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Enhancing the resilience of interconnected critical infrastructures to climate hazards

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Abstract.

In this work we propose a methodological risk and resilience framework to assess comprehensively multiple climate risks and related natural hazards, such as floods, forest fires, and droughts, for interconnected Critical Infrastructures (CI). As vital components of the normal functioning of modern societies, their resilience encompasses the operational elements, their structural integrity and the capacity to maximize business output under climate stressors. Critical infrastructures are commonly designed, built and maintained based on rigorous standards in order to withstand the climate and weather-related pressures, but shifts in climate characteristics may result in increases of the magnitude and frequency of potential risks, or expose specific CI to new risks not previously considered. A main objective of the proposed methodology is to provide scientific evidence for better understanding of how future climate regimes might affect the interconnected CI during their lifespan and accounting for ageing, and how to assess the cost-effectiveness of different adaptation measures. Additionally, an example in the flooding impact to Torbay in South West UK is presented.

Keywords: Climate Change, Flooding, Critical Infrastructures, Natural Hazards, Risk Assessment

1. Introduction

Critical infrastructures such as telecommunications, electric power generation and transmission, chemical industry, water supply systems, transportation, ICT networks and emergency services have become the components of a larger interconnected system. A disruption in one infrastructure has ripple, cascading effects into other infrastructures and eventually impacts the community and the broader economy. In this work we introduce the EU-CIRCLE innovative framework for supporting the resilience of interconnected European Infrastructure to climate pressures. As large scale systems, whose lifetime exceeds the order of decades, infrastructures are heavily exposed to natural disasters, often with devastating consequences to the society, economy and the environment. The increasingly dependent, interdependent and interconnected nature of critical infrastructures may expose EU societies to previously unseen risks, new vulnerabilities and opportunities due to disruption across multiple CI networks. Current analysis of historical incidents indicates that CI vulnerability tend to be focused on extreme weather events, which can disrupt the normal operation of infrastructures, causing often cascading impacts across infrastructures because of extensive interdependencies between them[1]. Acknowledging that infrastructure's vulnerabilities and impacts go far beyond physical damages (Hokstad 2012), the work within EU-CIRCLE project will be concerned with an assessment of the impacts to the services provided by CI, addressing impacts associated with the repair, and/or replacement of services but also including the externalities of the infrastructures operation, societal costs, environmental effects, and economic consequences due to suspended activities. According to current policy best practices (IPCC 2014, Hickel 2013) a climate change risk assessment usually considers (i) the possible threats that can emerge from an extreme event; (ii) the likelihood of an event occurring; and (iii) the consequences of the event. A climate change risk assessment provides information that allows a CI operator to manage risks, which can be achieved by changing the state of the system to reduce vulnerability, improve resilience and lessen potential climate impacts (Dawson 2015). Critical infrastructure resiliency (UK Cabinet Office, 2014) encompasses a much wider set of activities than that of conventional practices in the protection of critical infrastructures against multiple threats, and includes activities for prevention, protection and preparedness against natural hazards (Galbusera 2014).

[1] An extensive overview of CI sector's specific risk, resilience and adaptation overview is presented within EU-CIRCLE D2.1 "D1.2 State of the art review and taxonomy of existing knowledge", available at http://www.eu-circle.eu/wp-content/uploads/2017/01/D1.2-State-of-the-art-review-and-taxonomy-of-existing-knowledge.pdf

Interdependencies among infrastructures dramatically increase the overall complexity of the "systems of systems". There is therefore a need to consider multiple interconnected infrastructures and their interdependencies in a holistic manner (Bouchon 2006). Resiliency against climate change hazards includes multiple of activities, ranging from emergency response plans and capabilities, recovery plans, long term investment plans and changing technological elements of the infrastructures during their lengthy lifespan.

2. Risk and resilience framework for CI to climate change

With the on-going project EU-CIRCLE, significant effort is invested towards the establishment of a common risk and resilience framework for interconnected CI. The framework is based on the concept that each CI provides a minimum level of services to society, a flow of goods / commodities pertinent to the type of the infrastructure, while respecting the context and the unique characteristics of each sector. Additionally, the proposed framework is made highly flexible by including resilience capacities, once they are interpreted into modelling components, and allowing for the orchestration of different analytic components. The proposed approach also made possible to propose metrics for different types of impacts, both directly associated with the CI (physical damages, reduced performance, economic losses, losses of lives, low quality etc.) and indirect impacts to the society, the environment and other sectors of the economy. A number of indicators are defined, which are fully aligned to the EU and International policies, and significant work is in progress to expand them into operational metrics for quantifying CI resilience. The proposed approach accommodates various temporal scales, accounting for the short term impact of extreme events on the business continuity plans of the CI and the relevant long term adaptation options.

2.1. Related Policies

The strategic context of EU-CIRCLE is defined as a synthesis of numerous national and European policies, which are backed by validated scientific support for developing resilient CIP solutions. The main policies considered for this purpose are:

- The EU Strategy on Climate adaptation, as identified in COM(2013) 216
- National Risk Assessment Plans (NRA) as identified in SWD (2014) 134, Brussels, 8.4.2014,
- Directive 2008/114/EC, on the identification and designation of European critical infrastructures
- The Sendai Framework for Disaster Risk Reduction, and especially Priority 4.

2.2. Risk and Resilience Framework

The EU-CIRCLE project has defined a holistic framework aiming to identify and assess the risks caused by multiple climate-change stressors and climatic hazards to heterogeneous interconnected and interdependent critical infrastructures. This is considered to be the first step to ensure the resilience of vulnerable technological, social and economic systems to climate change impacts and improve climate proofing ability of the existing critical infrastructures (in terms of identifying indicators and reference states, anticipated adaptive / transformation activities, and investment costing). The framework allows to identify climate-driven CIP risks and to elaborate relevant capabilities (anticipation, absorption, coping, restoration, and adaptation) to ensure their resiliency. The determination of impacts in the multi-hazard risk framework is directly compatible with National Risk Assessments, EU Disaster Management Guidelines (EC SWD 1626 final/2010) and EPCIP Directive (114/2008) as well as with International initiatives (Sendai Framework) and related standards (ISO 31000), accounting for impacts directly affecting the CI and the corresponding consequences to the society, the environment and other sectors of the economy. The proposed framework, use consequence- time- and interdependency based Risk Modelling allowing to diagnose which direct consequences and inter-sectoral effects would likely emerge in what time frame after the occurrence of a climate-change driven disruptive event to the particular critical infrastructure. This allows to extend the EU-CIRCLE concept beyond the boundaries of individual risks and infrastructures considering damage assessment and modeling cascading impacts. An asset-based approach is used to assess risk for damages to CI due to climate stressors, leading to the identification of the respective impact to the performance of the CI operation. The risk assessment is based on the analysis of the elements of the CI network and the modelling of the relative critical services, which are provided by interconnected and interdependent infrastructures. This modelling approach enables users to link asset-based damage assessment with CI business continuity models, under extreme stress conditions and strive for optimal adaptation measures, quantified through proper CI risk metrics and resilience indicators.The sectors considered within the EU-CIRCLE framework include energy, water, ICT, transport and governmental services, all of them being highly sensitive to relative thresholds of hydro-meteorological extremes. The analysis of such extremes as well as the elaboration of the changing climate patterns is used to determine golden rules when adopting high safety and societal protection standards that are very costly on the one hand, and preventing major damage to equipment and structures that are likely to occur during the useful life of the infrastructure on the other hand. Most existing infrastructures have been designed under the assumption of stationary climate conditions using historic values and observations. Making infrastructure climate-proof and resilient from the socio-technical viewpoint, requires to consider climate change as a basic element of the infrastructure design. The EU-CIRCLE risk management framework, consists of the following steps (Figure 1):

1. *Establishment of CI (or regional) climate change resilience policy, or specific business oriented decision that will be addressed.* Typically, such policies have a timespan of multiple years and their objective may be related to specific issues or cross-sectoral matters. Relative policy questions to be answered can be: What must and what should be protected? Which potential consequences

are relevant (economic, social, environmental etc.) for this appraisal? What are the priorities? What is an acceptable risk and what is a non-acceptable risk?

2. *Identification, collection and processing of data related to climate and secondary hazards*. It involves analysis of the historic climate (and secondary hazards) data sets, mid- and long-term projections of climate regime, based on available data and provision of specialised simulations.

3. *Identification of assets, systems, networks, relations and functions*. The following approach is proposed: a) Compilation of a registry of CI assets relevant to the sectors considered in EU-CIRCLE and use an adequate level of granularity, b) Analysis of interconnections, networks and (inter-) dependencies including the various types, such as physical, cyber, geographic, logical or social (inter-) dependencies.4. *Assessment and evaluation of risks*, through a harmonized interoperable approach. Alternatively "translating solutions" will be created between the different risk and impact criteria.

5. *Selection and implementation of protective programmes, including adaptation options*, to modify risk level and to implement options to: a) reduce the likelihood of occurrence, b) reduce the impacts / consequences and exposure, c) transfer in full or partly the risk, and d) mitigate and manage the risk.

6. *Measurement of effectiveness*. Once one or more risk reduction measures are introduced, the progress towards achieving the relative objectives must be evaluated regularly. Risks, effectiveness, goals or other circumstances may change after initial implementation. WP5 proceeded with the design and development of the Climate Infrastructure Resilience Platform (CIRP) a Web based software that will assess potential impacts due to climate hazards, provide monitoring through new resilience indicators and support cost-efficient adaptation measures according to the outcomes of WP2, WP3 and WP4 and especially the Consequence – based Risk Management (CRM) generic approach as defined in WP3. CIRP is defined as an end-to-end collaborative modelling environment where new analyses can be added anywhere along the analysis workflow and where multiple scientific disciplines can work together to understand interdependencies, validate results, and present findings in a unified manner providing an efficient solution that integrates existing modelling tools and data into a holistic resilience model in a standardized fashion. The EU-CIRCLE risk assessment process is implemented as a Web-based software that assesses potential impacts due to climate hazards, provides monitoring through resilience indicators and supports cost-efficient adaptation measures. This is the Climate Infrastructure Resilience Platform (CIRP), which is an end-to-end collaborative modelling environment, where additional risk modeling and consequences analyses may fit. Multiple scientific disciplines can work together using the platform and they are supported to understand interdependencies, validate results, and present findings in a unified manner, providing an efficient solution that integrates existing modelling tools and data into a holistic resilience model in a standardized fashion. The analyses may refer to any part of the risk assessment and resilience evaluation workflow. A number of pilot cases are considered as examples for demonstrating the proof of concept and testing the aforementioned framework, using real-world cases. The EU-CIRCLE approach, applied to the case study of the coastal flooding in Torbay UK and its impact on urban infrastructures is described in the next session.

3. Flooding event at Torbay, UK

Torbay, which is located in the South West of England, hosts more than 3 million tourists every year that

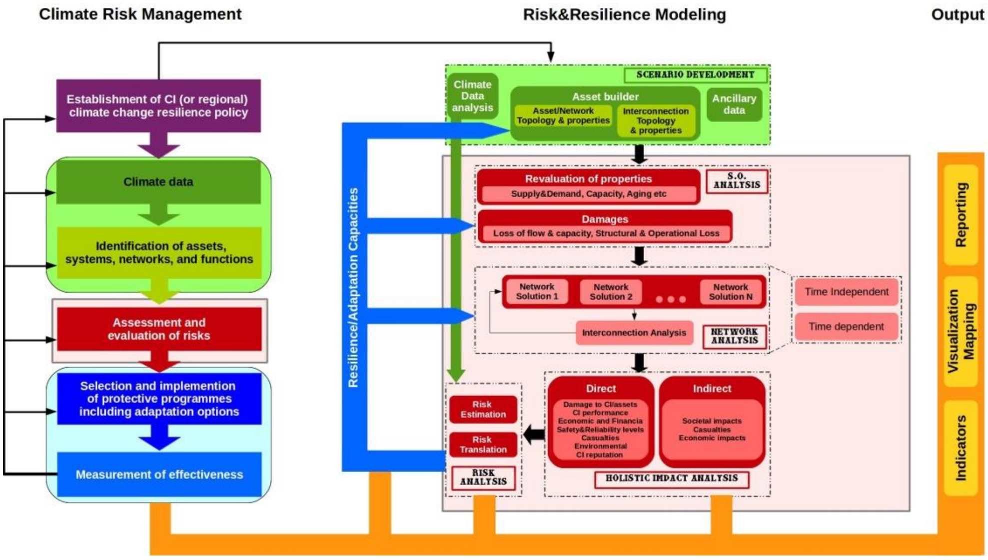

Figure 1. EU-CIRCLE Risk and Resilience framework

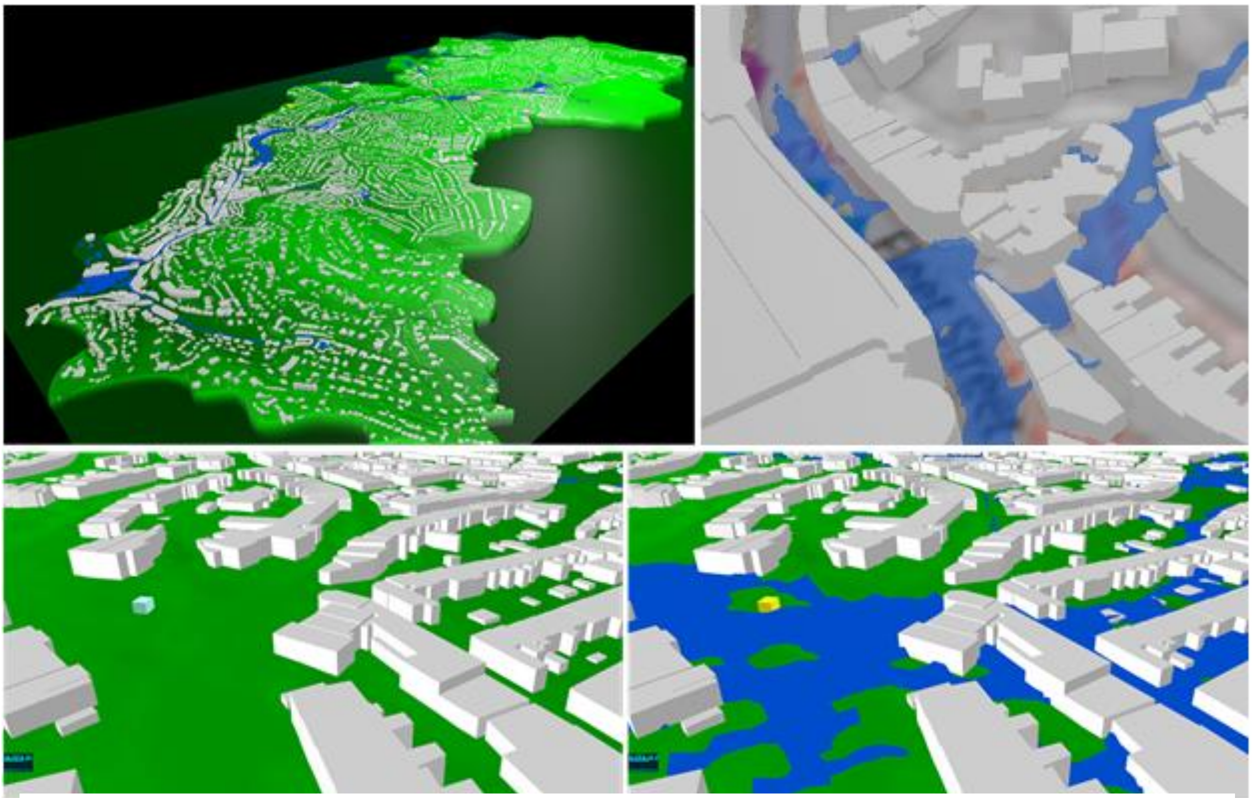

Figure 2. 3D Visualisation of flooding in Torquay

contribute over £450 million to local economy (English Riviera Tourism Company 2014). However, flooding, including coastal, fluvial and pluvial, has been a major threat to the area with more than 15 major incidents occurring since 1999. The rising sea levels and increasing rainfall intensity, linked to climate change, are expected to exaggerate the risk of flooding in Torbay in the future. Better adaptation strategies are urgently needed to safeguard CIs and services while improving resilience to climate hazards.EU-CIRCLE is reviewing the existing capacity of flood defenses and the drainage systems in Torbay, using a detailed hydraulic modelling approach to identify the CIs that are susceptible to flood risk. By considering the changing trends of weather parameters from climate projections, we further examine the systems' ability to cope with future climate change scenarios. The basis for this work are hydraulic models that were produced for Torbay and converted into Infoworks CS format (Infoworks 2017) to analyse selected current and future coastal, fluvial and sewer flooding scenarios (Torbay Council 2010). Within EU-CIRCLE the existing model data have been updated to improve risk assessment. Furthermore, a wider range of weather conditions and interventions are also being evaluated to better reflect the uncertainty in the assessment. To address uncertainty issues in modelling, a large number of simulations are required to cover the full spectrum of probability distribution for the flooding event. That, in turn, requires fast modelling tools to complete the analysis efficiently. Therefore, a rapid 2D flood simulation model (WCA2D; Guidolin *et al*. 2016), a part of the Cellular Automata Dual-DrainagE Simulation (CADDIES) framework (Guidolin *et al*. 2012), has been adopted, together with the updated Infoworks CS models, to provide comprehensive flood risk assessment. Instead of solving the computationally expensive and demanding shallow water equations of the full hydraulic model, WCA2D implements a set of simplified transition rules based on cellular automata (CA) to describe the flow movement on the surface (Guidolin *et al*. 2012, Ghimire *et al*. 2013). WCA2D also utilises parallel computing technologies, including multi-core CPU and GPU processing, to escalate its performance (Guidolin *et al*. 2015, Gibson *et al*. 2016). The WCA2D model was tested in Torquay catchment and compared to the results obtained from Infoworks CS. The case study results showed that WCA2D can produce comparable results with a fraction of the computing time required for Infoworks CS (Guidolin *et al*. 2016). Model inputs include high resolution terrain data obtained from LiDAR (LiDAR, 2017), building layouts from the Ordnance Survey (OS MasterMap, 2017), the rainfall intensity-duration-frequency analysis from the Flood Estimation Handbook (CEH, 2013), observations and flood extents of historical events, provided by the Torbay Council (another EU-CIRCLE partner), and the National Infrastructure Registry Database. The models were calibrated and validated against historical records. That is followed by using various syntactic rainfall events, storm surge conditions, and climate change factors as modelling inputs to evaluate the future flood risk. Additionally, the WCA2D model of the region has been coupled with a new 3D visualization tool, showing the progress over time of any flood scenario in the region. The tool is entirely written in Javascript and takes advantage of WebGL technology, using the Three.js open source library (Three Js Library, 2017) to allow in-browser animation, fully interactive manipulation and aesthetically pleasing immersive 3D visualization of user selected views and time sequence of events. This tool was developed within EU-CIRCLE. Figure 2 shows a snapshot of Torquay, a region in Torbay, under a future flood scenario. The top-left sub-figure shows the catchment of modelling domain while the top-right one displays the flood along the street in a user-selected local area. The bottom-left sub-figure illustrates a substation (coloured in cyan) in dry condition, which is inundated when the flood hits the location and consequently highlighted in yellow colour in the bottom-right sub-figure. The hazard maps are further applied to analyse their impact on CIs (e.g. energy, transportation, health care, emergency shelters), and to develop and evaluate mitigation strategies. The interdependencies among the CIs are also investigated through the process, as well as the effectiveness of various adaptation measures. The WCA2D flood risk analysis in Torbay will be implemented on the CIRP platform for the holistic evaluation of critical infrastructure resilience in EU-CIRCLE.

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