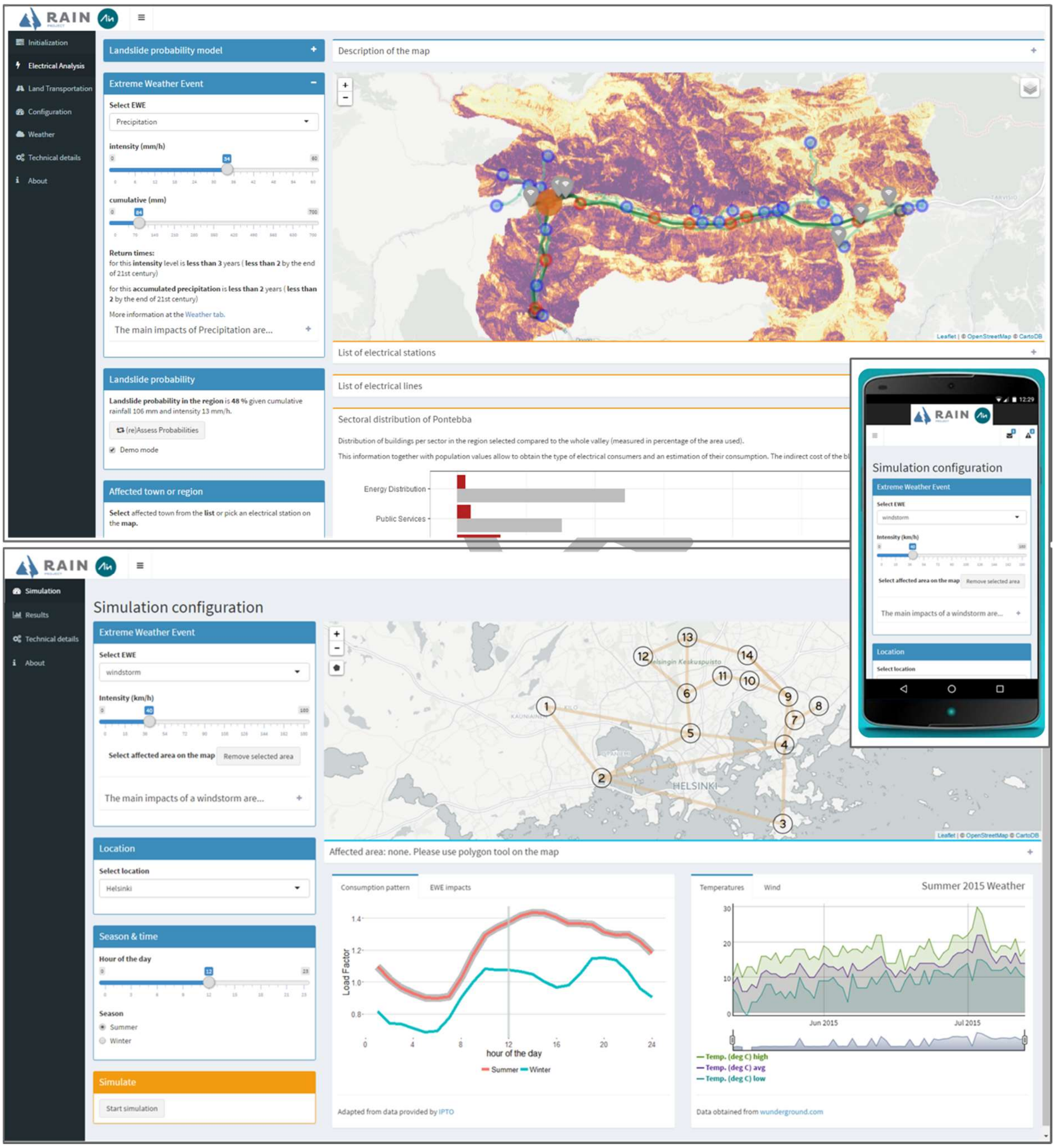


Figure 18 - Screenshots of the main page of the webtool for the Connectivity approach applied to the Alpine case study (top) and the Load flow computation approach applied to the Finnish case study (bottom). Inset shows the responsiveness of the webtool: it works well on mobile devices.

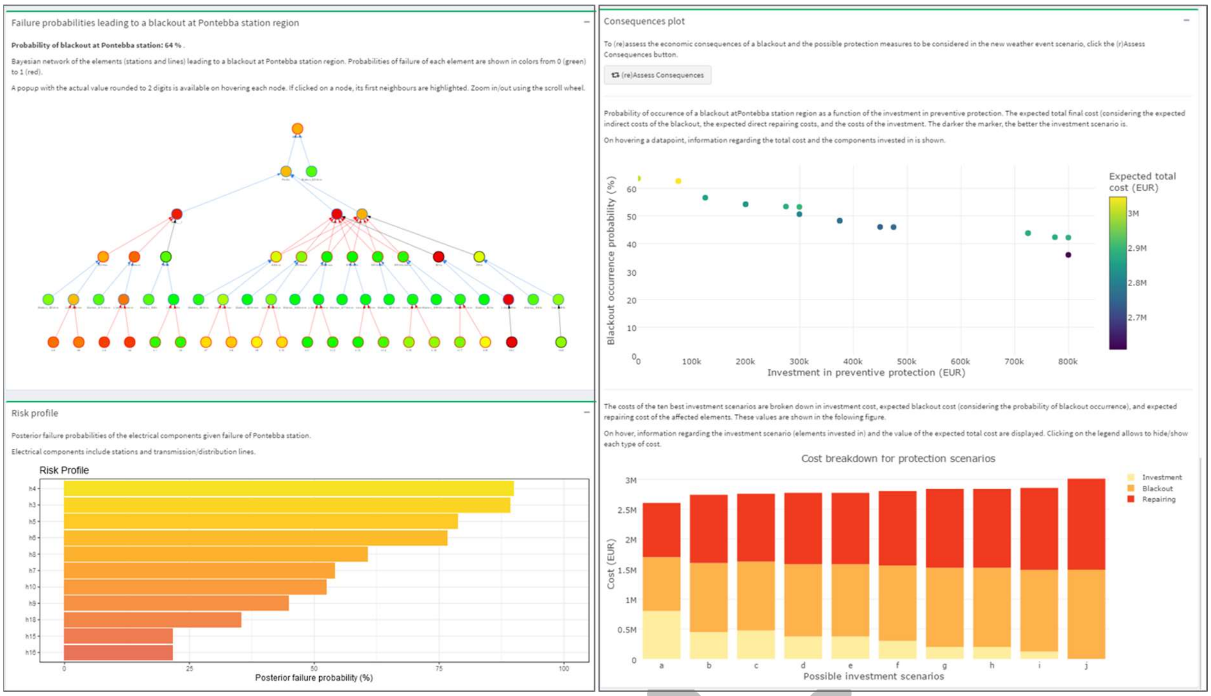


Figure 19 - Example of the consequences assessment in the Connectivity approach webtool. Left panel shows the Bayesian network automatically generated to assess the probability of a blackout in a region and the risk profile (the posterior failure probabilities of the critical elements given a blackout in the region). Right panel shows the economical and societal consequences.

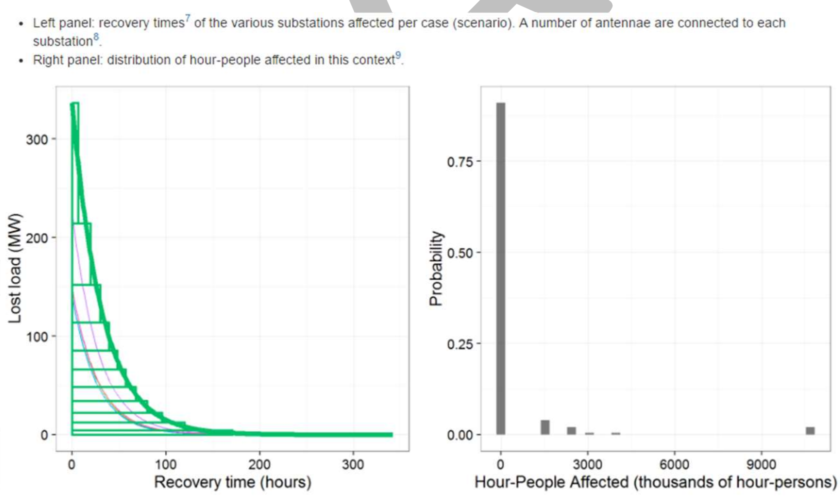
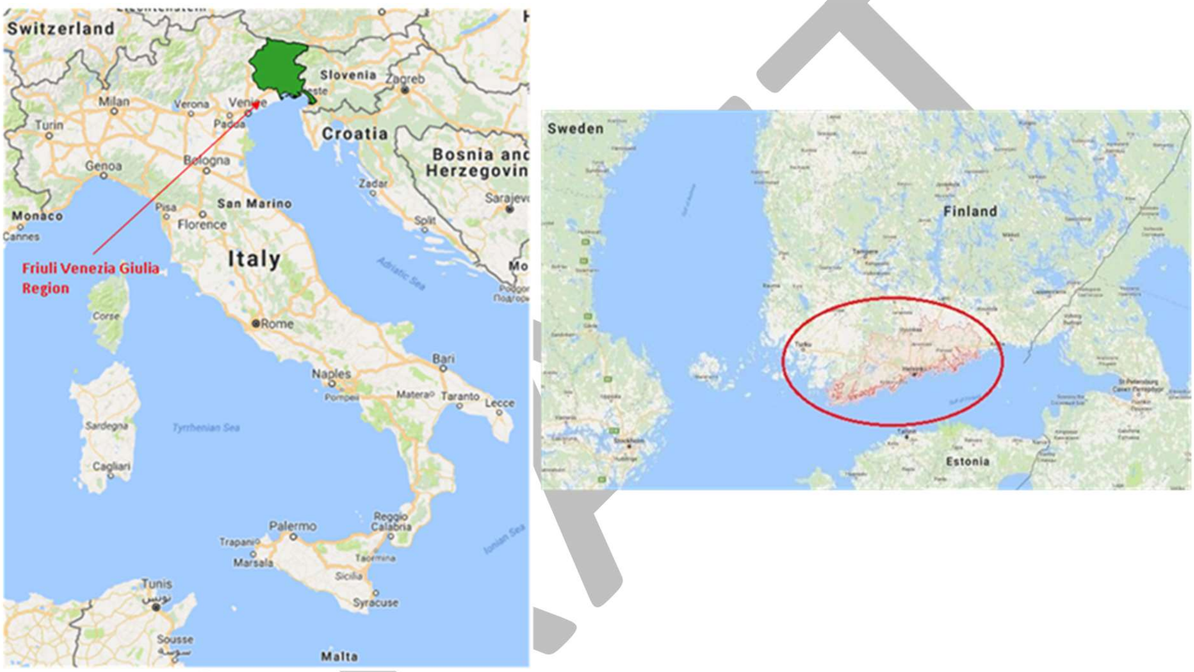


Figure 20 - Example of the assessment of the impact on the telecommunications network. The main failure mode is related to losing the energy supply and recovery time of such connectivity.

1.3.5. WP6 – Quantifying Risks and Benefits

In WP6, the risks to Critical Infrastructure (CI) from the impact of extreme weather events and the benefits of providing resilient CI were assessed. The main focus of the assessment involved the application of the Risk-Based Decision Making Framework, developed in WP5, to two case studies. The two case studies are based on past events which differ in terms of geographic location, geographic scale and hazard source events. Case study 1 is centred on a 2003 event in the Friuli Venezia Giulia Region (FVG) of North Eastern Italy, Figure 21(a). Case study 2 focuses on a 2005 storm surge event in the Uusimaa region of Southern Finland, Figure 21(b). The emergency response to each event has been examined in the context of the emergency management framework of the two case study regions.



(a) Friuli Venezia Giulia Region (FVG), Italy (b) Uusimaa region, Finland

Figure 21 - Case Study Areas

In the early stages of the project the factors considered when analysing the economic, social and security consequences that arise due to the impact of extreme weather events on critical infrastructure networks, were identified. Various stakeholder events were held to help refine and develop the approaches in quantifying the risks of critical infrastructure failure and the subsequent benefits associated with providing resilient infrastructure. Equally, these events were used to gather local stakeholder inputs into the case study analysis carried out at the later stages in the project.

Both case studies are formulated around multi risk scenarios, Figure 22, consisting of two main components: a) multi-hazard and b) multi-vulnerability scenarios. Hazardous events not only impact the critical infrastructure but can also effect each another (i.e. a cascading hazard, such as heavy rainfall causing landslides). Damage to a single critical infrastructure has multiple consequences and the consequence associated with multiple failures is not simply the sum of the individual failures. The first case study assessed the economic, social and security benefits of providing resilient critical infrastructure for road, rail and electrical networks faced with landslide and flooding hazards. In the second case study the risk to Southern Finland land transport and electrical infrastructure from storm surge events is assessed.

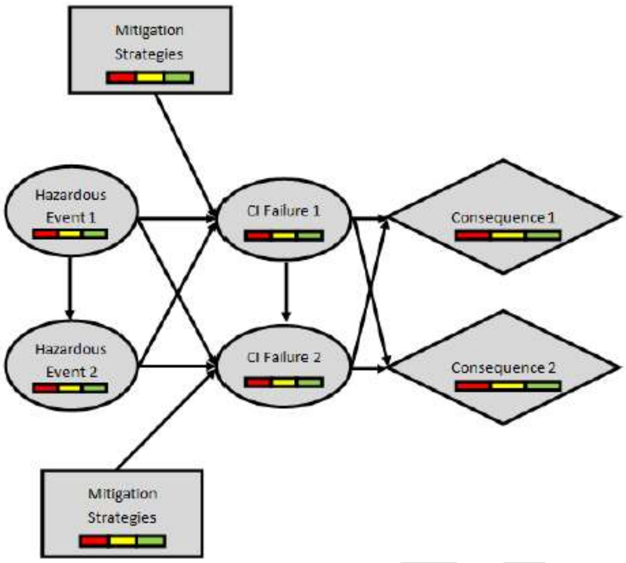
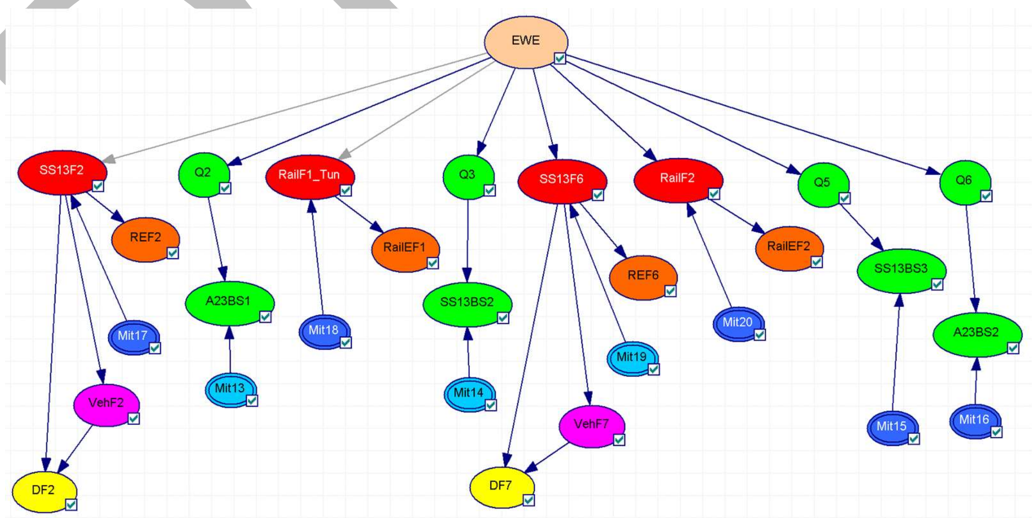
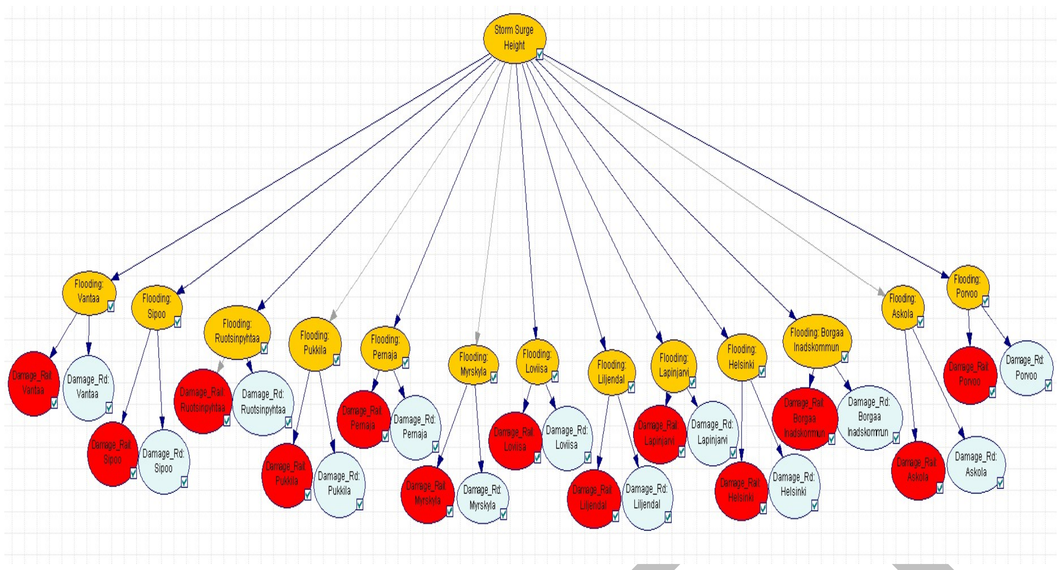


Figure 22 - Multi-mode Risk scenario

Bayesian Networks (BNs) were used to apply the Risk-Based Decision Making Framework to the case study areas. Figure 23 shows portion of the BN, which was used to analyse the risk posed by floodwater for the case study areas. The limited area of the North Eastern Italy case study area allowed for the multiple risks arising from extreme rainfall to be analysed at an individual infrastructure element (e.g. bridge level). The larger area of the second case study enabled the assessment of risk to land transport and electrical infrastructure networks, rather than individual elements, across Southern Finland. This can be seen in Figure 23 in which individual road segments are examined in case study 1 (SS13F2) while all roads within a municipality of Uusimaa are considered in case Study 2.



(a): Italian Case Study



(a): Finland Case Study

Figure 23 - Bayesian Network for Flooding Risk

Each node of the BNs contains information from expert opinion, stakeholder input, relevant literature and calculations carried out as part of the case study analysis. For instance in order to analyse the risk to an electricity line from high winds, fragility functions (provided by WP4) are used, Figure 24. For select critical infrastructure, a methodology to assess the risk of failure to a given hazard, using relevant characteristics of infrastructure, was developed.

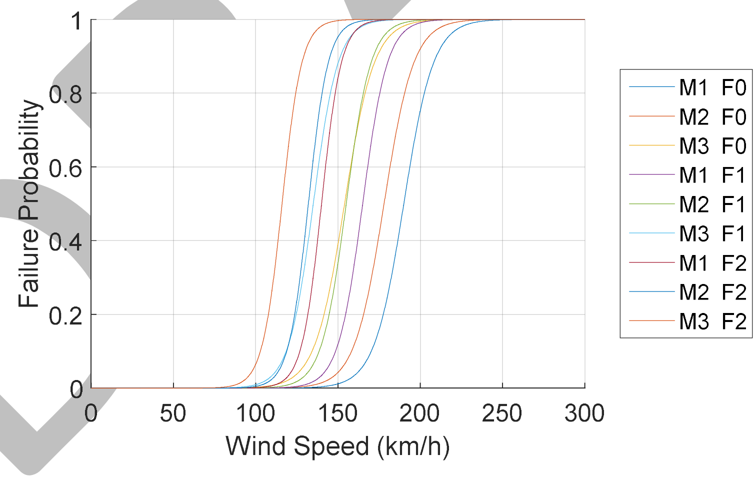


Figure 24 - Fragility functions for power line sections as a function of maintenance and forest status

In case study 1 in order to examine the benefits of critical infrastructure resilience, the effect of introducing mitigation measures is analysed. The optimal mitigation strategy, under an assumed budgetary constraint is found using the decision criterion developed in WP5. The optimal strategy, determined by a position measure of the average of the upper bound, lower bound and the expectation values (POS) reduces by a factor of 40 for the risk to the loss of life.

By bringing together the work from the other technical RAIN work packages in the application of the RAIN Risk-Based Decision Making Framework, an operational analysis framework that identifies critical infrastructure components impacted by extreme weather events and minimises the impact of these events on the EU infrastructure network is demonstrated.

1.3.6. WP7 – Mitigation Strategies

WP7 focused on the development of technical engineering solutions to increase the resilience of infrastructure to the effect of extreme climate events.

A comprehensive report on Analysis of Practical Remediation Strategies for discrete infrastructure systems is provided. This report focuses on the identification of engineering solutions, which increase the level of redundancy and prevent cascading effects. Solutions to mitigate the effects of extreme weather events identified in WP2 on the infrastructure elements identified in the project are considered. The report is divided into seven sections, each describing the specific impacts of severe weather hazards on different critical infrastructure which include; Tunnels and Bridges for road and rail networks, Road Pavements, Rail Tracks (including Switches and Crossings), Energy lines (cables, pylons & OH lines) and Dams which form parts of the Energy Infrastructure network and Slopes (both natural and manmade structures) which can be part of the transport (e.g. embankments) and energy (e.g. dams) networks.

Figure 25 - Examples of Remediation Strategies outlined in D7.1

Technical Impact Matrices (TIM) are developed as a method for assessing the advantages and disadvantages of various maintenance strategies for reducing the impact of extreme events on infrastructure systems. The assets examined include; Bridges for road and rail networks, Road Pavements, Cutting and embankment slopes (both natural and manmade), Rail Tracks (including Switches and Crossings), Tunnels, Electrical and Telecommunications Networks (energy lines, cables, pylons) and Dams which form parts of the Energy Infrastructure network and energy networks.

According to the European Commission Report Adapting Infrastructure to Climate Change (2013) the impact of weather stresses represents 30% to 50% of current road maintenance costs in Europe. Major failure of elements of infrastructure as a result of weather impacts is increasing; this is particularly the case for ageing rail networks. The report "Impacts of Europe's changing climate –

2008 indicator-based assessment" by the EEA and JCR, identifies the need to limit deterioration effects from adverse weather conditions (e.g. prolonged precipitation, heat stress, freeze-thaw cycle) and damaging consequences in case of extreme events (i.e. storms and floods) as a key factor influencing construction designs. WP7 has considered the effect of climate change on major infrastructure assets in the surface transport and energy domains. By first considering typical effects across a range of infrastructure, a set of likely hazards affecting elements of infrastructure were identified. Whilst some infrastructure elements, e.g. bridges and slopes are affected by multiple weather hazards, others such as tunnels and dams are primarily affected by one hazard.

Remediation measures which increase the resilience of elements were outlined. The methods can be broadly classified as (i) design and construction related (ii) retrofitted solutions and (iii) indirect methods. A methodology for scoring the technical impact of the available remediation measures is presented for a selection of critical infrastructural assets. The TIM ranking system was shown to be a robust method for recommending the optimum remediation methods while considering technical effectiveness, cost, human and financial loss and environmental impact and has the potential to be widely adopted a decision support tool for infrastructural management.

The TIM method developed allows asset managers to assess the impact of different maintenance strategies for reducing the impact of extreme weather events on infrastructure systems. This will facilitate decisions on how to invest limited funding to increase the safety and reliability of the network while considering such factors as; the available budget, political focus, technical, societal and environmental factors.

Defining the Problem

- Brainstorming among the group members must be organised into a goal statement

Choosing Influence Factors

- Goal Statement helps guide the selection of influence model factors. If there is more important factors the key ones must be identified and the rest grouped according to these.

Scoring the Impact Matrix

- The impact matrix contains numbers that represent the qualitative assessment of the strength of the impact that exists between the given factor and every other factor in the matrix. A scoring strategy 0-5 i.e. gives 0 value for no impact and 5 for strong impact. The ranking can also be descriptive (i.e. Catastrophic, Critical, Moderate , Marginal and Insignificant.)

Figure 26 - METHODOLOGY for Technical Impact Matrix

WP7 has developed a Pre-standardisation Document & Review of Crisis Coordination and Response Arrangements in the European Union which assesses the latest developments of the EU crisis coordination and decision-making arrangements and gives recommendations on how EU policies and infrastructure protection guidelines could be improved. It describes the full range of EU crisis management instruments that can be used to tackle internal and external crises. As such, it aims to develop holistic, all-hazards response strategies especially for large-scale and complex emergency situations caused by extreme weather conditions. As a pre-standardisation document, it provides information of policy instruments and decisions (case studies) at a national and international level. It also examines the functioning of the EU critical infrastructure protection and how it could be improved to provide a more robust European wide common infrastructure protection plan. In addition to that, the EU crisis coordination and the decision-making processes are analysed and simulations on how they would be implemented for a fictive land transport infrastructure interruption case caused by a sudden weather hazard in Finland are presented.

Finally, suggestions were made to improve the current mechanisms and their inter-connectivity using a worst-case scenario as a stimulus for future policy. These policy recommendations come from our active work throughout the EU and its Member States over the years as well as specific interaction with the other RAIN project work packages and feedback received from end users such as Fire and Rescue Services and Ministries´ (MOD, MOI, MOF) and the involvement of several RAIN project partners.

A recommendation summary is offered on techniques for mitigation of, adaptation to and coping with the potential impacts of extreme weather on infrastructure. This document serves as a summary of the infrastructure protection guidelines. Due to climate change, various mitigation and remediation strategies should be considered. The RAIN approach is to provide a framework to consider advantages and disadvantages for a range of possible approaches and give a decision maker a logical framework with which to choose an optimum solution. Guidelines to future management protection plans are also proposed. The report summarises the effects of climate hazards on European infrastructure and presents mitigation procedures, and adaptation and coping with potential impacts alleviate the impact on citizens.

A report on Early Warning Systems (EWS) is provided which discusses the operation and advantages/disadvantages of the EWS's which monitor the infrastructure conditions and can provide real-time information on the condition of assets and can give warning when indicators of potential failures reach pre-defined high-risk levels. For each infrastructure category the factors governing the choice of EWS, the available sensors and systems, and an example case study where and EWS has been implemented is discussed.

It was also shown that using modern technology and web-based applications it is also possible to monitor an entire asset network in real-time online. As extreme weather events are likely to affect more the one infrastructure type, and the failure of one asset may result in cascading effects on other assets, there is great potential to develop an interconnected system where the effects of the extreme weather event on each asset can be monitored in parallel on a single system. This system could have the capability of sending multiple early warnings to all of the crisis management stakeholders resulting in a more coordinated response.

1.3.7. WP8 – Dissemination & Exploitation

Dissemination, communication and exploitation represent central pillars of the RAIN project to guarantee outreach to technical and broad audiences thus supporting the spreading of the project achievement.

The objective of this WP was to promote the visibility of the project and disseminate its results amongst all types of stakeholders ranging from industry to system operators, policy makers and research institutes, as well as to raise awareness in the general public about the risks for infrastructures in response to extreme weather events.

The main scope has been to ensure the widespread dissemination of the knowledge and results generated by project to the relevant stakeholders inside and outside the consortium, including lessons learned from and exploitation to other modes. Highlights of this WP include the completion and maintenance of the RAIN website, the constant growth of the RAIN community (made up of stakeholder registered to the RAIN website and users linked on RAIN Social Media channels), the distribution of the RAIN newsletter and the RAIN brochures, the creation of a dialogue around RAIN topics via social media and journalistic articles, published on the website and distributed on the main news multipliers, the broadcast of the project Video News Release, the organisation of 2 workshops and a final event.

In particular, the VNR was produced for the purpose of broad public dissemination of the project's achievements. The video has been distributed to world TV stations: the pan European TV station Euronews published and broadcasted it, with an estimated audience of several million people and it was also launched on the EBU /Eurovision Worldfeeds in HD quality on 15th March 2016.

The editorial production has been rich: 15 articles and more than 20 press releases have been release on the website and then distributed to relevant scientific multiplayers. The articles outreach registered a wide audience: take-ups from multipliers and news aggregators generated more than 40.500 visits, while the project's news on social media have reached 437.730 people. The RAIN consortium have been extremely proactive in disseminating the results of the project via for example publications in International peer reviewed journals as well as at National/International conferences. Details are provided in the WP8 Deliverables.

Regarding the exploitation of project's results, a high-level business plan and exploitation strategy was developed (Deliverable 8.9) including projections for costs and revenues on a five years horizon using different scenarios. The strategy, which focuses on exploitation of the RAIN risk based decision making framework foresees inputs from all of the RAIN partners, Figure 27, according to their areas of expertise, in providing an important service to those stakeholders tasked with considering/mitigating the impacts of extreme weather events on critical infrastructures/infrastructure networks.

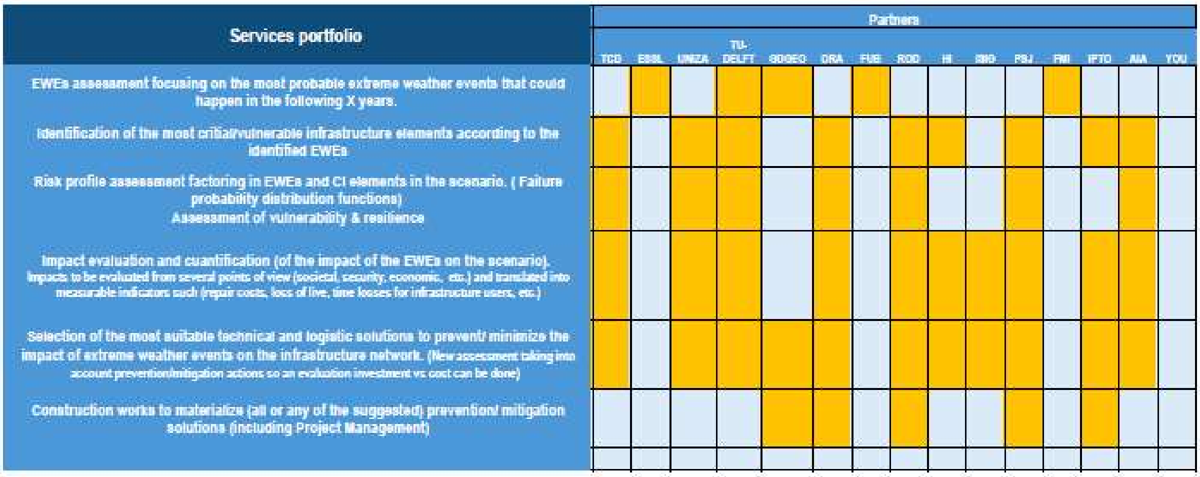


Figure 27 – RAIN Exploitation Strategy Services Portfolio

1.4 Potential impact and main dissemination activities and exploitation results

The potential impact and details of proposed exploitation and exploitable results associated with the project has been broken down into the various technical work packages, as follows:

1.4.1. WP2 - Hazard Identification

The survey conducted with CI operators and weather services increased the understanding on the needs of CI operators and managers, their preparedness, vulnerability of the system and the actions taken in order to reduce the risk. In addition, possible gaps in the warning system were identified and recommendations were given to improve the warnings for particular hazards, which help the improvement of the system.

The defined impact thresholds for winter phenomena with implication for CI and the results on the occurrence of hazardous winter phenomena and forest fire and changes on their probability and severity by 2100 provides valuable input for the risk based decision making framework that allows recommendations for adaptation strategies. The produced gridded datasets of probability are available for the end users, serving the CI operators, stakeholders and policy makers in the development of strategies in order to minimize the risk of damage of extreme winter events and forest fires on CI. The developed strategies allow savings in costs of repairs by reinforced preparedness and awareness and assure increase in safety.

The procedure developed within RAIN to estimate likelihoods of storms in a combined spatial-temporal manner forms the basis for a storm information system that is currently being installed at the Bundesamt für Seeschifffahrt und Hydrographie (BSH) by Freie Universität Berlin.

As a result of WP2, river and coastal flood maps with given probability of occurrence under present and future climate have been produced and placed in a public repository. Furthermore datasets on river discharges, storm surge heights, extreme water levels and sea level rise have also been included. The results can be used by the scientific community, practitioners and the public in general to investigate present and future levels of hazard at a European scale. The results of this study are already being used in a Horizon 2020 project, "BRIGAID", as a source of loading conditions that will be used in testing innovations dealing with disaster risk reduction. Also, use of the data for RAIN case studies shows that they fit into the risk-based decision-making framework, and it is a template for applications elsewhere.

The modelling work on the expected thunderstorm-related hazards is the first of its kind that addresses Europe. For the first time, the trends of phenomena such as large hail, tornadoes, severe gusts and lightning could be mapped. The results that show increases over Central Europe for these events, are important information not only for managers of CI, but also for other authorities and the insurance sector. Within a subsequent project ARCS financed by the Germany ministry of Education and Research, ESSL is refining the techniques applied in RAIN and correlate them with data of vulnerability and exposure. These techniques can be applied not only to climate models but also to operational weather forecast models. This is presently being done by ESSL within an assignment from the German Weather Service DWD. It is expected that they can help to improve the forecasting of these hazards on the time scale of 1 to 10 days ahead.

1.4.2. WP3 - Land Transport Vulnerability

UNIZA organized two experts and end user workshop focused on critical infrastructure protection:

1) August 2015, Zilina, Slovakia. The workshop programme included presentation of the RAIN project, results achieved within the WP3 and the whole project, discussion and recommendations to WP3 tasks and their results. The representative of the Ministry of Transport and Construction of the Slovak Republic presented actual issues of critical transport infrastructure identification and protection in Slovakia and relevant experiences from abroad. The options of cooperation in critical infrastructure identification were also discussed.

2) January 2017, Zilina, Slovakia. The workshop programme included the presentation of the RAIN project results related to the societal vulnerability assessment. Discussion about the application of these outputs in real practice was conducted. The actual situation concerning protection of critical infrastructure in the transportation sector as well as a practical view of the Critical Infrastructure importance from the position of the local administration was also discussed. The process of applying the “Methodology for measuring societal vulnerability due to failure of critical land transport infrastructure elements” in the town of RAJEC has started and the first results are prepared. The first negotiation, concerning the exploitation of the WP3 results in security management of the land transport infrastructure with the representatives of the Ministry of Transport and Construction of the Slovak Republic, has also been was conducted. Discussions have concerned effective ways of protecting line and point objects of land transport infrastructure, applying risk based decision making methods to identify potential critical infrastructure elements, quantifying their vulnerability, as well as elaboration of the methodology for assessing societal vulnerability of society as a result of transport infrastructure disruption or destruction.

RAIN was presented at the Civil Protection workshop held in Bratislava, Slovakia on 13 and 14 July 2016. This workshop was organized in the framework of the Slovak Presidency of the Council of the European Union. The workshop brought together leading stakeholders from governments, public and private enterprises involved in Civil Protection and Critical Infrastructure Protection.

The work performed and results of the RAIN project, in WP3, resulted in coming to the fore of the Faculty of Security Engineering, University of Zilina in the field of the critical infrastructure protection e.g. via:

- Active participation of researchers in the creation of national legal framework related to critical infrastructure protection in the sectors of Transport and Energy.
- Participation of researchers in detailed risk assessment of the sectors Transport and Energy elaborated for conditions of the Slovak Republic.
- Development of new study programme Security and Protection of Critical Infrastructure, including courses in relation to RAIN project, assigning final works for the 1st and 2nd degree of university education.
- Invitation of researchers for a meeting of experts EU-US-CAN in the field of critical infrastructure protection organized in the framework of the Slovak Presidency of the Council of the European Union 27/9/2016-28/9/2016.
- Initiating further research activities at national and international level.
- Invitation of researchers for NATO an exercise organized by the NATO Energy Security Centre of Excellence in Vilnius, Lithuania 16/5/2016-20/5/2016.

Hellenberg International organised 2 end user meetings:

1) October 2014 at the South-Savo Rescue Services Agency in Mikkeli Finland. The meeting aimed to introduce the RAIN project and to prepare cooperation for data collection of the Asta strom 2010. The interaction has helped the end users and stakeholders (South-Savo Region) to understand the mechanisms related to CIP and all hazards approach in crisis response and as such contributed also to build up the coherent situational awareness in those regions hit by Asta storm (2010).

2) January 2015 at the Helsinki City Rescue Department in Helsinki Finland. The meeting aimed to collect data about the winter storms Tapani and Hannu in 2011. The interaction has helped the end users and stakeholders (Uusimaa and capital region) to understand the mechanisms related to CIP and all hazards approach in crisis response and as such contributed also to build up the coherent situational awareness in those regions hit by winter storms (2011).

The 'ORT-application for vulnerability and resilience' developed within the RAIN project gives local and regional governments and infrastructure owners and operators the possibility to assess their own situation, analyse the present situation and preparation for several types of extreme weather events and decide on possibilities for improvements for the short and long term. Based on the proof of concept developed it is shown that, with the use of a dedicated set of criteria, within a short timeframe, a common analysis can be made. Sharing the outcome of such analysis between stakeholders a common understanding is reached as to where to invest to make the necessary improvements in terms of preparation.

1.4.3. WP4 - Energy & Telecommunications System Vulnerability

The work carried out in WP4 was oriented to fulfil the needs of WP5 with respect to Electrical and Telecommunications infrastructures against each of the most relevant meteorological threats studied, gathering information about their vulnerabilities and protection means. The potential impact for the research community or innovation department of infrastructure managers resides on taking these studies to continue them in particular directions, for instance:

1. Extending the methodology to some other threats not considered here, like earthquakes

2. Adapting the results to other environments / availability of resources (for instance in emerging countries)

3. Design maintenance programs according to the stress (historical and forecasted network usage) of each network component computing the each component failure probability given certain context.

Moreover, in a broader perspective, the studies carried out in this WP serve as a basis for the development of computational tools, for example the construction of the risk based decision support webtool.

The main dissemination channel for this WP is through the demonstrable features of the webtool that take advantage of the conclusions of WP4. For this scope, it is available freely online via the project website. The release of the source code and the sample database also represent a means of dissemination. The availability of such resources is communicated on the RAIN webpage and AIA's corporate website, plus social media sites (LinkedIn for instance) and promotional / demo videos on Youtube.

The intention of these dissemination activities is to attract the attention of potential users that could ask for details, customization or software developments to adapt the core modules to some specific business application, as in the insurance evaluation of risk on infrastructure assets. The exploitation of WP4 therefore is considered mainly through the exploitation of the tool.

1.4.4. WP5 - Risk Based Decision Making Framework

This WP has developed a neo-Bernoullian decision theory, to replace expected utility maximization, in managing infrastructural networks under exposure to extreme weather hazards. Expected value maximization leaves out relevant decision theoretical information on worst and best cases. In WP5 we have shown that the mean of the lower bound, expected value, and upper bound needs to be maximized, rather than the expected value. This may increase the investment willingness into safety barriers up to ten-fold.

Furthermore, a smart algorithm to deal with exponentially increasing computation times in large infrastructural networks with the presence of cascading effects has been developed in this WP. The so-called Probability Sort algorithm is an exploitable deliverable in order to estimate Markov Chains in modelling cascading effects in networks, for what otherwise would have been intractable (in)homogeneous transition matrices. The open source code of the algorithmic library is available on the Mathworks exchange platform.

The source code of the risk based decision making webtool developed in this WP has been released as open source licence (https://github.com/grupoaia/rain-fp7) which is, by itself, a dissemination channel to present the project concept. Moreover, it will be publicly available to potential users and researchers who can try it by running simulations. The concept and technology can be applied to broader fields where it can find commercial applications (for instance, insurance companies). Since the software requires some level of customization for commercial exploitation, the most feasible exploitation channel is through the provision of consulting services by members of the project consortium, as per the project exploitation strategy (D8.9).

1.4.5. WP6 - Quantifying Risks and Benefits

WP6 has demonstrated the application of methods and tools developed in RAIN to analyse critical infrastructure risk; illustrate the benefits of critical infrastructure protection and assist stakeholders in choosing optimal strategies to minimise consequences. The demonstration of such methodologies has the potential to assist decision makers regarding the protection of existing infrastructure and the future-proofing of newly planned infrastructure from the impacts of extreme weather events and hazards. Such methodologies assist in the development of resilient infrastructure.

Using work shop sessions to demonstrate to stakeholders, first hand, the development of Bayesian Networks in the application of the Risk-Based Decision Making Framework to analyse Critical Infrastructure risk due extreme weather events has proved both an effective method of creating understanding as well as an avenue for improving the models applied and the information therein.

1.4.6. WP7 - Mitigation Strategies

Deliverable 7.3 will serve as a pre-standardisation document and provides information of policy instruments and decisions (case studies) that could be implemented for CI protection at a national and international level. It also examines the functioning of the EU critical infrastructure protection and how it could be improved to provide a more robust European wide common infrastructure protection plan.

A series of mitigation measures to protect CI from climate hazards were identified and a ranked in terms of their efficacy. This information and the framework on which it is based can be used by infrastructure managers and operators to increase network resilience.

1.4.7. WP8 - Dissemination & Exploitation

WP8 carried out various successful dissemination activities, which provided a wide outreach for RAIN achievements.

The articles outreach registered a wide audience: take-ups from multipliers and news aggregators generated more than 40.500 visits, while the project's news on social media have reached 437.730 people. The RAIN consortium have been extremely proactive in disseminating the results of the project via for example publications in International peer reviewed journals as well as at National/International conferences (>35 publications), Table 2.

The video news release has been distributed to world TV stations: the pan European TV station Euronews published and broadcasted it, with an estimated audience of several million people and it was also launched on the EBU /Eurovision Worldfeeds in HD quality.

The RAIN community is composed by the stakeholders registered on the website (220) and the users following the RAIN Social Media channels: 117 users on Twitter and 45 members on the LinkedIn group. During the project, the website registered more than 13.000 sessions from 9.700 unique users.

The consortium was involved in the organisation and promotion of two workshops (both have been attended by more than 100 experts and have generated a fruitful discussion among experts) and in the RAIN final event, a successful conference held by Trinity College University with the participation of more than 60 stakeholders and experts.

All the presentations made by partners during events, fairs and conferences, as well as scientific publications are available to be downloaded on the project website.

Avenues for exploitation of project's results, have been detailed in a high level exploitation strategy, which is detailed in Deliverable 8.9. The strategy, focuses on exploitation of the various strands of the RAIN risk based decision making framework, with inputs from all of the RAIN partners according to their areas of expertise, Figure 27. The exploitable results represent an important service to those stakeholders tasked with considering/mitigating the impacts of extreme weather events on critical infrastructures/infrastructure networks.

Table 2 - List of publications by RAIN partners

Partner	Title	Full Reference	Link
TCD	Statistical Tools to Help the Decision Making Process within the Risk Analysis of Transportation Networks in Response to Extreme Weather Events	Nogal, M., O'Connor, A., Martinez-Pastor, B., and Caulfield, B., (2015), *International Forum on Engineering Decision Making – IFED 2015*, Japan, May 2015.	
TCD	A Dynamic Restricted Equilibrium Model to Statistically Determine the Resilience of a Traffic Network to Extreme Weather Events	Nogal, M., Martinez-Pastor, B., O'Connor, A. and Caulfield, B., (2015), *International Conference on Application of Statistics and Probability in Civil Engineering – ICASP 2015*, Vancouver.	http://hdl.handle.net/2429/53191
TCD	Evaluation of Resilience in Traffic Networks: Models and Characteristics	Martinez-Pastor, B., Nogal, M., O'Connor, A. and Caulfield, B., (2015), *ITRN 2015*, Galway, Ireland.	http://www.itrn.ie/uploads/MartinezPastor.pdf
TCD	Resilience of traffic networks: From perturbation to recovery via a dynamic restricted equilibrium model.	Nogal, M.; O'Connor, A.; Caulfield, B. and Martinez-Pastor, B. Reliability Engineering & System Safety, 156, pp.84-96 (2016).	http://www.sciencedirect.com/science/article/pii/S0951832016302915
TCD	Novel Probabilistic Resilience Assessment Framework of Transportation Networks against Extreme Weather Events	Nogal, M., O'Connor, A., Martinez-Pastor, B. and Caulfield, B., 2017. ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering, p.04017003	http://ascelibrary.org/doi/abs/10.1061/AJRUA6.0000908
TCD	Weather and Rail Delays: Analysis of Metropolitan Rail in Dublin	Brazil, W.; Nogal, M.; White, A.; Caulfield, B.; O'Connor, A. and Morton C. Journal of Transport Geography, vol. 59 pp. 69-76 (2017)	http://www.sciencedirect.com/science/article/pii/S0966692316304409
TCD	The role of transport information in extreme weather events: A scenario based experiment	Brazil, W.; Caulfield, B. and O'Connor, A. Transport Policy (2017)	http://www.sciencedirect.com/science/article/pii/S2213624X17300330
TCD	A multidisciplinary approach for risk analysis of infrastructure networks in response to extreme weather	Nogal, M., O'Connor, A., Caulfield, B., and Brazil, W. Transportation Research Procedia 14 (2016): 78-85 (2016)	http://www.sciencedirect.com/science/article/pii/S2352146516300436
TCD	Understanding the vulnerability of traffic networks by means of structured expert judgment elicitation.	Nogal, M.; Morales-Napoles O. and O'Connor, A. Proceedings of the Irish Transport Research Network Sept. 2016, Dublin (Ireland).	http://rain-project.eu/wp-content/uploads/2017/04/01-ITRN-2016-Nogal-et-al.pdf
TCD	Understanding the vulnerability of traffic networks by means of structured expert judgment elicitation.	Nogal, M.; Morales-Napoles O. and O'Connor, A. European Journal of Operational Research. Submitted	
TCD	Bi-phase methodology for sensitivity analysis of complex models, applied to the model of evaluating resilience in transport networks.	Martinez-Pastor, B.; Nogal, M. and O'Connor, A. Proceedings of the Civil Engineering Research in Ireland conference Aug. 2016, Galway (Ireland)	http://rain-project.eu/wp-content/uploads/2017/04/02-CER2016-Martinez-et-al.pdf
TCD	Assessment of the impacts of extreme weather events upon the pan-European infrastructure to the optimal mitigation of the consequences	Nogal M., O'Connor A., Groenemeijer P, Luskova M, Halat M, O'Brien E, Van Gelder P. and Gavin K. Proceedings of the 7th European Transport Research Conference TRA2018, Apr. 2018, Vienna (Austria) . Submitted	
TCD	A sensitivity analysis of a dynamic restricted equilibrium model to evaluate the traffic network resilience	Martinez-Pastor, B.; Nogal, M.; O'Connor, A. and Caulfield, B. TRB, no. 16-3456. Jan. 2016, Washington D.C. (USA).	http://www.tara.tcd.ie/handle/2262/76244
TCD	Extreme weather hazard effects in railway lines.	Grande Z.; Castillo, E.; Nogal, M. and O'Connor, A. Transportation Research Part D:	

		Transport and Environment (Submitted).	
ESSL	An additive regression convective hazard model for detecting trends in severe weather events	Rädler, A.T., P. Groenemeijer, E. Faust and R. Sausen, 2017: Journal of Applied Meteorology and Climatology, (Submitted).	
ESSL	Severe Convective Storms in Europe: Ten Years of Research and Education at the European Severe Storms Laboratory	Pieter Groenemeijer, Tomáš Púčik, Alois M. Holzer, Bogdan Antonescu, Kathrin Riemann-Campe, David M. Schultz, Thilo Kühne, Bernold Feuerstein, Harold E. Brooks, Charles A. Doswell III, Hans-Joachim Koppert and Robert Sausen, 2017: Bulletin of the American Meteorological Society, (Submitted).	http://journals.ametsoc.org/doi/pdf/10.1175/BAMS-D-16-0067.1
ESSL	Future changes in European severe convection environments in a regional climate model ensemble	Tomáš Púčik, Pieter Groenemeijer, Anja T. Rädler, Lars Tijssen, Grigory Nikulin, Andreas F. Prein, Erik van Meijgaard, Rowan Fealy, Claas Teichmann and Daniela Jacob: Journal of Climate, (Submitted).	
ZU	Quantification of impacts on the transport serviceability at the loss of functionality of significant road infrastructure objects	Bohus Leitner, Maria Luskova, Alan O'Connor and Pieter van Gelder, Communications : Scientific letters of the University of Žilina. - ISSN 1335-4205. - Vol. 17, no. 1 (2015), s. 52-60.	http://www.uniza.sk/komunikacie/menu/komunik.asp?id=4&rok=2015&cislo=1&p=o
ZU	Use of network analysis in conditions of critical infrastructure risk management	Eva Sventekova and Maria Luskova and Zdenek Dvorak. In: WMSCI 2016 : the 20th world multi-conference on systemics, cybernetics and informatics : July 5-8, 2016 - Orlando, Florida, USA : proceedings. Vol. II. - [S.l.]: International Institute of Informatics and Systemics, 2016. - ISBN 978-1-941763-43-8. - p. 247-250.	http://www.iiis.org/CDs2016/CD2016Summer/papers/RA678PM.pdf
ZU	Multilevel approach to measuring vulnerability due to failure of critical land transport infrastructure	Maria Luskova, Michal Titko, Bohuš Leitner. In: WMSCI 2016 : the 20th world multi-conference on systemics, cybernetics and informatics : July 5-8, 2016 - Orlando, Florida, USA : proceedings. Vol. II. - [S.l.]: International Institute of Informatics and Systemics, 2016. - ISBN 978-1-941763-43-8. - p. 224	http://www.iiis.org/CDs2016/CD2016Summer/papers/RA560NZ.pdf
ZU	Assessment of risks related to the states of crisis with influence on the funcionality of critical infrastructure	M. Titko, M. Luskova. In: Transport means 2016 : proceedings of the 20th international scientific conference : October 5-7, 2016 Juodkrante, Lithuania. - ISSN 1822-296X. - Kaunas: Kaunas University of Technology, 2016. - p. 207-212.	https://www.sgemworld.at/ssgemlib/spip.php?article2386
ZU	Analysis o risks associated with transport infrastructure elements failure due to extreme weather events	M. Titko, M. Luskova. In: Transport means 2016 : proceedings of the 20th international scientific conference : October 5-7, 2016 Juodkrante, Lithuania. - ISSN 1822-296X. - Kaunas: Kaunas University of Technology, 2016. - p. 207-212.	
ZU	International emergency pool funds and their usage in disasters solving	Jan Havko, Maria Luskova, Michal Titko. In: SGEM 2016 : international multidisciplinary scientific conferences on Social sciences & arts : conference proceedings : Book 2 Political sciences, law, finance, economics & tourism : 24-30 August, 2016 Albena, Bulgaria. Vol. III: Finance. Economics and tourism. - ISSN 2367-5659. - Sofia: STEF92 Technology, 2016. - ISBN 978-619-7105-74-2. - p. 369-376.	https://sgemworld.at/ssgemlib/spip.php?article2699
ZU	Transport critical infrastructure in Slovak Republic	Eva Sventekova, Zdenek Dvorak, Bohus Leitner . IMCIC 2017: the 8th international multi-conference on complexity, informatics and cybernetics: March 21-24, 2017 - Orlando, Florida, USA: proceedings: International Institute of Informatics and Systemics, 2017	
TU Delft	A Bayesian Network for extreme river discharges in Europe.	Paprotny, D., Morales Nápoles, O. (2015) In: Podofillini, L., Sudret, B., Stojadinović, B., Zio, E. and Kröger, W. (Eds.) Safety and Reliability of Complex Engineered Systems, CRC Press/Balkema, 4303-4311, doi: 10.1201/b19094-564	http://www.crcnetbase.com/doi/abs/10.1201/b19094-564
TU Delft	Extreme sea levels under present and future climate: a pan-European database.	Paprotny D., Morales-Nápoles O. & Nikulin G. (2016) Extreme sea levels under present and future climate: a pan-European database. E3S Web of Conferences, 7, 02001,	https://doi.org/10.1051/e3sconf/20160702001
TU Delft	Efficient pan-European river flood hazard modelling through a combination of statistical and physical models.	Paprotny D., Morales-Nápoles O. & Jonkman S. N. (2017) Efficient pan-European river flood hazard modelling through a combination of statistical and physical models. Natural Hazards Earth System Sciences, in review, doi:10.5194/nhess-2017-4,	http://www.nat-hazards-earth-syst-sci-discuss.net/nhess-2017-4/
TU Delft	Estimating extreme river discharges in Europe through a Bayesian Network, Hydrology and	Paprotny, D. and Morales Nápoles, O. (2016) Estimating extreme river discharges in Europe through a Bayesian Network, Hydrology and Earth System Sciences Discussions, in	http://www.hydrol-earth-syst-sci-discuss.net/hess-2016-250/

	Earth System Sciences Discussions	review, doi:10.5194/hess-2016-250,	
TU Delft	Bayesian decision theory: A simple toy problem	H. R. N. van Erp, R. O. Linger, and P. H. A. J. M. van Gelder. AIP Conference Proceedings 1757 (http://doi.org/10.1063/1.4959057), 2016.	http://aip.scitation.org/doi/abs/10.1063/1.4959058
TU Delft	An outline of the Bayesian decision theory	H. R. N. van Erp, R. O. Linger, and P. H. A. J. M. van Gelder. AIP Conference Proceedings 1757 (http://doi.org/10.1063/1.4959057), 2016.	http://aip.scitation.org/doi/abs/10.1063/1.4959057
FUB	Atmospheric conditions inducing extreme precipitation over the eastern and western Mediterranean,	U. Dayan, K. Nissen and U. Ulbrich Nat. Hazards Earth Syst. Sci., 15, 2525–2544, 2015,	www.nat-hazards-earth-syst-sci.net/15/2525/2015/
FUB	Increasing frequencies and changing characteristics of heavy precipitation events threatening infrastructure in Europe under climate change	K. M. Nissen and U. Ulbrich Nat. Hazards Earth Syst. Sci. Discuss., doi:10.5194/nhess-2016-337, 2016,	www.nat-hazards-earth-syst-sci-discuss.net/nhess-2016-337/nhess-2016-337.pdf
ROD	Probabilistic Analysis of Potential Impact of Extreme Weather Events on Infrastructures	O'Connor, A.J., OBrien, E.J., Hajializadeh, D.(2016), ' Probabilistic Analysis of Potential Impact of Extreme Weather Events on Infrastructures', Civil Engineering Research in Ireland 2014, QUB, Belfast, Ireland	http://hdl.handle.net/10197/7015
ROD	Quantifying the Impact of Critical Infrastructure Failure due to Extreme Weather Events	O'Brien, E. J., Hajializadeh, D., & Power, R. T. (2015). 'Quantifying the impact of critical infrastructure failure due to extreme weather events' 12th International Conference on Applications of Statistics and Probability in Civil Engineering, ICASP12 Vancouver, Canada	http://researchrepository.ucd.ie/handle/10197/7024
ROD	Quantification of Multi Risk Scenarios Subjected to Extreme Weather Events	Hajializadeh, D., Carey, C.H., OBrien, E.J. (2016), ' Quantification of Multi Risk Scenarios Subjected to Extreme Weather Events', Civil Engineering Research in Ireland 2016, NUIG, Galway, Ireland	https://ceri2016.exordo.com/files/papers/15/final_draft/015.pdf
FMI	A method to estimate freezing rain climatology from ERA-Interim reanalysis over Europe	Kämäräinen M, Hyvärinen O, Jylhä K, Vajda A, Neiglick S, Nuottokari J, Gregow H (2017): A method to estimate freezing rain climatology from ERA-Interim reanalysis over Europe, Nat. Hazards Earth Syst. Sci., 17, 243-259, doi:10.5194/nhess-17-243-2017	http://www.nat-hazards-earth-syst-sci.net/17/243/2017/

1.5 The address of the project public website and relevant contact details

http://www.rain-project.eu/

Partner no.	Main Contact	Organization	Role	Email Address
1	Prof. Alan O'Connor	Trinity College Dublin (TCD)	Coordinator, Participant in WP 3, 5, 6, 7, 8	alan.oconnor@tcd.ie
2	Dr. Pieter Groenemeijer	European Severe Storms Laboratory e.V. (ESSL)	Leader of WP2, Participant in WP 1, 2, 3, 8	Pieter.groenemeijer@essl.org
3	Dr. Maria Luskova	Zilinska Univerzita V Ziline	WP3 leader, participant in WP 1,4,5,6,7,8	maria.luskova@fbi.uniza.sk
4	Prof. Pieter van Gelder	TU Delft (TUD)	WP5 coordinator	p.h.a.j.m.vangelder@tudelft.nl
5	Prof. Ken Gavin	Gavin and Doherty Geosolutions	WP7 Leader, WP 2 Participant	kgavin@gdgeo.com
6	Mr. Carlos Bárcena	Dragados	WP3, 6, 7 & 8 Participant	cbarcenam@dragados.com
7	Prof. Uwe Ulbrich	Freie Universität Berlin (FUB)	Participant in WP 2 and 8	ulbrich@met.fu-berlin.de
8	Prof. Eugene O'Brien	Roughan & O'Donovan (ROD)	Participant in WP 1, 5, 7 and 8. Coordinator of WP6.	Eugene.obrien@rod.ie
9	Dr. Timo Hellenberg	Hellenberg International OY	WP2, 3, 6, 7 & 8 Participant	office@hellenberg.org
10	Ms. Chiara Bianchizza	Istituto di Sociologia Internazionale di Gorizia I.S.I.G	WP3, 5, 6, 7 & 8 Participant	bianchizza@isig.it
11	Mr. Peter Prak	PSJ	WP2, 3, 5, 6 & 8 Participant	peter.prak@PSJADVIES.NL
12	Dr. Andrea Vajda	Ilmatieteen Laitos	PI from FMI, participant in WP2, 8	andrea.vajda@fmi.fi
13	Alice De Ferrari	Youris.com	WP8 leader	youris@youris.com
14	Dr Dimitrios Bechrakis	Independent Power Transmission Operator (IPTO or ADMIE)	Participant in WP 4, 5, 6, 7 and 8	dmpexrak@admie.gr
15	Dr. Milenko Halat	Aplicaciones en Informática Avanzada (SPAIN)	WP4 coordinator	halatm@aia.es

