INFRARISK Report Summary
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Final Report Summary - INFRARISK (Novel Indicators for identifying critical INFRAstructure at RISK from natural hazards)

Executive Summary:
Over the past number of decades, extreme natural hazard events have resulted in widespread destruction, including fatalities and infrastructure damage, to regions in Europe and worldwide. The complex interdependencies of infrastructure networks and the associated hazards have been highlighted through multi- and cascading hazard effects, resulting in significant consequences in terms of infrastructure damage, mobility disruption and economic losses.

The objective of the INFRARISK project was to develop reliable stress tests for critical European road and rail infrastructure due to extreme natural hazard events. To do so, a framework has been proposed, which can be used to perform stress tests for distributed road and rail networks. The ultimate goal of the project was to provide methodologies and tools that can be employed to aid decision-making regarding the protection of existing road and rail infrastructure and the development of new infrastructure.

The proposed stress test framework can be employed to evaluate the potential losses associated with the occurrence of low probability, high consequence hazard scenarios in terms of the consequences to road and rail transport infrastructure. The implementation of this framework is supported through the development of an overarching methodology to ensure acceptable levels of infrastructure related risks due to natural hazard events.

Novel methods have been proposed to analyse extreme, low probability hazard scenarios, which include earthquakes and floods, as well as cascading hazard scenarios, such as earthquake-triggered landslides. To quantify the associated consequences for road and rail transport networks, novel methodologies have been proposed for developing and assigning fragility functions to network elements to characterise the exceedance probability of specified damage states as a function of the hazard intensity. Additionally, agent-based modelling approaches have been specified to determine the associated transport disruption for distributed networks.

The INFRARISK approach robustly models the spatio-temporal processes associated with hazard identification and consequence analysis, and propagates the associated uncertainties within the methodology. The overarching methodology supports the analysis of multi-hazard stress tests for distributed transport networks to quantify the associated losses, which has been demonstrated for two European case studies. An online INFRARISK Decision Support Tool (IDST) has also been developed, which supports the stress test framework. Additionally, an online database has been developed, which allows users to upload and perform queries on data relating to historical failures of critical transport infrastructure.

The overall objective of the INFRARISK project is to provide the next generation of European infrastructure managers and owners with the necessary methodologies and support tools to analyse the potential impacts of extreme natural hazard events and to aid in the decision-making process regarding the protection of critical infrastructure. To this aim, significant dissemination activities have been conducted during the project, which have included videos, educational materials, policy briefs, fact sheets, a dedicated sample training course for infrastructure owners and a final dissemination conference, which was broadcasted on television and is also available online.

Project Context and Objectives:
Extreme natural hazard events have the potential to cause devastating impacts to transport infrastructure, resulting in
significant disruption for road and rail passengers, and associated economic losses. In Europe, an increasing number of extreme natural hazard events have occurred in recent decades due to a combination of climate change effects, and changes in physical and social systems. For the period between 1998 and 2009, almost 100,000 fatalities occurred due to natural hazards and more than 11 million people were affected, resulting in losses of approximately €200 billion. These natural hazards have included earthquakes, floods, and landslides. For example, the 2009 earthquake that occurred in the L'Aquila region of Italy resulted in approximately €2 billion in losses. Additionally, flooding that occurred in the Elbe Basin in 2002 in Italy resulted in approximately €20 billion in losses and landslides that occurred in the town of Sarno, Italy, in 1998 claimed 160 lives.

Given the potential impact of natural hazards, it is necessary to quantify the effects of natural hazards on European infrastructure, particularly critical infrastructure. Reliable transport infrastructure is particularly valuable to society as it facilities the effective transportation of people and goods. The European Union (EU) has over 4.5 million km of paved roads and 212,500 km of rail lines, and the European single market is highly dependent on reliable road and rail infrastructure for the mobility of people and for the distribution of goods. For example, approximately 49.4% of distributed goods in the EU are transported via road and 72.3% of EU passengers travel on roads. Overall, road transport generates approximately 2% of Europe’s GDP and has generated approximately 5 million jobs. Rail transport in the EU is equally important, which supports approximately 11.7% of all distributed goods and 6.6% of passengers in the EU. Furthermore, transport infrastructure plays a vital role in terms of the resilience of societies to natural hazards, facilitating the transportation of emergency goods and services as part of disaster management activities immediately following natural hazard events, and enabling societies to ‘bounce back’ following such events by avoiding the disruption of daily activities and preventing economic losses.

The INFRARISK project, ‘Novel indicators for critical INFRAstructure at RISK from natural hazards’, was funded according to the EU’s 7th framework programme under the call topic ENV.2013.6.4-4 ‘Towards stress tests for critical infrastructure against natural hazards’. The project commenced in October 2013 and reached completion in September 2016. The project consortium consisted of 11 partners from across Europe and was coordinated by Roughan & O’Donovan Ltd., a Civil / Structural Engineering Consultancy based in Ireland. The INFRARISK consortium consisted of five small and medium-sized enterprises (SMEs), five research institutes or universities and one large enterprise, and comprised structural engineers, geotechnical engineers, infrastructure contractors, flooding experts, seismologists, security experts, social scientists, computer scientists and experts in database development.

The objective of the INFRARISK project was to develop reliable stress tests for critical European road and rail infrastructure due to extreme natural hazard events. To do so, a framework has been proposed, which can be used to perform stress tests for distributed road and rail networks. The proposed stress test framework can be employed to evaluate the potential losses associated with the occurrence of low probability, high consequence hazard scenarios in terms of the consequences to road and rail transport infrastructure. The implementation of this framework is supported through the development of an overarching methodology to ensure acceptable levels of infrastructure related risks due to natural hazard events. The ultimate goal of the project was to provide methodologies and tools that can be employed to aid decision-making regarding the protection of existing road and rail infrastructure, and the development of new infrastructure. The INFRARISK approach robustly models the spatio-temporal processes associated with hazard identification and consequence analysis, and propagates the associated uncertainties within the methodology. The overarching methodology supports the analysis of multi-hazard stress tests for distributed transport networks to quantify the associated losses, which has been demonstrated for two European case studies. An online INFRARISK Decision Support Tool (IDST) has also been developed, which supports the stress test framework. Additionally, an online database has been developed, which allows users to upload and perform queries on data relating to historical failures of critical transport infrastructure.

The project was arranged according to seven technical work packages (WPs). In the WP entitled ‘Single Risk Assessment’, methodologies have been outlined for road and rail infrastructure due to earthquakes, floods and landslides, in terms of both the hazard assessment and the infrastructure vulnerability assessment. In particular, novel methods have been proposed to analyse extreme, low probability hazard scenarios, which include earthquakes and floods, as well as cascading hazard scenarios, such as earthquake-triggered landslides. Additionally, methodologies have been proposed to assess multi-risk interactions in terms of both the hazard (i.e. cascading events or joint occurrence of independent events) and in terms of the vulnerabilities (i.e. cumulative effects of successive damages). In the ‘Space-Time modelling of Structural Behaviours and
Natural Hazards’ work package, modelling approaches have been developed for spatially-distributed infrastructure networks, such as agent-based modelling approaches, to evaluate the impacts of spatially and temporally varying environmental hazards.

The proposed methodologies have been unified according to the ‘Harmonisation’ work package, in which an overarching methodology is outlined, that can be used to determine whether the level of infrastructure-related risk due to natural hazards is deemed to be acceptable or not. Furthermore, the overarching methodology can be used to perform stress tests for critical infrastructure networks due to extreme natural hazard events according to the framework proposed in the ‘Stress Test Framework’ work package. Novel algorithms to overcome the computational effort associated with the stress testing of infrastructure networks have also been proposed in this work package, along with a decision-making protocol that can be used to determine the optimal intervention or mitigation measures to be undertaken to reduce the losses associated with an extreme natural hazard scenario. The proposed methodologies were applied to two European case studies in the ‘Case Study Simulation’ work package to demonstrate reliable stress tests for critical road and rail infrastructure networks. In addition, databases for Critical Infrastructure (CI) and major historical failures were developed in the ‘Risk Profiling of Natural Hazards and Infrastructure’ work package.

The overall objective of the INFRARISK project was to provide the next generation of European infrastructure managers and owners with the necessary methodologies and support tools to analyse the potential impacts of extreme natural hazard events and to aid in the decision-making process regarding the protection of critical infrastructure. As such, an online INFRARISK Decision Support Tool (IDST) was developed in the ‘Implementation Strategy’ work package, which can be used to perform stress tests for road or rail networks due to natural hazards. The proposed methodologies have been practically integrated into the IDST under specific process workflows and modules, and the tool is publicly available at the following web address: [https://infrarisk.it-innovation.soton.ac.uk](https://infrarisk.it-innovation.soton.ac.uk).

Additionally, numerous dissemination materials were produced during the project to raise awareness of the project outputs amongst stakeholders. These have included videos, educational materials, policy briefs, fact sheets, press releases, posters, newsletters, as well as a dedicated sample training course for infrastructure owners/managers. 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 European stakeholders. The event was also broadcasted on television and recordings of the presentations are currently available online. All of the dissemination materials produced in the project are currently available on the project website: [http://www.infrarisk-fp7.eu/](http://www.infrarisk-fp7.eu/).

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

WP2 - Risk Profiling of Natural Hazard and Infrastructure

WP2 focused on the development of online databases for critical infrastructure and historical failures, as well as the impacts of climate change on the occurrence of natural hazards. A database has been specified for critical infrastructure in Europe, which can be used to populate information in relation to critical TEN-T infrastructure elements, such as bridges, tunnels, slopes and road/rail surface elements. This sample database has defined the architecture for critical transport infrastructure and provides information to the users about obtaining the required information from publicly available sources. Further information is available in Deliverable D2.1 ‘Critical Infrastructure Database’.

A Geographical Information System (GIS) Knowledge Base of major global infrastructure failures has also been developed in WP2. The technical infrastructure for this database is based on DataGraft, a cloud-based service for data transformations and data access. It allows the user to simplify the creation of Linked Data and map the data we have collected into RDF data compliant with the RDFS schema that was developed. In addition, a graphical user interface (GUI) application prototype has been developed that can show data from the GIS Knowledge Base in a map. The knowledge base applies techniques from the emerging field of Linked Open Data (LOD), which uses the semantic standards Resource Description Framework (RDF) for representing data on the Web and SPARQL to query the data. The project has also developed a Resource Description Framework Schema (RDFS) vocabulary for infrastructure components and events that can be used to formally represent and exchange data between web applications. Further details can be found in Deliverable D2.2 ‘GIS Knowledge Base’.

WP2 also investigated the effects of climate change on the occurrence of natural hazards and the associated impact for critical
infrastructure. Slope assets, such as cuttings and embankments, were focused on specifically, and elements along the Irish rail network were examined. The most susceptible sites were predicted on the basis of a statistical analysis of a critical infrastructure database and historical failures. A comparison was subsequently conducted with estimates of the impacts of future rainfall scenarios on critical rail infrastructure rail assets. This demonstrated the effectiveness of the use of critical infrastructure and historical failure databases. A comparison of landslide susceptibility was also conducted for slopes along the Irish rail network, for existing climatic conditions and future climatic scenarios in terms of predicted rainfall scenarios.

WP3 - Single Risk Assessment
The objective of WP3 was to consider single event risk analysis methodologies for various hazards to evaluate the impact of road and rail infrastructure networks. Methods for the risk assessment of each hazard considered (i.e. earthquakes, floods and landslides) were harmonised by decomposing them into source events, hazard events and infrastructure events, as described in deliverable D3.1 ‘Hazard Distribution Matrix’. A harmonisation framework has been proposed to assess multi-risk interactions in terms of the hazard (i.e. cascading events or joint occurrence of independent events) and in terms of the vulnerabilities (i.e. cumulative effects of successive damages). A seismic hazard methodology has also been developed to consider low probability ground motions affecting critical transport infrastructures networks. The approach is based on Monte Carlo simulation techniques. It provides the same results as conventional probabilistic hazard assessment using the total probability theorem for the same input models, with several advantages consisting on allowing to develop long-duration synthetic earthquake catalogues to derive low-probability amplitudes, a more powerful and flexible handling of uncertainties, and making straightforward the link with probabilistic risk analysis. This approach does not affect the mean hazard values, allowing a distribution of maximum amplitudes that follow a general extreme-value distribution to be obtained. This facilitates the analysis of the occurrence of extremes, i.e. very low probability of exceedance, from unlikely combinations; which could be applied in the development of stress tests. Further information is available in a technical report to Deliverable D3.1 entitled ‘Development of seismic hazard modelling for low-probability extreme ground motions’.

Harmonised multi-hazard fragility functions have also been derived in this work package, with the objective of providing the probability of various functionality losses given different intensity measures for the infrastructure elements at risk (e.g. peak ground acceleration, water height, etc.). A link between the fragility function damage states has been established with the failures modes at component level and the functionality losses of the network element. The use of Bayesian Networks has then enabled the assembly of the probabilities of functional losses, at the level of bridge systems, for instance. This approach has been applied to a bridge case study, for which ‘functionality-based’ multi-risk fragility functions have been derived, with the ability to account for the interactions between hazard types at the fragility level. Finally, global Bayesian Networks and Event Trees have been developed to represent the probabilistic risk assessment steps for each hazard type. Details are provided in deliverable D3.2 ‘Fragility Functions Matrix’ and D3.4 ‘Single Risk Analysis’.

Potential sources of aleatory and epistemic uncertainties associated with natural hazards and their impacts on transport infrastructure have been investigated and current methods of uncertainty propagation were reviewed as part of this work package. Regarding uncertainty propagation, at the level of the network system, Bayesian Network formulations have been investigated in order to explore the multi-dimensional space of solutions (i.e. efficient identification of rare events within the space of solutions). Due to high computational costs, an exact Bayesian Network formulation becomes intractable for real-world road networks. Therefore approximate formulations, based on the learning from Monte Carlo simulation outcomes, have also been investigated. As a result, such a Bayesian Network has the potential to be used as a decision support system, thanks to the inference properties of the Bayesian theories (i.e. updating of the probabilities of occurrence of a given event when some observations or refinements are applied to some uncertain models).

Finally, multi-risk analyses were performed for a road network, thus demonstrating the adverse effects of multi-risk interaction with respect to the aggregation of single risk losses. Within this framework, multi-hazard fragility functions were used to perform risk analyses within different time windows, depending on whether earthquake and flood hazard events may be coupled to compute cumulative losses. Further information can be founded in Deliverable D3.3 ‘Uncertainty Quantification’.

WP4 - Harmonisation
Work package 4 has proposed an overarching risk assessment process for infrastructure due to natural hazards, along with a demonstration of how the process can be implemented in practice by using it to estimate risks in the region of Chur,
Switzerland. In addition, an explanation of how computer models can be designed and structured to support this process has been presented. The overarching risk assessment process is applicable independent of the natural hazards to be considered, the infrastructure objects to be taken into account, as well as different types of possible consequences. In addition, the process can be adapted to simple and complex system representations remaining flexible to include multiple events at each modelling stage. Particular effort has been dedicated to the incorporation of the spatial and temporal characteristics of natural hazards and the related consequences, which necessitates the use of geographic information system (GIS) and mapping technology.

Although it is intended that the proposed overarching risk assessment methodology can be used to evaluate the risk for infrastructure networks due to a variety of hazards (e.g. earthquakes, floods, etc.), there is particular benefit to the methodology in the context of climate change. The increase in the intensity and frequency of meteorological events, such as storms and droughts, requires reliable and effective methods of risk quantification. The proposed methodology can be seen as one piece of the puzzle responding to this challenge by providing a structure to assess the risk due to extreme events, facilitating decision making with regard to improving the resilience of critical infrastructure.

The general process to ensure acceptable levels of risk consists of three phases: 1) Initiate, 2) Conduct risk assessment, 3) Conduct intervention program. The risk assessment process is, therefore, a tool to help decision makers regarding the management of risk. The process has been constructed whilst bearing in mind that different decision situations will require different types of models and different levels of detail, as well as the fact that in many cases it is desirable to conduct a risk assessment iteratively. This is consistent with the principles of working in phases, e.g. a qualitative analysis may initially be employed, whereas a quantitative analysis may be employed at latter stages were more budget and time resources are available.

The risk assessment phase contains five tasks: (i) set up risk assessment, (ii) determine approach, (iii) define system representation, (iv) estimate risk, and (v) evaluate risk. To demonstrate the proposed methodology, the overarching risk assessment process was applied to an example region of Chur in Switzerland to determine the risk to a road network due to extreme rainfall events and cascading landslide hazards, as described in deliverable D4.2 ‘Final Model, Methodology and Information Exchange’. Computer modelling was employed to model rainfall in terms of flood and rainfall-triggered landslide hazard scenarios. Additionally, models were demonstrated to simulate the response of the infrastructure elements along the road network, traffic flow scenarios and various restoration sequences for the network. The risk assessment process was ultimately employed to determine whether the risk associated with the road network in the region of Chur was deemed to be acceptable or not. The risk was quantified in monetary value, in terms of the following:

- The restoration costs for the network infrastructure, i.e. the costs to clean-up, repair or replace the network elements;
- The additional travel time costs due to the network disruption;
- The cost associated with travel unavailability along the network.

This example demonstrated how the proposed risk assessment process can be used to determine if there is an acceptable level of risk associated with an infrastructure network due to natural hazards. This overarching methodology may be employed by infrastructure managers in a wide range of situations in which they might be, including variations in the following:

- types of infrastructure to be included in the assessment;
- types of hazards to be included in the assessment;
- available expertise;
- available time;
- need for detailed information;
- available computer support.

WP5 - Space-Time modelling of Structural Behaviours and Natural Hazards

WP5 have developed space-time models to analyse the impact of natural hazards on structural behaviour of critical infrastructures that may be location and/or time dependent. An integrated spatial-temporal database has been developed that can be used to evaluate infrastructure related risk due to natural hazards, as described in Deliverable D5.1 ‘Integrated Spatio-Temporal Database’. The database includes data of natural hazards, infrastructure and the environment to a range of disciplines and at different scales. This database contains different forms of spatial data including polygons (e.g. land use), networks (e.g. road and rail), spatial-temporal data (e.g. daily rainfall) and tabulated data (e.g. hazard attributes). The
database can be accessed by using both GIS operations and SQL queries for modelling the infrastructure’s response behaviour under multi-hazards scenarios.

This integrated spatial-temporal database was subsequently applied to analyse the risk of occurrence of landslides, as described in deliverable D5.2 ‘Space-Time Modelling of Structural Behaviour of Critical Infrastructure’. A Random Forest data mining method, which relates the historical data in terms of the type and occurrence of landslides, was compared to a suite of geomorphological conditioning factors to determine the likely occurrence of landslides, as well as the type of landslide. This methodology was demonstrated for a case study region in Northwest Italy to demonstrate the efficacy of the proposed data mining approach.

To analyse the consequences of the impacts of extreme natural hazard scenarios on transport infrastructure networks, various methods were evaluated, as described in deliverable D5.3 ‘Infrastructure Platform’. A betweenness centrality methodology was employed to determine the most vulnerable elements along a road network in terms of traffic disruption. Additionally, a traffic simulation software was employed to determine the consequences in terms of traffic disruption for a road network following a natural hazard event.

Finally, wavelet analysis was employed in this work package to model the temporal and spatial variability of natural hazards at different scales, as described in deliverable D5.4 ‘Wavelet Models of Environmental Cycles’.

Overall, WP5 has developed spatial-temporal modelling approaches that consider the spatial and temporal variability of natural hazards, as well as their impacts on transport infrastructure networks.

WP6 - Stress Test Framework

The objective of WP6 was to develop a stress test framework for critical road and rail networks that can be used to determine the potential losses associated with extreme natural hazard scenarios. Stress tests can be used as a decision-making tool with regard to the strengthening of network infrastructure elements or to determine alternative non-engineered mitigation actions that minimise the potential losses. Stress tests, therefore, refer to the analysis of a particular system or subsystem under a specific set of adverse conditions to determine the potential losses. The outcome of stress tests can be used to inform decisions regarding the protection of existing or future-planned infrastructure, which can contribute to the resilience of critical transport networks.

The selection of appropriate stress test scenarios may be based upon historical scenarios or can be based on hypothetical/synthetic scenarios that are constructed to take account of plausible changes in circumstances that have no historical precedent. To do so, structured brainstorming sessions, such as General Morphological Analysis may be employed to elicit this expert knowledge based narrative from the relevant experts and stakeholders. Two other techniques that may be employed include extreme value theory, which applies statistical analysis to the tails of return distributions, and the maximum loss approach, which estimates the combination of factors that would cause the largest loss to the system under consideration.

In the INFRARISK project, the stress test framework was developed specifically for road and rail infrastructure network, which may be modelled as fault tree systems with a large number of (dependent) components. As the number of dependant components within an infrastructure increases, the fault tree grows exponentially. To overcome these computational limitations, novel algorithms were proposed within WP6, including the ‘Nested Sampling’ and ‘Probability Sort’ algorithms, as described in deliverable D6.2 ‘Stress Test Framework for Systems’. A Bayesian decision theoretical framework was also proposed in this work package, as described in deliverable D6.3 ‘Decision-Making Protocol’, which can be employed to determine the optimal actions that can be taken by an infrastructure manager or owner to minimise the risk associated with an infrastructure network due to extreme natural hazards. The proposed approach is based on a summation of the lower bound, expected value and the upper bound of the outcome distribution in contrast to the traditional evaluation, which is based on expected values only.

In WP 6, a landslide susceptibility map and a Random Forest (RF) algorithm were also used to develop a rainfall threshold prediction model for the Piedmont region of Italy, as reported in deliverable D6.4 ‘Suitability Analysis of Data-Mining Models for Stress Tests’. Additionally, a methodology was developed to estimate the wider economic impacts of road network disruption caused by natural hazards, as described in deliverable D6.5 ‘The Wider Economic Impact of a Natural Hazard – An Agent Based Approach’. This methodology has made novel use of origin-destination travel data and economic indicators to estimate the economic loss associated with travel disruption due to the impacts of natural hazard scenarios on road and rail transport networks.
WP7 - Implementation Strategy

WP7 consisted of the development of a strategic INFRARISK Decision Support Tool (IDST) that has been specified, designed and developed to ensure that the methodologies developed in the project are practically integrated and can be used under specific process workflows and modules to perform stress tests for road and rail networks. The IDST is a web accessible information system portal with integrated databases, data processing and analytics modules with supported geo-information maps and visualisation tools. It is available online at the following web address: https://infrarisk.it-innovation.soton.ac.uk/.

The IDST provides details of the European case studies analysis in WP8 as examples. It also provides a user-friendly system environment for infrastructure managers to perform stress tests to quantify the potential losses for road and rail networks due to extreme natural hazard scenarios. Stress tests can be saved on the IDST and reports can be produced. A link to the GIS Knowledge Base that was developed in WP2 of the project is also provided on the IDST.

Details of the most recent version of the IDST are described in deliverable D7.4 ‘IDST System v2.0’ and the functionality of the IDST is described in deliverable 7.5 ‘IDST Validation and User Manual’.

WP8 - Case Study Simulation

In WP8, two European case studies were analysed to demonstrate the systematic application of the methodologies developed in the INFRARISK project. Specifically, the methodologies developed in WP3, 4, 6 and 7, were tested on European road and rail case studies. The process of selecting the case studies began at an early stage of the project, as described in deliverable D8.1 ‘Critical Infrastructure Case Studies’. The case studies are located along the trans-European (TEN-T) network, which provides critical infrastructure corridors throughout Europe and facilitates the effective transportation of people and goods, supporting economies and contributing to the European single market. Each case study focused on a particular transport infrastructure network (i.e. road or rail) and a particular source hazard (i.e. earthquake or rainfall). Stress tests were performed for the case studies according to the overarching risk assessment methodology that has been developed in the INFRARISK project.

The first case study consists of a regional road network in the province of Bologna in northern Italy. Stress tests are performed for low probability, high consequence seismic hazard scenarios and the cascading landslide hazard effects. The direct consequences were quantified in terms of the cost of repairs for structural elements along the road network (i.e. bridges, tunnels and road sections). In addition, the indirect consequences were quantified in terms of the travel time increases encountered by road users as a result of the network disruption, as well as the associated economic losses at national level.

The second case study consisted of a rail network in Croatia for which stress tests are performed for low probability, high consequence flooding scenarios. Similarly, the direct consequences were quantified in terms of the costs of physical repairs to the network and the indirect consequences were determined in terms of the travel delay times for passengers and freight transport. Further information can be found in deliverable D8.2 ‘Case Study Results’.

The case studies demonstrate reliable stress tests for European road and rail infrastructure networks and validate the methodologies proposed in work packages 3, 4, 5, and 6 through their systematic application to existing networks.

WP9 - Dissemination and Exploitation Activities

WP9 has promoted the visibility of the project and disseminated its results to reach a wider audience. Specific focus has been put on all types of stakeholders ranging from industry to operators, policy and decision makers, and research institutions as well as the wide public. All products and dissemination materials have been made available in the project website, which has been updated every couple of months. The project website contains all of the dissemination materials, products and public documents that were produced during the lifetime of the project.

Various dissemination materials were produced and communication outreach activities were conducted throughout the project. Information in relation to these products and events was uploaded to the project website. These materials have been produced according to deliverable D9.1 ‘Detailed Dissemination and Communication Plan’ and are contained in deliverable D9.3 ‘Project Dissemination Materials’.

Dissemination activities have included the production of educational materials in the form of videos to heighten the public awareness and understanding of the main topics addressed in INFRARISK. These included three videos entitled ‘Natural hazards’, ‘Critical infrastructures’, and ‘Stress Tests’. Other audiovisual materials produced included a sample training course that was produced for infrastructure managers and owners.
A Final Dissemination Conference for the project was held on September 29th 2016 in Madrid. This was attended by a large number of stakeholders and public authorities. The conference was recorded and these videos are currently available on the project website. Several members of the project consortium were interviewed during the conference by a team of Spanish TV Channel TVE24h to promote the awareness of the project outputs. This has been report in the TV program entitled ‘Europa 2016’, which is also available on the project website. This one-day event was arranged according to three sessions:

• Session 1 consisted of an introductory welcome was presented by the hosting partner, Dragados (M. Segarra), in which the importance of the project research and the outcomes were emphasised. This was followed by two keynote speeches. The first speech was given by the project coordinator, E. O'Brien, who presented an overview of the project. The second keynote speech was given by the chairperson of the project Advisory Board, B. Bell, who presented his insight regarding the protection of critical infrastructure from an infrastructure manager’s perspective.

• Session 2 comprised four presentations that described the main topics and methodologies / tools developed within the project, as follows:
  > the stress test framework developed in the project;
  > the methodologies developed in relation to hazard assessment for extreme earthquake, flood, and landslide scenarios, and the vulnerability assessment of road and rail infrastructure networks;
  > the European case studies that were used to perform stress tests for critical road and rail networks;
  > the two software tools that were developed in the project: 1) the INFRARISK Decision Support Tool (IDST) and the GIS Knowledge Base.

• Session 3 consisted of a panel discussion, which included the coordinating projects RAIN (A. O’Connor) and INTACT (P. Petiet) and key members of bodies relating to critical transport infrastructure and natural hazards: J. Lóbez (Crisis Management, Ministry of Transport and Public Works, Spain), J. Rodríguez (Spanish Construction Technology Platform, Spain), A. Ansal (European Association of Earthquake Engineering).

A large number of relevant European stakeholders were invited to the conference, including public authorities, practitioners, infrastructure operators and managers, construction and management companies and enterprises. An initial announcement for the event was distributed in April 2016 through construction platforms and networks, which included the following: the European Construction Technology Platform (ECTP), the European Network of Construction Companies for Research and Development (ENCORD), the Conference of European Directors of Roads (CEDR), the Forum of European National Highway Research Laboratories (FEHRL), Plataforma Española Tecnológica de Construcción (PTEC) and Asociación de Empresas Constructoras y Concesionarias de Infraestructuras (SEOPAN). A further announcement for the final dissemination conference included a detailed programme, which was sent via email to over 1000 European contacts. Approximately 70 participants attended the final dissemination conference. The education material videos that were produced during the project were showcased in the conference room during the registration period, as well as during the breaks. A live webcast of the event was broadcast and the event was also recorded. Further information is available in deliverable D9.6 ‘Final Conference Summary Report and Broadcast Video’.

To identify the potentially exploitable aspects of the INFRARISK project, a template document was prepared and distributed to all project partners. The aim was to facilitate the exploitation of the project results according to this business plan to progress the initial vision of INFRARISK to a fully-fledged operational plan. D9.4 ‘Business Plan’ describes how the exploitable results were identified, any IPR issues noted, as well as the proposed market analysis and strategy and financial planning that will be adopted. The document also describes formal modalities by which partners will continue to cooperate after project completion (IPR, Agreements, and External Parties). The Technological Implementation Plan, which forms part of the Business Plan, is also described and details the results of the project and the plans that the partners will have to use those results and to encourage others to use them in the future.

Several collaborative activities have been conducted between the INFRARISK project and similarly themed EU projects, as described in Deliverable D9.8 ‘Cross Work Programme Coordination Report’. These activities included various meetings, workshops, information exchanges and special sessions at dissemination events to establish effective collaboration between the projects. In addition, a dedicated report was produced with the STREST project, entitled ‘INFRARISK & STREST Coordinated Report’, which describes some of the common synergies and recommendations jointly arising from the projects.
Potential Impact:
The potential impact associated with the project has been broken down into the various technical work packages, as follows:

WP2 - Risk Profiling of Natural Hazard and Infrastructure
The GIS Knowledge Base developed in WP2 represents a usable demonstrator that shows the application and benefits of DataGraft, and will be used as a showcase in the acquisition of future research and development projects. The knowledge base can also be made available for use by other European projects. The associated developed vocabulary has the potential to become a standard vocabulary for interexchange of data online in relation to infrastructure components and natural hazards.

WP3 - Single Risk Assessment
The multi-hazard fragility framework, which is based on the aggregation of hazard-specific component fragility curves, may be applied to any type of infrastructure elements or structures and to any type of natural or man-made hazards. This approach is compatible with the multi-risk framework that has been proposed in the previous FP7 project MATRIX, since it addresses the issue of multi-risk interactions at the vulnerability/exposure level. The method for the derivation of multi-hazard fragility functions has been published in an international journal paper, which ensures that researchers and engineers can exploit it and apply it to other infrastructure elements and hazard types, thus contributing to the enrichment of a catalogue of multi-hazard fragility functions.

At the infrastructure levels, quantitative assessment methods based on Bayesian Networks are complementary with simulation-based approaches such as the one that has been proposed in the FP7 SYNER-G project. Close collaboration with the developers of the SYNER-G simulation tool ensures that both methods can be integrated: the inference abilities of the Bayesian Network framework have the potential to lead to a powerful decision support tool, which could be used by emergency managers (i.e. updating of the probabilistic loss estimations given the observations that are gathered from the field).

WP4 - Harmonisation
The risk assessment methodology is a methodology that is independent of the natural hazard to be considered, the infrastructure objects to be taken into account as well as different types of possible consequences. It can be adapted to simple and complex system representations remaining flexible to include multiple events at each modelling stage, and even set them up in cascading form. It includes a particular emphasis on the incorporation of the spatial and temporal characteristics of natural hazards and the related consequences, which necessitates the use of geographic information system (GIS) and mapping technology.

The methodology will benefit the infrastructure managers who use it to set up risk assessment methodologies for their specific cases. It may also be used by regulatory agencies to establish stress tests for infrastructure managers. If implemented, infrastructure managers will be able to develop tailor made risk assessment processes to allow them systematic assessment of their infrastructure related risks. Such assessments will allow them to determine the interventions that should be executed to reduce their risk if necessary and enable them to communicate clearly to government how much risk they have and what should be done about it. If used by regulators it will enable them to determine the stress tests to be executed by infrastructure managers so that they have an overview over all infrastructure related risks.

An example application of the overarching methodology has also been presented in WP4 for a road network in the Chur region of Switzerland. This application will benefit the road managers who use it to set up risk assessment methodologies for their specific cases. It may also be used by regulatory agencies to establish stress tests for infrastructure managers. As with the general methodology, if used by regulators it will enable them to determine the stress tests to be executed by infrastructure managers so that they have an overview over all infrastructure related risks.

The results of WP4 can be used in future research and implementation projects where there is interest in developing specific risk assessment methodologies for specific situations, in determining stress tests to be used to check if infrastructure managers have acceptable levels of risk or not, and in developing optimal risk reducing intervention programs for large amounts of infrastructure. The work done in INFRARISK is currently being implemented in the DestinationRAIL European Union Horizon 2020 research project where a risk assessment methodology for the Irish rail network managers is being developed. A dissemination event is planned in Switzerland early in 2017 to which road and rail managers will be invited in effort to generate interest in future work. Contact has also been made to Prorail and the UIC, in an effort to disseminate the results. Additionally, the researchers who worked on the project will publish the results of the INFRARISK project in international
scientific journals and present the findings at suitable national and international conferences. They will also publish their research work that has had its origin in the INFRARISK project but will continue on now that the INFRARISK project is completed, including the work on 1) the use of random networks to approximate risk in situations where little information is available, 2) the modelling of restoration intervention programs, which is key to the evaluation of risk, 3) the development of advanced graphical interfaces within GIS system to facilitate decision making by infrastructure managers, and 4) the modelling of losses of service due infrastructure failures in network infrastructure. In each case the INFRARISK project will be acknowledged for helping to spawn the research ideas.

WP5 - Space-Time modelling of Structural Behaviours and Natural Hazards

WP5 has developed a spatial-temporal modelling approach which can be used analyses natural hazards impact to critical infrastructures. The spatial-temporal database set up would support quantitative modelling of the source events which can trigger hazards, such as rainfall. Source events can lead to different ‘hazard events’. The magnitude, location and type of hazard which occurs are determined by both the source event and the environment.

The impact on road and rail networks can be seen as either an ‘infrastructure event’, where we are interested in the damage caused to a specific element of the network, such as a road segment, bridge or tunnel or a ‘network event’, where we look at how the hazard has affected the network. This can be in terms of the effect on traffic flow such as travel time delay. Calculating travel time delay for given scenarios can be used to calculate indirect economic losses caused by damage to the road network. This is done by assigning an economic value to people’s time. The indirect economic cost will depend on both the delay and the duration of the reduction in the network’s serviceability.

The spatial-temporal model can be used to inform planning and mitigation strategies to protect infrastructure and reduce risk. For example the traffic equilibrium modelling approach can be used to model the effects of restoration. After a hazard event causes damage, the entire network will not be restored instantaneously. There will be many phases of restoration based on the damage that has occurred and the recovery plan that exists. Over time different parts of the network will be restored to various capacities. At various stages during the restoration process, the traffic model can be rerun to observe how the restoration is impacting traffic flow and hence indirect economic costs.

WP6 - Stress Test Framework

The potential impact of the developed stress test framework is that it:

- allows infrastructure managers as well as regulatory bodies / inspectorates of road- and rail infrastructure, to elicit stress scenarios of natural hazards in a structured manner based on expert judgement and statistical extrapolations of past events;
- provides sampling algorithms to propagate numerically a stress scenario through a complex network of road/rail infrastructure with many components with a huge number of possible damage states of the system. Such algorithms have specifically been developed for Infrarisk within WP6 and are expected to have a large impact;
- provides a novel decision protocol to compare different outcome probability distributions according to a Bayesian decision-theoretical framework. In Deliverable D6.3 it is derived that this comparison should be based on the worst, average, and best case scenarios. This is in contrast to the traditional evaluation, which is based on expected values only. Also here a large impact of this protocol is expected.

Another significant innovation of WP6 is the application of Agent Based Modelling (ABM) for simulating the indirect consequences of a natural hazard. This enables us to transfer the research result on individual infrastructure fragility curve and restoration curve into the road network vulnerability and resilience study. Additionally, the integration of ABM traffic model allows us to study the resilience at regional and national level. These simulation models can be applied for the emergency planning to predict the location of the vulnerable infrastructure as well as the resources needed for the organising emergency restoration process. Another important characteristic of this research is the use of transport Origin-Destination data to estimate the indirect economic loss.

WP7 - Implementation Strategy

The IDST development led by the University of Southampton provides an open environment for further development with the enrichment of the existing critical infrastructure and natural hazard databases. It provides an integrated common operational picture for the practitioners in crisis management and spatial planning in urban environment with critical infrastructure. Our work on the IDST has been well received at the final conference of INFRARISK in Madrid last September 2016 hosted by one of our partners (DRAGADOS). The technology used, such as Django framework for the development of the IDST enables the
potential extension of the IDST system functionalities in the future. Our interest is to exploit such asset for furthering our research and development programmes on crisis management in urban environment under the smart cities and big data programmes of H2020 in Europe and; Research Councils and Innovate UK in the UK.

WP8 - Case Study Simulation
WP 8 has demonstrated systematic application of the methodologies proposed in the INFRARISK project to two existing networks along the TEN-T European road and rail networks. Each case study focused on a particular transport infrastructure network (i.e. road or rail) and a particular source hazard (i.e. earthquake or rainfall). The case studies demonstrate reliable stress tests for critical European transport infrastructure that may assist infrastructure managers and owners in performing stress tests for their own networks. 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 natural hazards. Such methodologies assist in the development of resilient infrastructure.

WP9 - Dissemination and Exploitation Activities
The Final Dissemination Conference (29th September 2016, Madrid) during which the main achievements and results of the project were presented was attended by a very high number of stakeholders related to infrastructure management and operation. The conference was announced and disseminated through construction platforms and networks: European Construction Technology Platform (ECTP), European Network of Construction Companies for Research and Development (ENCORD), Conference of European Directors of Roads (CEDR), Forum of European National Highway Research Laboratories (FEHRL), Plataforma Española Tecnológica de Construcción (PTEC) Asociación de Empresas Constructoras y Concesionarias de Infraestructuras (SEOPAN). The final announcement which included the detailed programme of the Final Dissemination Conference was sent through e-mail to more than 1000 contacts of companies and enterprises all over Europe. The results of the project have been communicated through the participation of partners in international key scientific/technical conferences and national conferences (16 international and 2 national have been attended or will be attended in the next months after the closing of the project).

Six papers were published in peer-reviewed journals, ten articles were published in conference proceedings, and 2 articles were published in specialized EU publications. A number of further publications have been either submitted or are in the preparation phase.

A sample training course has been produced, which has the potential to be employed by infrastructure managers and decision makers to perform reliable stress tests for critical transport infrastructure due to extreme natural hazard scenarios.

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Related information

Result In Brief
Novel tools to evaluate the effects of natural hazards on transport infrastructure

Documents and Publications
final1-publishable-summary-additional-documents.pdf

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