EU-CIRCLE

A pan-European framework for strengthening Critical Infrastructure resilience to climate change

D3.5 Holistic CI Climate Hazard Risk Assessment Framework

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Statement

This deliverable introduces the second version of the EU-CIRCLE general risk assessment framework that can be used to examine the risk of damage to critical infrastructure under the increasing stress of climate change and associated climate hazards. The holistic approach consideres also secondary impacts to society, economy and environment that emerge as consequences of critical infrastructure disruptions

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Executive Summary

This deliverable presents approaches for risk assessment and risk management as they have been developed and established in European Countries and beyond. It is based on D3.4 and other relevant deliverables, as it is described in Section 1.

On the base of that, it develops a general framework for the assessment of the risks of failures in critical infrastructures as a result of climate hazards. This general framework includes a selection of approaches for describing and modelling of:

- assets,
- dependencies and interconnections between them,
- assessment of failure impacts,
- propagation of risks through networks,
- uncertainties.

On the base of scientifically validated and well established approaches, we suggest a sequence of the following steps for the holistic risk assessment:

1) Scenario development,
2) Critical infrastructure network topology and description,
3) Structural and Operational analysis,
4) Network analysis, taking into account interconnectivity and resilience characteristics and
5) Holistic impact analysis

For each step, the deliverable provides general guidance. Also, this deliverable describes the relevant categories of impacts, approaches to handle and process scenario data, to deal with uncertainty and to aggragate the variety of impact indicators to an overall risk estimation.

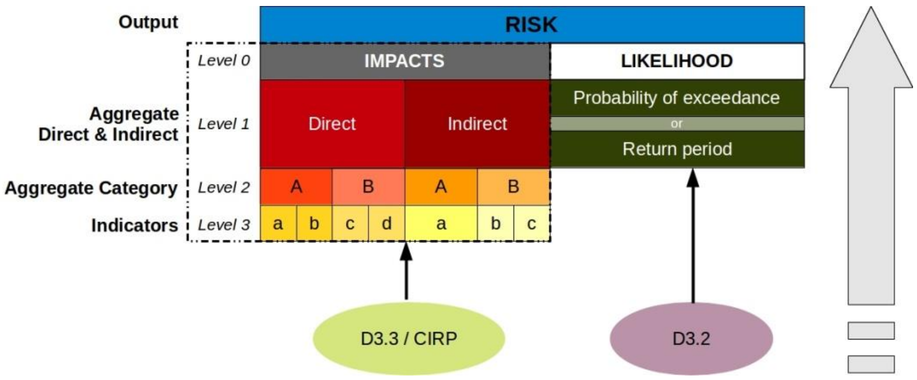

Figure 1: EU-CIRCLE climate change Risk assessment methodology

The selected approaches are suitable to conduct the case study analysis foreseen within EU-CIRCLE but also, they are considered to be of relevance to many other assessment challenges.

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1 Introduction

A reliable and trustworthy infrastructure network of networks in any region is a driver of economic prosperity, quality of life and wellbeing and also a vital element in the response to disasters and major hazards. The consequences of infrastructure disruptions on society and the economy can therefore be devastating, with serious implications for their welfare, safety and capacity to return to normality. The face of climate change, as described by its non-stationary properties, whether it is increased variability and extreme events or a change in the mean values, will have significant impacts on infrastructures as illustrated in D1.2.

It is routine for all CI stakeholders, from operators to emergency responders and policy makers, to take into consideration future climate conditions at all stages of a CI's lifetime, from the planning, building, operating, maintaining, retrofitting and even decommissioning, as described in many national regulations and EC policy documents. The goal of the EU-CIRCLE project is to develop a climate change risk management methodology, for new and existing infrastructures, including long-lived assets that will experience more severe climate conditions over their life spans, to ensure continued delivery of essential services to society.

EU-CIRCLE introduces a conceptual approach, where the decision-making focus is shifted from climate change risk reduction (DRR) to climate resilient infrastructures. Our approach as described in Deliverable D4.1, proposes that infrastructures are operated in a way that not only reduces exposure to climate relevant risks but also maintains service with minimal disruptions, rapidly recovers in case of damage, and adapts to changing conditions in ways that mutually benefits CI operators and society. Within the framework, the present deliverable is key, as it provides a means to establish "climate-resilient" infrastructures that are able to continue their business against diverse climate related risks.

This deliverable introduces a coherent way of assessing the risk of climate change to interconnected CI within a region, that is critically dependent upon the location of infrastructure assets, the assets' condition, and their ability to withstand or adapt to hazards. It is expected that the majority of today's CI will be fully operational over the next several decades, where today's climate model predictions may or may not be realised, and may be exposed to adverse and extreme conditions which could affect their longevity and performance. As a result, it is anticipated that this would lead to increased operating and capital expenditures, shortened life spans, service disruption, or even failure, with significant negative consequences to society, economy and national interests. It is also possible that CI operators will be faced with increased risk premiums. Multiple hazards occurring at the same time or shortly after each other, such as flooding occurring after forest fires or even non-climate related hazards such as earthquakes, could exacerbate climate change impacts, especially if systems are already strained and interdependent.

A key element of the EU-CIRCLE risk assessment is the recognition that CIs are increasingly interdependent, especially in urban areas. The proposed approach takes into consideration the negative impacts that are caused by interconnections and interdependencies, both due to service degradation and CI failure, which may result in societal impacts tens of kilometres away from the original location of the hazard, even crossing borders. Such impacts can range from small, temporary disruptions to major failures causing significant and widespread damages and lengthy recovery times. For example, in the EU-CIRCLE French Case Study, electricity outages set up domino effects which led to road closures, hospital and emergency response delays, problems in water networks and the surrounding industry.

A changing climate can also contribute, along with other factors such as changing demographics, to altering the demand for certain types of infrastructure, such as energy, transportation, and water systems. Demand for energy and water, for example, may rise in response to higher temperatures. As climate-related impacts increase, demographic shifts and changes in land use may occur as people migrate to more hospitable locations, which in turn could change the demand for infrastructure assets and services in these locations. Such risks may affect the EU's effort to transition to a low-carbon economy because it strongly depends on a resilient clean energy infrastructure system and also energy security.

While the type, frequency, and severity of climate-related hazards will vary by location, state of the art research presented in D1.2 demonstrated that CI in nearly all EU regions will be exposed to climate risk. Recent extreme weather events and vulnerability assessments of future conditions together demonstrate that climate change is a significant threat to operations of CI. The present deliverable introduces a coherent risk assessment framework which could provide guidance related to the resilience capacities of CIs i.e. to anticipate the hazard, absorb it, cope with it, recover from it and overall adapting in the long term to future climate conditions.

European infrastructure is ageing and deteriorating, further stressed due to population growth and changing demographics, urbanization, deferred maintenance caused by funding constraints, and technological changes. All these factors combined increase pressure on the infrastructure system that may compromise its resilience capacities to various hazards. Over the five case studies conducted through the EU-CIRCLE project, several different types of damages to infrastructure and resulting cascading failures were studied with the aid of CI operators and stakeholders. As it happened in the Torbay case study, storm Emma[1] which battered the city on the 2nd of March 2018, was a phenomenon far exceeding the climate projections for 50 years and onwards. Thus, the necessity to have a comprehensive foundation to assess climate risk both for present climate conditions and future climate changing conditions is equally vital. Vulnerability and risk assessment forms the bridge to ensuring that climate change is considered in CI design, operation and maintenance, and that highly vulnerable assets are identified early-on so that cost-effective engineering and/or operational solutions can be developed.

In order to derive the methodology described in this deliverable , the consortium has faced several challenges, including: 1) a lack of detailed data from historic disasters especially related to infrastructures; 2) limited access to infrastructure operational information and economic data; and 3) a reluctance from CI operators to participate in research projects. Infrastructure systems designed using inadequate data are vulnerable to failure, compromising public safety and prosperity. This is also the starting point for further using the outcomes of this Deliverable and the project as a whole to provide recommendations for:

- Updating building standards and codes and increasing the technical capacity of CI stakeholders (e.g. governments, funding agencies) involved in all relevant infrastructure decisions.
- Improving the technical and scientific basis for designing, planning, evaluating, and implementing infrastructure projects, services, and systems, taking into consideration the inherent climate risks and also resilient capacities of the CI.
- Ensuring that emergency responders and those that use CI services under stress conditions, such as response to major disasters, better address climate-related risks, costs, and benefits.
- Promoting collaboration across sectors and agencies and supporting coherent decision-making to plan in advance for climate-resilient CIs.

1.1 Working methodology

This deliverable is a joint effort of multiple partners working mainly in WP 3, with contributions from colleagues working on further work packages. Continuation of D3.4 which has been accepted

[1] http://www.torbay.gov.uk/LocalNewsPaperIndex/entry/9f74571b-9ed5-44dc-9735-718e296ff287
https://www.newsflare.com/video/186681/other/storm-emma-batters-torbay-2-march-2018

during the midterm review. The workings steps undertaken to develop this deliverable are the following:

- literature study on frameworks for risk assessment, mainly from the following sources:
  - International standards
  - Description of programmes implemented by cities, regions, nations
  - Meta studies on risk assessment and risk management approaches
- extensive discussion among the WP 3 partners on the suitability, pros and cons of framework approaches
- distillation of most common approach deployed for risk management and preparation of draft framework description
- amendment of classical risk management procedure (eg ISO31000) by aspects introduced with resilience
- extensive discussion with partners involved in WP 5, CIRP development, and WP 6, during the conduction of the EU-CIRCLE case studies
- presentation of risk management approach during the consolidation workshop (May 2016, Milano)
- rework, review and finalization of framework description.

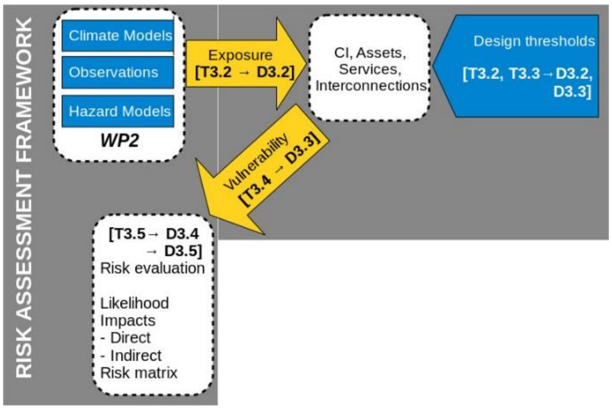


Figure 2: Interconnections between Tasks of EU-CIRCLE concerning Deliverable 3.5

1.2 Links to other WPs

This development takes into consideration the first findings of the work within other work packages, especially from WP 1:

- D1.1:introduces a definition for "risk assessment" as "a methodology to determine the nature and extent of risk by analysing potential hazards and evaluating existing conditions of vulnerability that together could potentially harm exposed people, property, services, livelihoods and the environment on which they depend."
- D1.2: introduces into objectives of risk assessment and approaches from various countries. This deliverable provides also a state of the art review and taxonomy of existing knowledge
- D1.3 introduces to the strategic context which needs to be considered in assessment of risks

- D1.4, which reports on the methodological framework

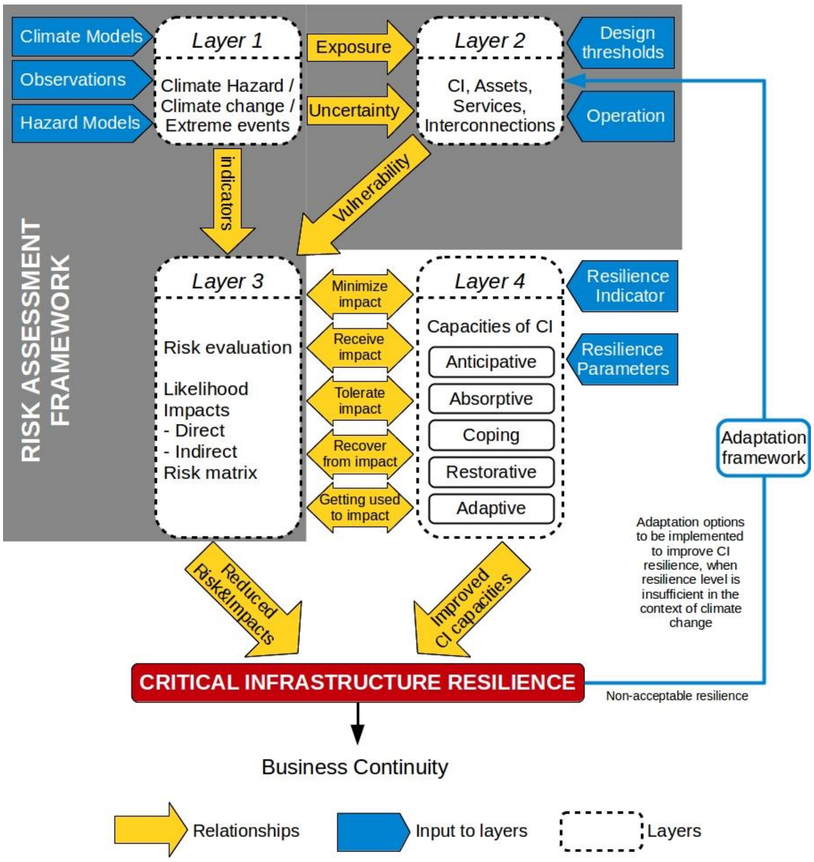


Figure 3: Illustration oft he risk assessment framework implemented in EU-CIRCLE

WP2 provides the necessary climate and hazard information needed for the risk assessement and is utilized for:

- Identify if an asset/network is exposed to the climate variability and extreme events
- Estimates the likelihood component of the risk methodology (Section 3.2)
- Assessing the impacts of the infrastructure to the hazard

More details on specific topics introduced in D3.5 will be reported in deliverables of WP 3, namely:

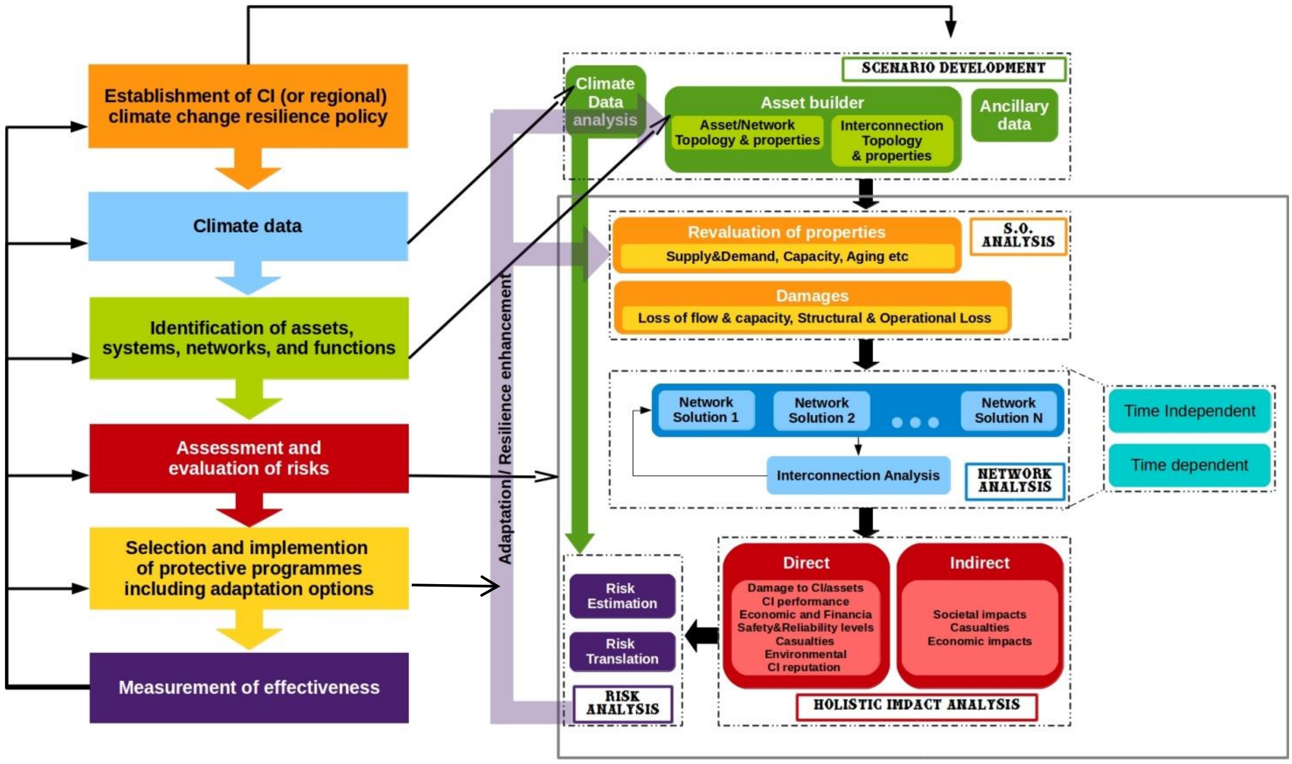
- D3.1: Descritpion of the CI assets and their interconnections
- D3.2: Report of climate related critical event parameters
- D3.3: Inventory of CI impact assessment models
- D3.6. Risk model metadata

Furthermore, this deliverable is linked with WP4:

- D4.1, which defines resilience, provides a resilience framework, defines its constitutent parts and furthermore explains the relation between risk management and resilience
- D4.5 related to the development of D3.5 to reduce the risk and to improve resilience.

2 Risk management approach of EU-CIRCLE

This chapters introduces the EU-CIRCLE risk management framework, through a detailed description of its main components, and potential application in studies related to Critical Infrastructure resilience to climate change. The framework process, schematically depicted in Figure 4, introduces elements from the processing of climate information and related climate hazards (WP2), and the CI resilience and adaptation approach (WP4). The described modeling process to estimate and quantify risk will be introduced into the CIRP (WP5)



Risk management process Risk Modelling process

Figure 4: EU-CIRCLE framework

2.1 Overall concept and process steps

The proposed approach within EU-CIRCLE aims to provide a comprehensive framework to identify the risks of multi – climate hazards to heterogeneous interconnected and interdependent critical infrastructures, as the first step to improving resilience of vulnerable social and economic support systems to climate change impacts while climate proofing existing critical infrastructure (in terms of identifying indicators and reference states, anticipated adaptive / transformation activities, and investment costing).

The infrastructures which are assessed within EU-CIRCLE are highly sensitive to high or low values of meteorological parameters, as identified in "D1.3 EU-CIRCLE strategic context". The analysis of extremes or changing climate patterns is used to determine an optimum balance between 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 such infrastructure on the other hand. Most existing infrastructures have been designed under *the assumption of stationary climate* conditions using historic values and observations. This basic concept assumes that although climate is variable, these variations are however constant with time, and occur around an unchanging mean state. This assumption of stationarity is still common practice for design criteria for (the safety / security levels of) new infrastructure, even though the notion that climate change may alter the mean, variability and extremes of relevant weather variables is now widely accepted. Even new infrastructures, or expansion – adaption of existing ones is typically designed on the basis of historical information on weather and climate extremes as these have been identified in pertinent engineering standards, such as the European standards on structural design (EUROCODES).

Our aim is to use a validated scientific approach based on the existing operational approaches to identify existing, evolving and emerging climate risks/opportunities, vulnerabilities to interconnected infrastructures and adaptation options; approaches that are summarised in the following elements:

- Assessment of risks using improved methods of assessment and new knowledge, from the literature, partners' expertise and opinions of stakeholders.
- Identification of how climate change risks to CI interact with other socio-economic factors to affect the level of risk or opportunity.
- Assessment of the perceived level of "acceptable risk", i.e. the level of risk that each infrastructure owner/operator or societal group is willing to accept before supporting the implementation of any disaster risk reduction and/or climate change adaptation actions
- Estimation of the effect of different risks acting together (multi-hazard), either due to concurrent timing, acting on the same location or the same receptor (coincidence).
- Assessment of how ageing or asset (infrastructure) state deterioration has an impact on risk levels, safety margins and its reliability. Determining whether changing climate patterns in the future should lead to changes in engineering standards and climate thresholds, to make CI more robust to hazards of greater magnitude and frequency.
- Assessment of the magnitude of impact for different hazards and for different impact / consequence categories.
- Assessment of the uncertainties, limitations and confidence in the underlying evidence, data used and analysis for different risks.
- Production of risk estimates that can directly communicate the evidence in such a way that is credible, robust, relevant and can be used to inform decisions (e.g. adaptation, risk reduction) by stakeholders, governments etc.
- Provision of new insights and improved evidence-based analysis of recorded disasters and their major impacts, through their re-examination.

The framework description itself must be flexible and generic enough to facilitate a multitude of different assessment situations, and at the same time provide meaningful guidance and allow to compare outcomes.

2.2 Risk management within EU-CIRCLE

This section is devoted to describing the background to the EU-CIRCLE interpretation of the risk management process. It is based on the following documents and operational contexts:

- International Standards on Risk management ISO 31000 (ISO, 2009), AS/NZS 4360 (AS/NZS, 1999) and subsequent additions.
- Definitions and categorization of interdependencies between infrastructures from Rinaldi et al. (Rinaldi 2001 and 2004),
- The National Infrastructure Protection Plan Risk Management Framework (NIPP) of the U.S. Department of Homeland Security (DHS 2013 a, b) as introduced in chapter 2.

- Analytical steps related to resilience capacities as described in EU-CIRCLE "D4.1 Resilience framework".

Ideal workflows for risk management are provided by international standards such as ISO 31000 (ISO 2009) and AS/NZS 4360. The following figure is taken from ISO 31000 standard and depicts the ideal risk management process.

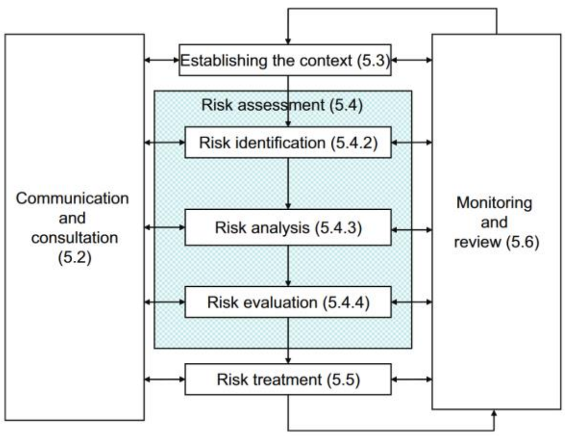


Figure 5: Risk management process proposed by ISO 31000 (ISO31000, 2009)

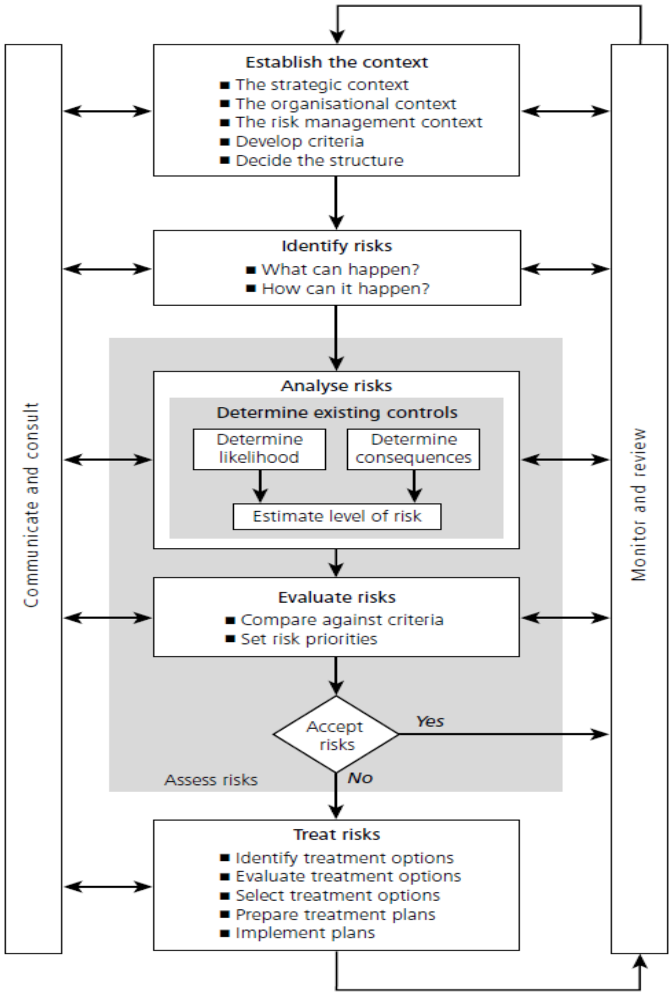


Figure 6: Risk management process proposed by AS/NZS 4360 (AS/NZS, 1999)

Risk management is depicted in both standards identically. However, ISO 31000 is considerably more generic and abstract whilst AS/NZS 4360 provides more concrete advice by means of explanations, definitions and examples. The following figure presents the risk management process as proposed by AS/NZS. However, neither the ISO nor AS/NZS standards on risk management explicitly address resilience as a development objective or as a diagnostic approach.

Comprehensive studies on (national) frameworks as well as software tools dedicated to risk management, including risk assessment, are provided for example by Pederson et al. (2006), Yusta et al. (2011) and Giannopoulos et al. (2012). Yusta analysed 55 methodologies and applications related to risk assessment and discovered variations between them in terms of:

- critical infrastructure sectors considered,
- modelling techniques (such as agent based / systems dynamics / rating / network theory),

- maturity and availability of detailed methodological information and software tools (e.g. restricted access/ commercially available / in development), and
- risk assessment stages actually facilitated.

Further differences can be explained by the target audience. However, commonalities exist in the general approach to how risk is assessed, which is considered for the analytical stages and should be undertaken for the management of risk:

- hazard identification,
- risk assessment,
- prioritization of actions,
- programme implementation, and
- measurement of effectiveness.

Smaller differences obviously exist in the clustering of single procedural steps to more generic, aggregated working stages. For example: "prioritization of actions" can be conceived either as a single working step or can constitute one element within "programme implementation".

The NIPP describes the aim of a risk management framework is to establish the process for combining consequence, vulnerability, and threat information (DHS 2013a and DHS 2013b). It aims to merge the efforts in the protection of critical infrastructures and key resources from both the public and private spheres. The NIPP includes the following steps[2]:

1. Establishment of security objectives
2. Identification of assets, systems, networks, and functions
3. Assessment and evaluation of risks
4. Selection and implemention of protective programmes
5. Measurement of effectiveness

The five working steps of the NIPP provide the frame of reference for the EU-CIRCLE risk management framework, which has being modified according to the project's scope and objectives (Figure 4). The following steps make up the EU-CIRCLE risk management process:

1. Establishment of CI (or regional) climate change resilience policy, or specific business oriented decision that will be addressed within the proposed framework
2. Identification, collection and processing of climate related data and secondary hazards
3. Identification of assets, systems, networks, and functions
4. Assessment and evaluation of risks
5. Selection and implemention of protective programmes including adaptation options
6. Measurement of effectiveness

Step 1 - Establishment of CI (or regional) climate change resilience policy

This step includes the identification of the resilience policy(ies) of a CI or of a region within which interconnected CI networks reside. Typically, these policy objectives have a timespan of multiple

[2] Yusta et al. (2001) describes the NIPP as a six-step process, whereas the DHS call it five-step. DHS aggregates step 3 and 4 as „assess and analyse risks". Content wise, there is no difference.

years and may be related to specific issues or cross-sectoral matters. Typical questions to consider in this step include for example:

- 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?

Within this step, internal and external factors are also identified. According to ISO 31000, these includes – but are not limited - to:

- Social, cultural, political, legal environment;
- Key drivers and trends having an impact on the objectives;
- Policies, strategies already in place;
- Capabilities such as resources and knowledge;
- Organizational structures, roles and accountability, relationships between actors.

Step 2 – Identification, collection and processing of climate related data and secondary hazards

This step involves the identification of the (climate related) pressures and parameters that influence the interconnected network of CI within a region of interest. It involves analysis of the historic climate (and secondary hazard) data, future climate projections from existing databases and/or if this required the provision of specialised simulations.

A particular challenge is to take into account the compound events by using the dependencies that exist, between climate drivers and/or hazards in order to estimate the event's likelihood (see Section 3.2) more accurate. The result can differ considerably compared to the case where all drivers and hazards are treated as independent.

Step 3 – Identification of assets, systems, networks, and functions – Interdependent Infrastructure analysis

This step will identify and characterise the infrastructure that is likely to be affected by climate hazards. In order to achieve this, a structured analysis of all CI elements that provide "critical services" will be undertaken. The following approach is proposed:

- Compilation of a registry of assets for all EU-CIRCLE relevant sectors .
- An analysis of interconnections, networks and (inter-) dependencies including the various types, such as physical, cyber, geographic, logical or social (inter-) dependencies.

An extensive analysis of the CI network(s) asset definition and interconnection is elaborated in D3.4. An extensive analysis and assessment of the identified assets within EU-CIRCLE are delivered in D3.1.

Step 4 – Assessment and evaluation of risks

The primary aim of the EU-CIRCLE framework is to provide a common ground whereby different risk assessment methodologies and modelling schemes, from the critical infrastructure and the natural hazards communities can co-exist and interact in a logical manner. To achieve this, different risk assessment schemes will be harmonized into a single interoperable approach or alternatively "translating solutions" will be created between the different risk approaches.

The minimum basis of the proposed risk assessment framework is to be compatible with

- ✓ the National Risk Assessments
- ✓ EPCIP programme
- ✓ IPCC report
- ✓ Sendai Framework with Disaster Risk Reduction International standards, e.g. ISO 31000 Risk Management.

A common understanding and clear elucidation of the final risk estimation allows for the easy and direct interpretation of the derived risk metric. Within EU-CIRCLE different alternatives could be employed such as numeric estimation of risk (given restrictions in providing a single number from different types of impact estimates) and/or uing the risk matrix approach in accordance with recenet practices and with a finite number of classes. As an example, *risk matrices in national risk assessment plans* have been set with quantified probability/likelihood and impacts/consequences on a 5x5 scale (the Risk Matrix approach in Figure 7), these categories differ and could lead to different interpretations of severity of risks and, ultimately, different conclusions. According to this report some of the risk matrices are numbered 1 to 5 or use letters A to E; 1 and A being low probability/impact and 5 and E being high probability/impact, whereas other approaches use a specific terminology to express ranges.

Additionally, within EU-CIRCLE the “acceptable level of risk” should be determined by users of the CIRP, which will guide the analysis of adaptation policies and mitigation options and provide a reference level for comparison. The acceptable level of risk is a “user defined” parameter.

Probability/Likelihood ↑						
	Very likely/Certainly					**Critical**
	High				**High**	
	Medium			**Medium**		
	Low			**Low**		
	Very low, unlikely	**Very low**				
		Negligible, minor,	Small	Medium, moderate	high	Severe
	Consequences →					

Figure 7. Example 5x5 Risk matrix

The level of very low risk (blue) usually is considered as broadly acceptable or negligible risk. On the other hand, a level of Critical risk (red) is considered as a non-acceptable risk i.e. this risk cannot be justified on any grounds. The rest of the risk levels within the risk matrix (green, yellow and brown) are usually considered as tolerable risk, meaning that it is tolerable only if risk treatment (reduction) is impractical or if its resource requirements (financial and human) are grossly disproportionate to the improvement gained.

The proposed risk modeling approach of EU-CIRCLE is described in section 3.

Step 5 - Selection and implemention of protective programmes including adaptation options

This step involves, according to ISO 31000, the process of “selecting one or more options for modifying risks and implementing those options”. The AS/NZS Standard 4360 formulates:

"Selection of the most appropriate option involves balancing the cost of implementing each option against the benefits derived from it". An ideal work flow for step 5 is proposed by AS/NZS 4360 which is also the basis recommended for EU-CIRCLE. Risk treatment activities need to be identified, selected and implemented, if one or more risks are considered to be non-acceptable.

In detail, this step consists of the following:

- Identification of resiliency enhancement(s) / adaptation option(s), that aim to:
  - reduce the likelihood of occurrence;
  - reduce the impacts / consequences;
  - transfer in full or partly the risk;
  - avoid risk.
- Assessment of the risk treatment, resiliency enhancement , CI adaptation options options
- Preparation of risk treatment, resiliency enhancement , CI adaptation plans
- Implementation of risk treatment plans (out of the scope of EU-CIRCLE)

Within the EU-CIRCLE approach, risk treatment may be approached using a hierarchical strategy and examining different alternative options leading to the elimination and/or reduction of risk levels. The priority of the examined solutions is related to the elimination of an identified risk, followed by suggested actions towards risk reduction. ***The risk treatment options are directly linked to the CI resilience capacities identified in "D4.1 EU-CIRCLE CI resilience framework to climate hazards 1st version".***

Table 1: Link between EU-CIRCLE Risk Management and Resilience

Resilience Capacity (D4.1)	Reduce Likelihood	Reduce Consequences	Transfer risk	Avoid Risk
Anticipatory	X	X	X	X
Absorptive		X		
Coping		X	X	
Restorative		X	X	
Adaptive				X

Step 6 - Measure effectiveness

Once one or more risk reduction measures are introduced, progress towards achieving the objectives must be evaluated regularly. Risks, effectiveness, goals or other circumstances may change after initial implementation. Monitoring and review helps to keep the plans relevant.

Within EU-CIRCLE this step will be implemented during the analysis of the examined case-studies (WP6) in order to assess the capacity of the risk management framework to (according to ISO31000 & NIPP 2013 goals):

- ensure that risk controls are effective and efficient in both the design and operation of CI;
- obtain further information to improve the risk assessment process;

- analyse and learn lessons from events (including near-misses), changes, trends, successes and failures;
- identify when risk treatments and policy objectives must be revised; and
- identify emerging risks.

Horizontal implementation

Within EU-CIRCLE, the Climate Infrastructure Resilience Platform (CIRP) which will inherently include the developed risk assessment framework, will support the climate related policy objectives. These technologies must be adapted to the actual, individual assessment context. The concrete and most relevant results include:

- The definition of goals;
- Nature and types of causes and consequences and how they will be measured;
- Assessment of the likelihood of appearance of a hazard under present and future climate scenarios;
- Timeframes of the likelihood and consequences;
- Identification and specification of the decisions that have to be made;
- Definition of methodologies regarding risk assessment (how is the level of risk determined);
- Determination of a methodology for evaluating effectiveness.

3 Risk quantification

The EU-CIRCLE framework can be simply described as a platform that incorporates a range of analyses and processes in order to estimate the future risk of CIs with and without proposed adaptation actions. Essentially, the result of all analyses, is a variety of indicators that illustrate the consequences of hazard(s) to coupled CIs. The procedure is a series of steps:

- Determine which hazard(s) and CIs are under study
- For each hazard estimate:
  - Exposure [see Deliverable D3.2]
  - Likelihood [see paragraph 3.2 of the present report]
- Utilize various models and methodologies to estimate:
  - CI assets and network damages [see Deliverable D3.3]
  - Network interdependency analysis [see Section 4 of the present report]
  - Impacts [see Section 5 of the present report]
- The results of the models is a variety of indicators (depending on the analysis) that represent the consequences of the hazard to the CIs [see Section 5]

Each indicator examines a different aspect and its meaning, and thus its usefulness, is understandable mainly from an expert. Moreover, the overall risk, that a hazard poses to CIs, is difficult to be quantified. The latter is addressed by transcoding each indicator to a five class scale, and grouping the ones that belong to the same category (see Section 5) sequentially, up to the point that one impact estimation is calculated. By combining the overall impact and likelihood, the risk is quantified. The procedure is described analytically in the paragraphs below.

3.1 Core methodology

The core methodology for quantifying the overall risk is based on a five class scale and a set of mixing rules. Basically, the “reaction” of CIs to a hazard is summed up to a set of indicators that have different units and meaning, depending on the case under study or the calculation the user desires. They can range from *the number of assets fully destroyed* to *total time that person is left without two or more CI services*. The difficulty is to unify the different indicators and assess the overall risk.

In order to calculate the overall impact, a bottoms-up methodology is applied. Each indicator is matched to a class (1 to 5) according to a predefined table (see Section 5 and Annex 2: Impacts classification table). That way a “unification” of units and variables is performed, hence calculations between different indicators is possible. The resulting classification creates the bottom level (Level 3 of Figure 88) of the risk assessment method. As a next step, the impacts are grouped (Level 2) according to the categories described in Section 5 and Annex 2: Impacts classification table, by applying a set of combination rules (average, geometric mean, weighted average etc) that are described in Annex 1: Description of mixing rules. As such, the different levels of risk are constructed up to Level 0. The same procedure is applied for the likelihood. In that case, there is only one level (Level 0) and the classification is performed according to Annex 3: Likelihood classification table. The total risk is the combination of impacts and likelihood.

The current methodology can be used for either a single or combined hazards (see paragraph 3.1.1 & 3.1.2).

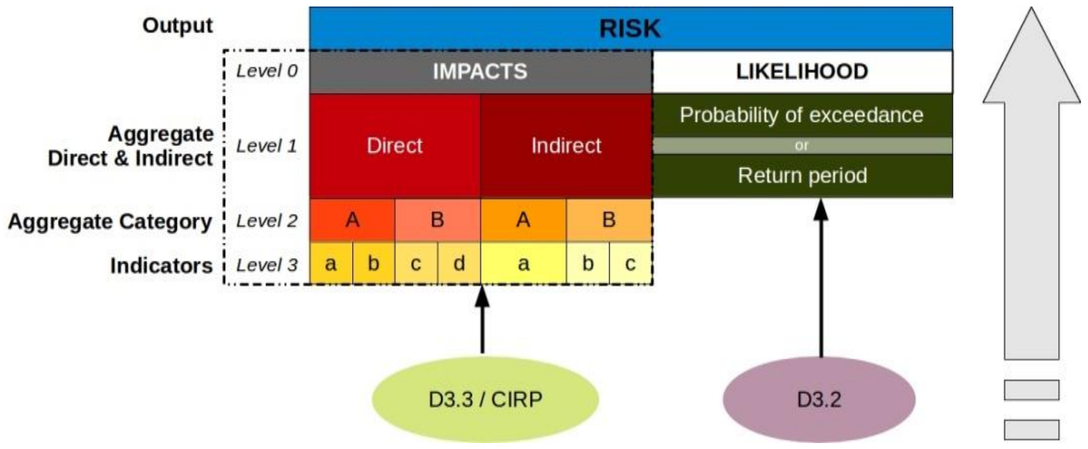


Figure 8 : Illustration of Risk assessment core methodology

3.1.1 Risk from single hazard

The implementation for the single hazard analysis, consists of several steps as it is shown below. In brief, the hazard affects the CI and the impact is matched to a class (Level 3). The impacts are grouped in Levels 2 to 0 to a single class value by applying a set of mixing rules.

A. Hazard

High resolution climate models are used to determine the future hazard and used as input to the EU-CIRCLE framework

B. Estimate likelihood

High resolution climate models are taken into account for calculating the probability of exceedance or/and the return period of a hazard. Then the table in Annex 3: Likelihood classification table is used to match either one to a five class scale, from VERY LOW to VERY HIGH.

C. Estimate consequeces

The consequences to CIs consist of all the analyses that estimate a reaction of the infrastructure to a hazard.

I. Impact models

The impact models are analyses and processes (see Section 4) that result in a range of indicators. The different indicators ara matched to a five class scale, from NEGLIGBLE to SEVERE, using the table in Annex 2: Impacts classification table.

II. Connect to categories

Using the same table as before, the indicators are grouped sequentially until only one value, the overall impact, is estimated.

D. Estimate risk

By combining the overall impact and likelihood, the overall risk is calculated.

Figure 9: Illustration of single hazard risk method

The algorithm scheme is presented below:

- Match likelihood values to 5 classes scale using Table of likelihood
- Match all indicators of level 3 to 5 classes scale using Table of indicators
- Combine indicators in “units” of 5 classes for each level using one of the methods:
    - Average, or
    - Geometric mean, or
    - Weighted average etc.
- Combine indicators of level 3 to complete level 2 and repeat procedure until level 0
- Combine likelihood with impact of level 0 to create risk indicator

3.1.2 Compounded hazard

A combination of sequential physical processes, appearing as a result of escalated hazards with multiple events causing extensive damage or impact, are referred to as a Compound Hazard (UN 2014: Compound Disasters and Compounding Processes – Implications for Disaster Risk Management). Examples of high –impact Compound Events include (i) droughts, heatwaves, wildfire (ii) extreme precipitation and storm surge interactions. In case of climate change impact studies, the analyses of impact of future hazards becomes difficult.

The EU-CIRCLE framework incorporates the Compound Hazard in “Estimation of likelihood” step (see paragraph 3.2), in order to quantify the risk in future CIs as accurately as possible. The procedure is the same as before, with a different calculation in step A (likelihood step).

A. Hazard

High resolution climate models are used to determine the future hazard and used as input to the EU-CIRCLE framework

B. Estimate likelihood

<u>The sequential occurrence of climate drivers</u> in high resolution climate models are taken into account for calculating the probability of exceedance or/and the return period of a hazard. Then the table in Annex 3: Likelihood classification table is used to match either one to a five class scale, from VERY LOW to VERY HIGH.

C. Estimate consequeces

The consequences to the CIs consist of all the analyses that estimate a reaction of the infrastructure to a hazard.

I. Impact models

The impact models are analyses and processes (see Section 4) that result in a range of indicators. The different indicators ara matched to a five class scale, from NEGLIGBLE to SEVERE, using the table in Annex 2: Impacts classification table.

II. Connect to categories

Using the same table as before, the indicators are grouped sequentially until only one value, the overall impact, is estimated.

D. Estimate risk

By combining the overall impact and likelihood, the overall risk is calculated (as described in Annex 4: Combination table of Impact and Likelihood).

3.1.3 Multi-hazard risk assessment

In case of combined hazards, the same procedure applies as many times as the number of hazards. In the end the different risks indicators, can be compared and/or combined into a single one, using the same set of combination rules.

A. MultiHazard

High resolution climate models are used to determine the future hazards and used as inputs to the EU-CIRCLE framework

B. Estimate likelihood of multiple hazards indepentently

High resolution climate models are taken into account for calculating the probability of exceedance or/and the return period of a hazard. Then the table in Annex 3: Likelihood classification table is used to match either one to a five class scale, from VERY LOW to VERY HIGH.

C. Estimate consequeces of multiple hazards indepentently

The consequences to the CIs consist of all the analyses that estimate a reaction of the infrastructure to a hazard.

I. Impact models

The impact models are analyses and processes (see Section 4) that result in a range of indicators. The different indicators are matched to a five class scale, from NEGLIGBLE to SEVERE, using the table in Annex 2: Impacts classification table.

II. Connect to categories

Using the same table as before, the indicators are grouped sequentially until only one value, the overall impact, is estimated.

D. Estimate risk of multiple hazards indepentently

By combining the overall impact and likelihood, the overall risk is calculated (as described in Annex 4: Combination table of Impact and Likelihood).

E. Compare different risks

The multiple risk values that are estimated, can be compared and the useful information for each hazard can be deduced indepentently.

F. Combine risk

Using the same method of combination as before, the multiple risks are combined and the overall risk of the multi-hazard case is estimated.

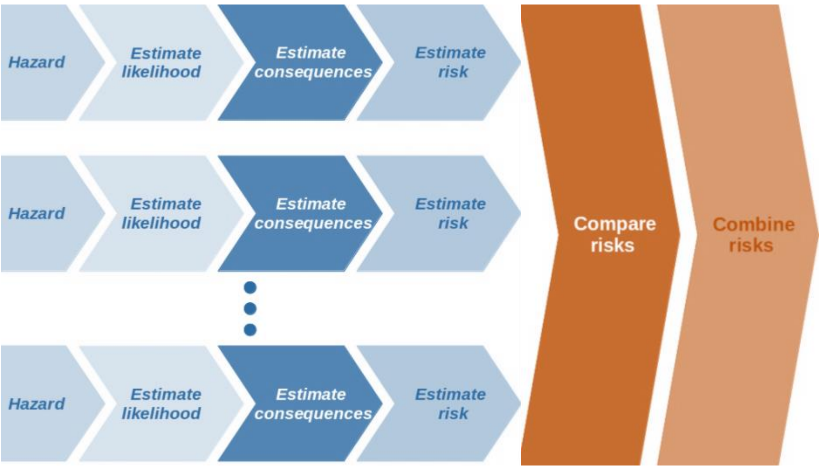


Figure 10: Illustration of multi-hazard risk method

The algorithm scheme is presented below:

- Match likelihood values to 5 classes scale using the Table of likelihood
- Match all indicators of level 3 to 5 classes scale using the Table of indicators
- Combine indicators in “units” of 5 classes for each level using one of the methods:
    - Average, or
    - Geometric mean, or
    - Weighted average etc.
- Combine indicators of level 3 to complete level 2 and repeat procedure until level 0
- Combine likelihood with impact of level 0 to create risk indicator
- Repeat procedure for different hazards and compare risk indicators

3.2 Likelihood

Likelihood (probability of occurrence) refers to the initial probability of a risk scenario to occur and is usually defined as:

- frequency of one or more incidents at various time scales (as defined by CZ, IE, LT, NO, PL, HU in their NRAs)
- probability of occurrence within 1 year (as defined by EE, EL in their NRAs)

Within EU-CIRCLE the number of different categories of likelihood/probability of occurrence can be user defined, although the most common approach (e.g. NRAs) followed is the 5x5 risk matrix process:

VERY LOW or VERY RARE	**LOW**	**MEDIUM**	**HIGH**	**VERY HIGH or VERY LIKELY**

The levels of likelihood, in the framework of EU-CIRCLE, are defined by the internationally accepted descriptive terms, classified into a set of five categories, corresponding to numerical values from the NRAs and IPCC (Table 2)[3] :

Table 2: Examples from classifications of likelihood by the MS in their NRAs.

<table>
<tr><th>Country</th><th colspan="2">Very Low</th><th>Low</th><th>Medium</th><th>High</th><th colspan="2">Very High</th></tr>
<tr><td>CZ</td><td colspan="2">Occurs less than once in 1000years</td><td>Occurs once in 100 – 1000 years</td><td>Occurs once in 10 – 100 years</td><td>Occurs once in 1– 10 years</td><td colspan="2">Occurs more than once in 1year</td></tr>
<tr><td>EE</td><td colspan="2">Probability within 1 year: 0.005% to 0.05%</td><td>Probability within 1 year: 0.05% to 0.5%</td><td>Probability within 1 year: 0.5% to 5%</td><td>Probability within 1 year: 5% to 50%</td><td colspan="2">Probability within 1 year: 50% +</td></tr>
<tr><td>EL</td><td colspan="2">Probability within 1 year: less than 0.001%</td><td>Probability within 1 year: 0.001% to 0.01%</td><td>Probability within 1 year: 0.001% to 0.01%</td><td>Probability within 1 year: 0.01% to 0.1%</td><td colspan="2">Probability within 1 year: more than 1%</td></tr>
<tr><td>IE</td><td colspan="2">Once every 500+ years</td><td>Once every 100-500 years</td><td>Once every 10-100 years</td><td>Once every 1-10 years</td><td colspan="2">More than once every 1 year</td></tr>
<tr><td>LT</td><td colspan="2">Less than once in 100 years</td><td>Once in 50 to 100 years</td><td>Once in 10 to 50 years</td><td>Once in 1 to 10 years</td><td colspan="2">More often than once a year</td></tr>
<tr><td>PL</td><td colspan="2">1 in 500 years or even more rarely</td><td>1 in 100 years</td><td>1 in 20 years</td><td>1 in 5 years</td><td colspan="2">Once a year or more</td></tr>
<tr><td>SE</td><td colspan="2">≤0.0001 on a yearly basis</td><td>0.0001 – 0.001 on a yearly basis</td><td>0.001 – 0.01 on a yearly basis</td><td>0.01 – 0.1 on a yearly basis</td><td colspan="2">>0.1 on a yearly basis</td></tr>
<tr><td>UK</td><td colspan="2">Between 1 in 20,000 and 1 in 2000</td><td>Between 1 in 2,000 and 1 in 200</td><td>Between 1 in 200 and 1 in 20</td><td>Between 1 in 20 and 1 in 2</td><td colspan="2">Greater than 1 in 2</td></tr>
<tr><td>IPCC</td><td>Exceptionally unlikely</td><td>Very unlikely</td><td>Unlikely</td><td>Medium</td><td>Likely</td><td>Very likely</td><td>Virtually certain</td></tr>
<tr><td>IPCC</td><td><1%</td><td>1-10%</td><td>10-33%</td><td>33-66%</td><td>66-90%</td><td>90-99%</td><td>>99%</td></tr>
</table>

The table presented in Annex 3: Likelihood classification table, or Table 3, is the transformation matrix prosposed within the EU-CIRCLE project, and can be modified according to selected application.

Table 3: Likelihood classification table

	VERY LOW	**LOW**	**MEDIUM**	**HIGH**	**VERY HIGH**
LIKELIHOOD/CLASS	1	2	3	4	5
Return Period	Occurs less than once in 100 years	Occurs once in 50 – 100 years	Occurs once in 10 – 50 years	Occurs once in 1– 10 years	Occurs more than once in 1 year
			or		
Probability of occurence	Probability within 1 year: 0.005% to 0.05%	Probability within 1 year: 0.05% to 0.5%	Probability within 1 year: 0.5% to 5%	Probability within 1 year: 5% to 50%	Probability within 1 year: 50% +

[3] Note that IPCC also uses a different terminology for the likelihood of an event.

Moreover, there are cases that a climate driver isn't characterized as a hazard, but a sequential appearance of different drivers, which change the propability of occurrence of a hazard. Such a hazard is called compound. The EU-CIRCLE framework incorporates compound hazards in likelihood estimation. Besides the frequency of one or more incidents, the calculation takes into account the probability of occurrence of climate drivers that enhance the hazard under investigation.

3.3 Impact

Consequence of a risk is defined as a measure of the disruption and impact of a climate hazard not only on a single asset, but to society in general and is thus used in conjunction with likelihood to assess its overall severity. Such an approach proposed within the EU-CIRCLE framework for the determination of the incident consequences will build upon a two level hierarchy. The proposed analysis within EU-CIRCLE tries to incorporate two conceptually different but highly interrelated types of impacts that clearly identify the influence of interconnected critical infrastructures on society and its functioning.

Thus, a two tier approach is proposed where:

- ***Direct impacts*** to the interconnected CI network are identified, and described and quantified through different indicators; and
- ***Indirect impacts*** to society, that arise due to the inability of CI to function according to their intended scope.

A more detailed description of the impact categories and subcategories can be found in Section 5 and the proposed table is presented in Annex 2: Impacts classification table

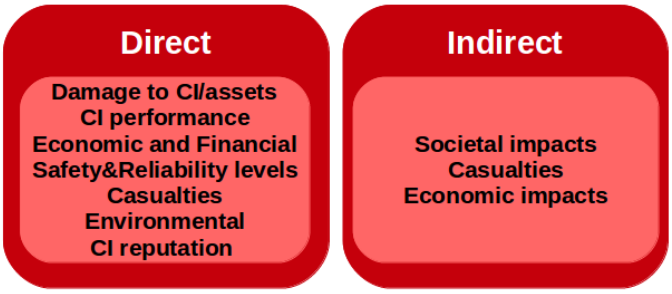


Figure 11: Proposed direct and indirect impacts (selection)

3.4 Risk matrix

As an example, *risk matrices in national risk assessment plans* have been set with quantified probability/likelihod and impacts/consequences on a 5x5 scale (the Risk Matrix approach in Figure 77), these categories differ and could lead to different interpretations of severity of risks and, ultimately, different conclusions. According to this report some of the risk matrices are numbered 1 to 5 or use letters A to E – 1 and A being low probability/impact and 5 and E being high probability/impact, whereas other approaches use a specific terminology to express ranges.

Additionally, within EU-CIRCLE the "acceptable level of risk" should be determined by users of the CIRP, which will guide the analysis of adaptation policies and mitigation options and provide a reference level of comparison. The acceptable level of risk is a "user defined" parameter.

Probability/Likelihood ↑	Very likely/Certainly					**Critical**
	High				**High**	
	Medium			**Medium**		
	Low			**Low**		
	Very low, unlikely	**Very low**				
		Negligible, minor,	Small	Medium, moderate	high	Severe
	Consequences →					

Figure 12. Example 5x5 Risk matrix

The level of very low risk (blue) usually is considered as broadly acceptable or negligible risk. On the other hand, a level of Critical risk (red) is considered as non-acceptable risk i.e. this risk cannot be justified on any grounds. The rest of the risk levels within risk matrix (green, yellow and brown) are usually considered as tolerable risks, meaning that it is tolerable only if risk treatment (reduction) is impractical or if its resource requirements (financial and human) are grossly disproportionate to the improvement gained. The table used in EU-CIRCLE framework is presented in Annex 4: Combination table of Impact and Likelihood.

4 Modelling risk within EU-CIRCLE

The EU-CIRCLE approach for assessing risk can be used to support the entire project's objectives and scope of assessing an interconnected infrastructure's exposure to climate stressors and determining which hazards carry the most significant consequences (section 5) leading to an assessment of their present day resilience. **The Consequence – based Risk Management (CRM) generic approach has been selected**, and analyzed in the following paragraphs to support the intended analysis of EU-CIRCLE. The key advantage of this approach is that it uses an optimization-based prescriptive model of system operation as the starting point for the study of infrastructure behaviour: *these models inherently accommodate disruptions to infrastructure as straightforward changes to input data* (Kim (2008), Gardoni (2009), Garcez & Almeida (2014), Wennersten et al. (2015), Shand et al. (2015)).

The proposed modeling approach encompasses an identity simulation of infrastructures' operating protocols, mimicking decisions for sustaining flow of services using quantitative tools that can help determine how to operate a system, even in the presence of disruptions. This technique requires that the essential domain-specific details about the infrastructure system's operation in terms of its operator's goals and the limitations on its capabilities are captured and depicted. It also incorporates unambiguous measures of system performance for the infrastructure, and of the different business continuity alternatives and adaptation measures to be introduced.

A special feature of the applied CRM approach is that it places the modelling and analysis of interconnected and interdependent infrastrutcures as a core component. CIs are fundamentally (inter-)connected through a wide variety of mechanisms and dependency types (Rinaldi et al., 2001), such that a mutual relationship exists between the states of any given pair of components in the systems and/or networks. For instance, power grids depend on gas networks to fuel generation units. Water networks provide cooling and help to control emissions from coal-based power generators. Water and gas networks are heavily dependent on power for operating pumping stations and control systems. If a particular system is damaged, this damage is propagated to other systems due to the interdependent nature of the systems (i.e., cascading failures). Therefore, an emerging need exists for modelling complex and interdependent critical infrastructure to better understand their susceptibility to potential hazards.

Consequence-based Risk Management has been used in climate/disaster risk reduction across regions or systems that incorporate identification of uncertainty in all components of climate risk modeling and quantify the risk to societal systems and subsystems (Kumar (2015), Cimallaro (2016)). It also enables policy-makers and decision-makers to ultimately develop risk reduction strategies and implement mitigation actions. The result of this action will be introduced into the Climate Infrastructure Resilience Platform, an IT tool that integrates spatial information, data, and visual information into an environment for performing climate loss assessment and analysis. The developed interface integrates a variety of data types aand sources from diverse users and CI stakeholders. The proposed EU-CIRCLE risk methodology facilitates the definition and connection of CI specific and generic analyses to create workflows, explore and introduce new scientific possibilities by creating new workflows from the existing components.

A workflow of the EU-CIRCLE variant of the CRM process (Figure 13) where different climate hazards (scenarios) will be examined corresponding to specific policy/scientific questions such as those described in D1.3 and D1.5 are illustrated below:

- What is the current risk level of one infrastructure in a region, due to a specific climate hazard, and how is the risk estimate anticipated to change in the future?

- Which asset of an infrastructure is most vulnerable to extreme events, and could propagate its impacts to other interconnected infrastructures' assets?
- What is the most damaging climate hazard in a region? how is this attributed to its constitutional elements (society, economy, etc)? how will its behaviour change in the future?
- How resilient are the infrastructures of a region to a specific climate hazard?
- Which is the optimal adaptation measure for an infrastructure under a list of potential alternatives? Is the same adaptation measure also beneficial for other climate hazards?

Scenarios will be simulated and assessed starting from **a baseline scenario** (without the presence of a hazard) and compared to the impacts from another scenario run (with the presence of hazards). In general, damages derived from hazard events can be described through damage functions on the critical parts of Critical Infrastructures assets which directly or indirectly affect demand, supply, and capacity on the networks nodes which in turn results in changes of the network's attributes. Subsequently a simulation will be performed consecutively on the CI network (e.g. starting from the electricity network) and then to another network (e.g. transportation) and so on, until all parts of the interdependencies between networks (e.g. electricity and transportation network) are accounted for. During the preliminary analysis, damages-impacts are placed into the interconnected network, while in the last step, an analysis of the new modified interdependent network is performed comparing the results with those of the basic scenario analysis, in order to define on the one hand which assets are affected while on the other hand to predict network functionality. The consequence of a risk is defined as a measure of the disruption and impact of a incident not only on a single asset, but on society in general and is thus used in conjunction with likelihood to assess its overall severity by combining the likelihood and the consequence assessments using a 5-categories risk matrix. This matrix constitutes the basis of our risk assessment framework. It is an important tool used to map each combination of likelihood, probability and consequence severity to a single risk level (Very Low, Low, High, Severe and Critical).

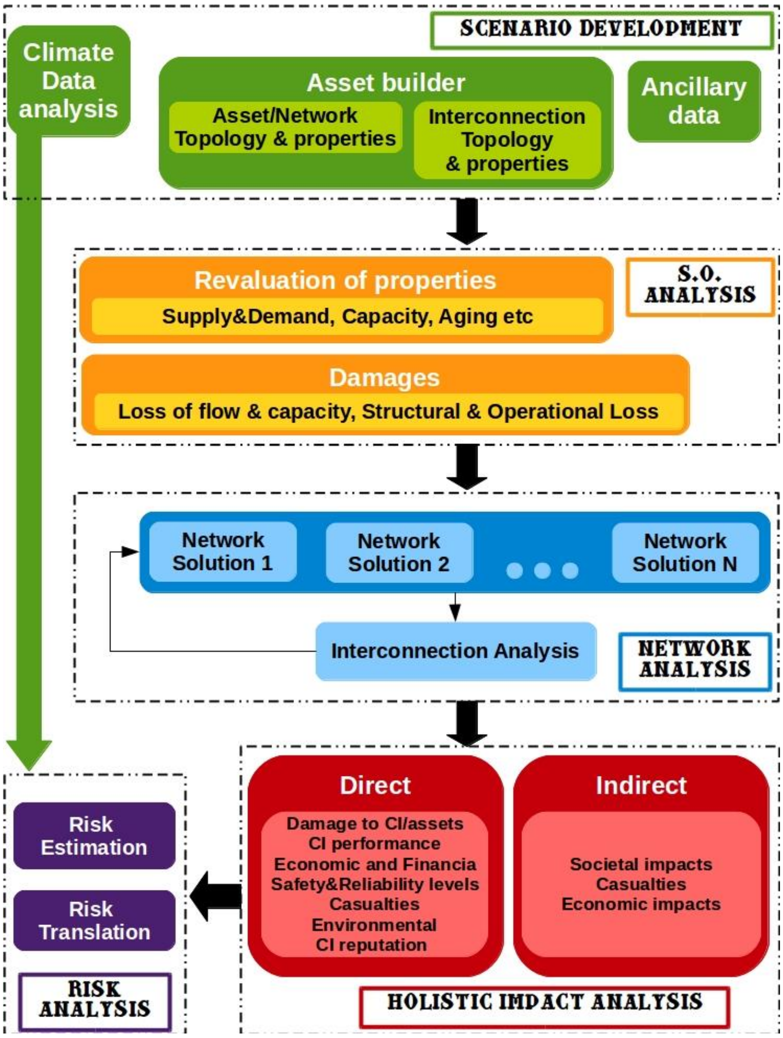


Figure 13: EU-CIRCLE generic risk modelling methodology

The proposed CRM approach within EU-CIRCLE has the following features

- ✓ Arbitrary level of spatial disaggregation depending on the desired analysis;
- ✓ Attention to different timescales, which is highly dependent on the climate information used;
- ✓ Multi-hazard risk assessment with cross-sectoral interactions assessment;
- ✓ Consideration of resilience capacities - adaptation options.

The EU-CIRCLE modelling approach, implementing the CRM, that will be implemented in CIRP, can be categorized in five distinct steps as schematically demonstrated in Figure 133 and analysed in the following paragraphs, namely 1) Scenario Development SD, 2) the Structural & Operational analysis SO, 3) the Network analysis NA, 4) Impacts assessment IA and 5) Risk and Resilience estimation RR; the links of which to the EU-CIRCLE risk management process is presented in Figure 4.

Model Step 1: Scenario Development (*SD*) constitutes the initial phase of the proposed approach whereby:

- the scientific question or policy objective is determined as well as a selection/processing of the existing data needed to reach the overarching objective
- the climate data from multiple sources are processed and ingested
- The network(s) is created using a network builder tool from inputs including the topology, properties and interconnections of CI assets. The resulting infrastructure consists of connections between nodes of the same networks, interconnections between different networks, flow values that characterize the link between nodes and capacity as a property of nodes.

The result of the network builder combined with the climate data are used as inputs for the second step.

Model Step 2: The Structural & Operational (SO) analysis accept as input the constructed network –and- climate data and returns as output quantifiable information on how different assets react to different intensity events (see D3.3). The asset behavior can be deduced via, fragility equations, tabulated values and/or any other model that express changes from the normal state due to a hazard. Two different options exist:

- changes to network properties which include changes in supply and demand of nodes and capacity of links, without any physical or operational damage.
- changes to the network properties due to structural damages (partial or full), personnel loss, etc.

Model Step 3: The Network analysis (NA) procedure utilises the results of the SO step and calculates for each network the simulated flow and estimates how each network affects its interconnected networks; see Section 4.1 of this document.

Model Step 4: The Holistic impact analysis (IA) is conducted where the quantified impacts due to the hazard under examination are calculated using the results of the NA step and other relevant information from the SO analysis (see D3.3). The impacts include direct consequences to the infrastructure and also impacts to society.

Model Step 5: The Risk and Resiliency Analysis (*RR*). Using the estimated likelihood of the event (step1) and the results from the impact analysis (step4), the risk of a specific hazard is estimated and the resilience of the network (RR) is calculated.

Due to existing assumptions, simplifications, and discretization of analysis parameters, the assessment results will contain uncertainties. The accuracy of the description of the assets, their properties and how they react to a hazard, and the hazard itself, are uncertainty factors in the methodology. In order to make the results produced more accurate and reliable, it is necessary to improve the description and information of the infrastructure and to perform a sensitivity analysis concerning the hazard chosen, the fragility and damage curves/functions and the discretization of the topology.

The goal of the proposed approach is to enable us to perform extensive simulations of heterogeneous and interconnected networks, such as water, energy, transport, ICT, also allowing for the total (100% reduction) or partial loss of service. This can be achieved with the description of networks as a set of nodes and links between them. Moreover, connections between different kinds of networks are necessary in order to carry out interdependency analyses between different kinds of networks. Thus, the network analysis methodology can be categorized horizontally, that means each network is solved separately, and vertically , which refers to capturing the effect from one network to another. After the completion of network analysis and interdependency analysis, a holistic impact analysis and a risk assessment can be performed.

4.1 EU-CIRCLE supported analysis

4.1.1 Maximum hazard

In the EU-CIRCLE framework, a first approach to estimate the effect of a hazard to the CI under study, is the Maximum Hazard analysis. The idea is to use the maximum impact of the hazard to each CI asset. This is accomplished by using:

(a) the values of the hazard, and

(b) the behaviour of the each asset expressed in terms of fragility equations, tabulated values and/or any other model that express changes from the normal state.

By applying the hazard uniformly to all the assets and calculating the effect to each one, a first indication of the vulnerability can be deduced for each asset independently.

4.1.2 Dynamic scenario simulation

In case that the hazard input is time-dependent, the same approach as before (see 4.1.1) can be implemented but for each time-dependent value of the hazard. It is noted that for each time-step i, the CI state of time-step i is the result of time-step $i-1$. The result is processed and can give a rough estimation of the behavior of the CI, during the evolution of an extreme event.

4.2 Network performance decay / degradation due to climate change

Taking into account the importance of the effectiveness of the safety and operating processes of interconnected infrastructures and the change of behaviour due to climate stressors, the safety and reliability states can be used as an impact indicator. As such the following indicators may be used:

- the mean lifetime of the component / asset in the safety state subset $\{u, u+1, ..., z\}$
- the standard deviation of the component / asset lifetime in the safety state subset $\{u, u+1, ..., z\}$
- the intensity of ageing of the critical infrastructure component Ei/the intensity of critical infrastructure component Ei departure from the safety state subset $\{u, u+1, ..., z\}$
- the critical Infrastructure mean lifetime $T(r)$ up to exceeding critical safety state r
- the standard deviation of the critical infrastructure lifetime $T(r)$ up to the exceeding the critical safety state r

Mode	Example of Infrastructure Asset	Design Lifetime	Potential Climate-Related Vulnerabilities
Trans-portation	Paved Roads	10-20 Years	Softening, deterioration, and buckling caused by heat. Scour (or sediment removal) and erosion caused by flooding and storm surge. Sea level rise inundation. Accelerated corrosion in coastal areas caused by sea level rise. Road closures caused by landslides and washouts during heavy precipitation events. Damage to foundation caused by changes in soil moisture.
	Rail Tracks	50 Years	Buckling and deformation caused by heat. Scour and erosion caused by flooding, storm surges, and extreme precipitation events. Railway subsidence caused by groundwater depletion.
	Bridges	50-100 Years	Erosion and scour caused by flooding, storm surges, and sea level rise inundation. Accelerated corrosion in coastal areas caused by sea level rise and saltwater intrusion. Reduced vertical clearance over major waterways caused by sea level rise. Damage to foundation by changes in soil moisture or higher waterway levels.
Energy	Transmission Lines	50 Years	Lower transmission efficiency caused by increased temperatures; peak demand during highest temperatures compounds vulnerability. Wooden utility poles destroyed and damaged in wildfires. Lines disrupted or shut down by smoke and particulate matter ionizing the air and creating an electrical pathway away from transmission lines.
	High-Voltage Transformers	40 Years	Service disruptions caused by more frequent and severe precipitation events, flooding, and wildfires. Lower transmission efficiency caused by increased temperatures.
	Generating Plants and Substations	35-80 Years 35-45 Years	Inundation of coastal power plants and substations caused by king tides, storm surge, and sea level rise. Service disruptions caused by more frequent and severe extreme heat, precipitation events, flooding, and wildfires.
Water	Reservoirs and Dams	50-80 Years	Lower water availability caused by higher temperatures and droughts in some regions can decrease water supplies and hydropower. More severe precipitation events threaten dam integrity or dam breaching. More frequent and severe wildfires leave ash and eroded sediment in drinking water supplies.

	Treatment Plants and Pumping Stations	60-70 Years	System overwhelmed with storm water resulting from more extreme precipitation events and, in coastal areas, with seawater driven by storm surge. Increased water quality treatment needs during drought periods.
	Drinking Water Distribution and Storm and Sewage Collection Systems	60-100 Years	Storm water management and collection complicated by more extreme precipitation events and changes in water availability caused by higher temperatures.

Table 4 : Average life expectancy of selected infrastructure types and potential climate-related vulnerabilities

4.3 Proactive maintenance

Proactive maintenance is a management strategy to provide and maintain the service of CIs. It is a strategy to select most effective treatments to preserve assets, to retard their future deterioration and to maintain or to improve their functional condition. Proactive maintenance typically includes corrective and preventive maintenance as well as minor rehabilitation. In case of climate change a multi-year planned strategy can be more beneficial from the user, owner and environmental prespective.

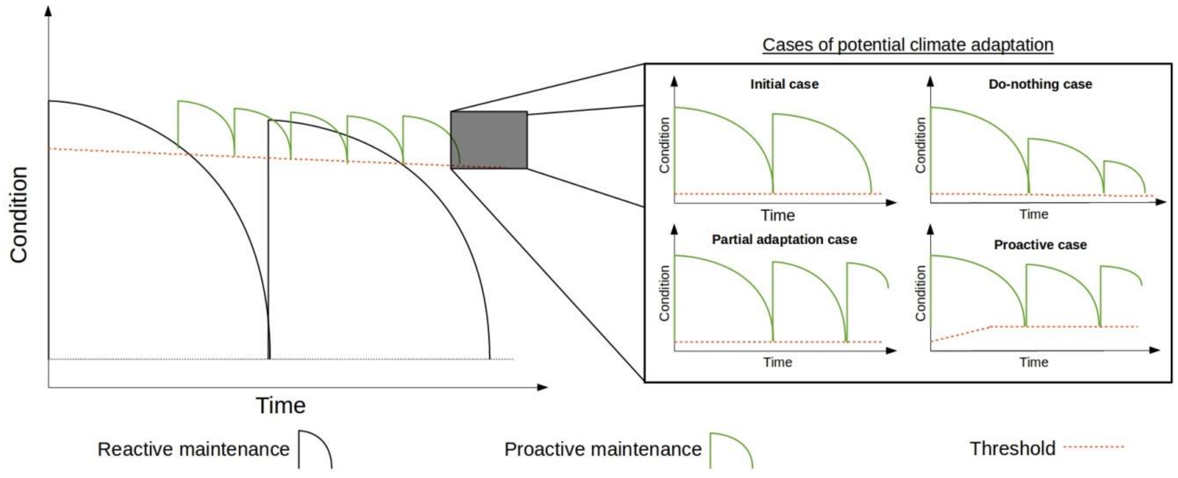


Figure 14: Illustration of proactive and reactive maintenance approach

Four different cases are presented in Figure 144, as a potential progress to mitigate the climate-related effects:

1. **Initial scenario** (no climate change): traditional approach (no preservation approach)
2. **Do-nothing** (climate change): inadequate activities; shorter initial performance gains and steeper deterioration curves; passive adaptation – no change in threshold; results: poor condition, high user and agency costs, safety concerns.
3. **Partial adaptation** (climate change): adaptation; full performance recovery and much better resilient performance; still no change in threshold.
4. **Proactive adaptation** (climate change): adaptation; full performance recovery and fully adapted resilient performance; adjusted condition threshold; inevitable higher agency costs as compared to initial case but enhanced overall condition that leads to improved safety levels.

4.4 General network description

In the general EU-CIRCLE framework, the examined network consists of Generation (Supply) nodes G that produce the flow PR of services (either energy, water, transport of goods, data in the ICT domain, chemical prodcuts) in the links, Distribution(Demand) nodes D that consume the flow CS and Intermediate nodes $I$where the incoming flow is transmitted. These nodes are assets of the infrastructures with discrete properties and whose properties (such as the capacity) may (or maynot) be impacted by a specific climate hazard.

There are specific cases where a node has both properties of Generation and Distribution node without being at network endpoints, simultaneously, such a chemical factory that receives a flow of chemicals and produces a flow of a transformed product. The links are characterized by a value $f$equal to the flow multiplied by a "cost" number. The term "cost" expresses a property of the link that affects the flow, for example in electric grids, the loss of voltage due to distance can be defined as "cost". The "cost" parameter, in our approach, is used in order to mathematically express our problem in terms of minimum cost and maximum flow optimization.

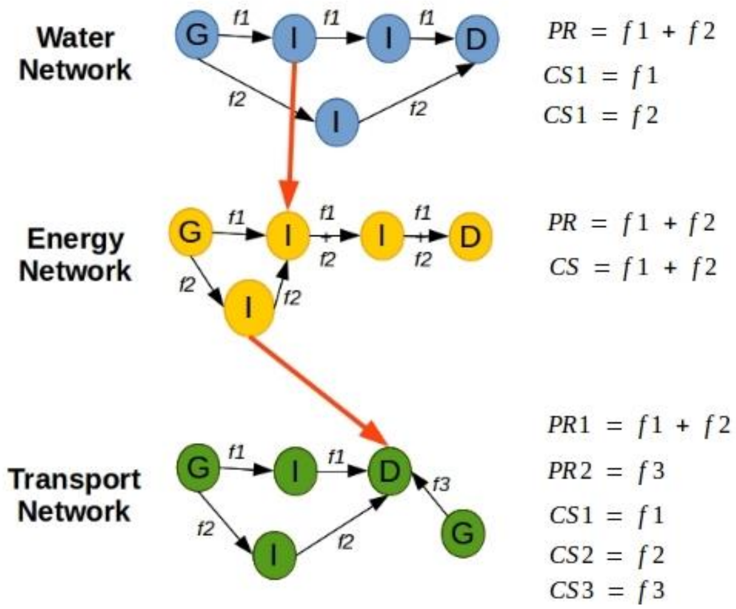


Figure 15: Three type network representation

4.4.1 Asset / Network Dynamics during extreme condiitons

EU-CIRCLE also accounts for the dynamics of an infrastructure (or in one of its assets), when under stress from a climate hazard. Again this is related to the state of the asset, which can be directly translated to the performance level of the infrastructure. This section is mainly relating to describe the main temporal stages of a hazard.

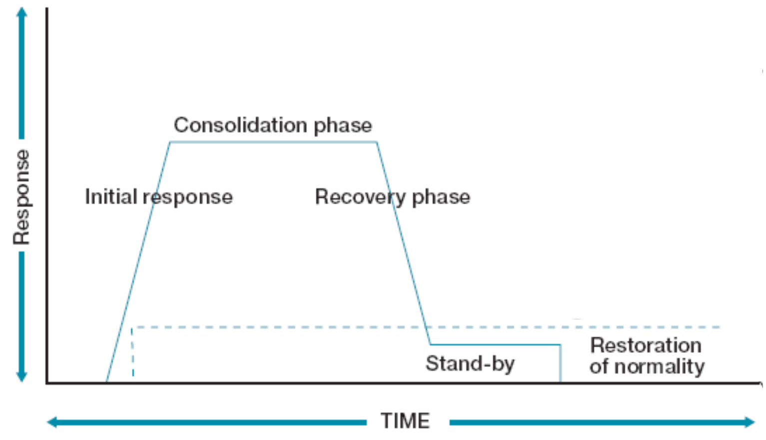


Figure 16: Time stages of hazard

The CI / asset will fall in different states during each of these stages, which according to the EU-CIRCLE procedure are translated into capacity levels or system performance levels.

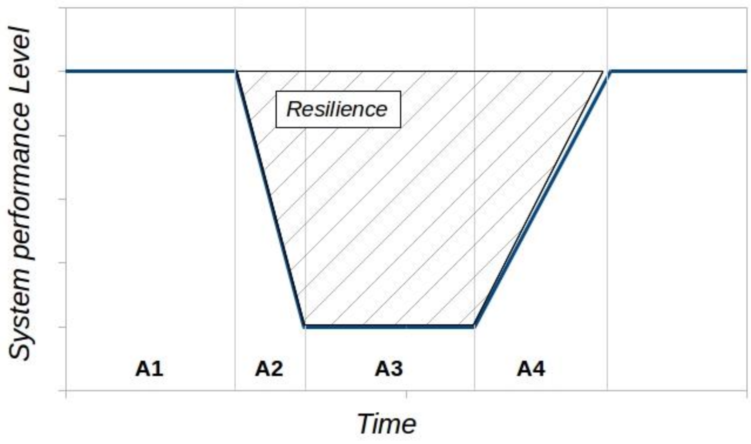


Figure 17: Asset response over time.

This process can be approximated in discrete stages, prevention stage, damage stage, response and assessment stage, recovery stage and restoration to normality. These three stages can be an inherent reflection of the resilience capacities (see D4.1 EU CIRCLE CI Resilience Framework to climate hazards – first version) of the system. Overall the system's present resilience is defined/quantified as the area of the inverse trapezoid in Figure 17. In detail:

- A1 (normality) depicts the normal state of the CI during which the system shows no degradations. The incident may have occurred or not but the CI remains unaffected.
- A2 (absorb) depicts the immediate post-incident time interval during which the system shows performance degradations. This is the phase of the plastic degradation of service-supply, in the sense that the system would not be able to recover its full functionality without human intervention. If a time dependent simulation is chosen, then caution should be made that the CI maximum capacity reduction limts (e.g. due to damages) are reached for the hazard under examination, before proceeding into the next interval.
- A3 (response) depicts the interval of time during which the degradation of the system performance is stabilized. No additional degradation is observed but the recuperation of the system functionality is not observed either. During this stage, coping with the catastrophic

events occurs and alternative options to maintain or/and replace the services materialize.

- A4 (recovery) depicts the interval of time during which the recovering actions are progressively undertaken. This is related to the ability of a CI to continue services and reconnects with its operational environment.

This concept has been also used in Ganin et al. (2016), Bruneau and Reinhorn (2007) and Cimellaro et al. (2009) that introduced the time element in the CI modeling process. The element of recovery time was introduced by (Porter et al. (2001); Bruneau and Reinhorn (2007); Cimellaro et al. (2009), (2010)), indicating the period necessary to restore the functionality of a structure, and infrastructure system to a desired level that can operate or function the same, or close to, or better than the original one.

For the purposes of EU-CIRCLE, each stage for each asset and hazard can be modeled through a first order approximation requiring only the rate of capacity change (either negative for the disaster stage or positive for the restoration) and a time interval. It is possible that stages A3 and A4 could be merged, or a different approximation is used.

Interdependency analysis

For the purpose of the EU-CIRCLE project a generic syntax for the description of a specific network state is used, as denoted in the previous section . This generic variable, $S_i(t)$, with property k, referring to the node i of the network j is defined as:

$$S_{i[\text{Node}],j[\text{Network}]}^{k[\text{property}]}(\text{t})$$

The diffusion of relevant information, such as the present state of operation, between interdependent networks is a key component of the network analysis. In more detail, the interconnection links are characterized by a function that expresses the way the one network influences the operation of the interconnected networks. In general terms, it is defined as:

Equation 1
$$NS_{i,j} = function\left(PS_{i,j}, PS_{i\prime,j\prime}, interconnection\ type\right)$$

$NS_{i,j}$ denotes the Network State of node i of the network j, $PS_{i,j}$ stands for Previous State of node i of the network j. Interconnection types according to Rinaldi et al. are used as described in Section 2. In mathematical terms, the failure of node $i$due to loss of service LS in a network $j$is designated as $E_{\text{ij}}^{\text{LS}}$. The event E_{ij}can then be define as the union of the events $E_{\text{ij}}^{\text{LS1}}$, $E_{\text{ij}}^{\text{LS2}}$, …, $E_{\text{ij}}^{\text{LSn}}$.

Equation 2
$$E_{\text{ij}} = E_{\text{ij}}^{\text{LS1}} \cup E_{\text{ij}}^{\text{LS2}} \cup \ldots \cup E_{\text{ij}}^{\text{LSn}}$$

Loss of service incorporates the damages due to a hazard, such as flood, and the non-functionality due to a failure of a node from another network, for example the waste water network (blue dots in Figure 155). By solving each network independently and then considering their interaction the proposed approach analyses a system of infrastructures. Infrastructure networks can be seen as layers which overlap each other and share some nodes which are presented in both networks and are connected by inter-infrastructure edges. This approach brings many benefits:

1. It discerns the analysis and results of layers and interdependencies and aids the understanding of where critical points are located and which are the tighter and more stressed inter-links. While the single infrastructure assessment is mature, the interdependency studies are still at a development stage.
2. Moreover, giving the possibility to each infrastructure manager of running the model of a given layer and then controlling the interaction between the different layers at a higher level is closer to the professional practice adopted during an emergency response phase.
3. In the end, the diffusion of informatics tools, like Geographic Information Systems (GIS), in both the emergency response and the risk planning sector, suggests the adoption of a unified methodology. The GIS platform has great potentialities and it can be effectively used to organize input data and visualize outputs. Their relational databases are shaped with a layer structure which is in accordance with the one proposed above.

Time independent analysis (TI)

Under this approach, any specific hazard E which is associated to physical quantities (water depth, floods, forest fires, extreme temperatures etc.) and has a large spatial extent, can impact various parts of the infrastructure with different intensities.

The vulnerability of exposed assets (nodes and links) is represented by the fragility curves, which define the probability of failure of each node depending on the type of hazard considered. Therefore, for each node there are as many fragility curves as the type of hazard acting. The probability of state change P_{ij} of a node under a specific event E, is obtained by inserting the value of the E into the node fragility curve. The assignment of probabilities to the nodes and how they change their state if the event affects them, is part of Structural and Operation Analysis (SO).

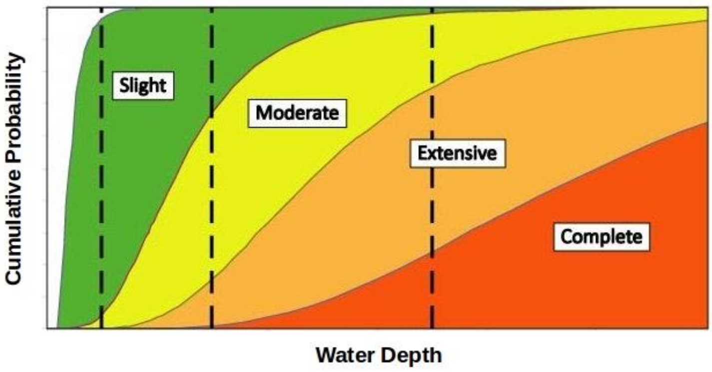


Figure 18: Fragility curve.

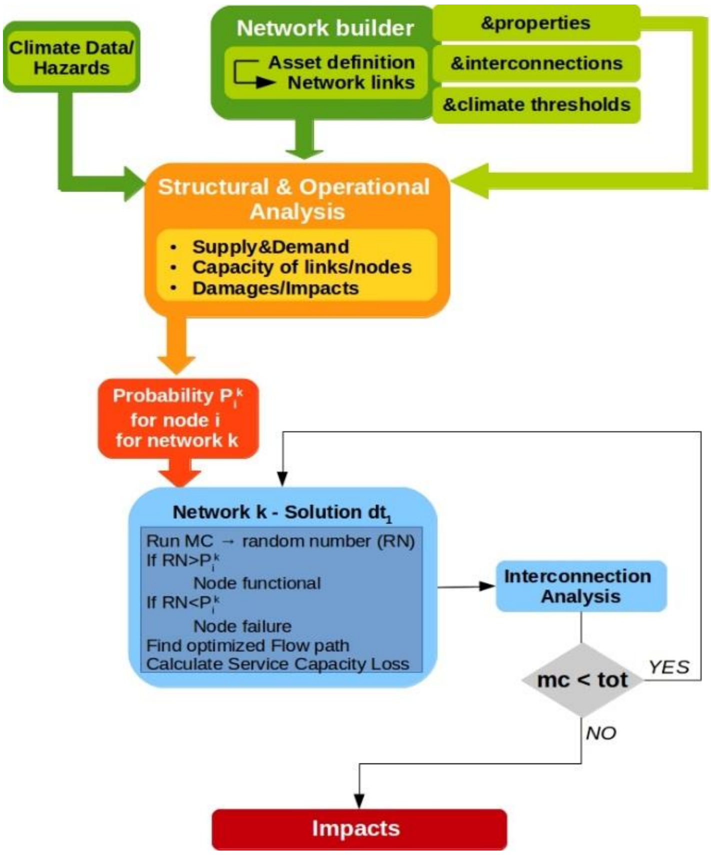


Figure 19: Standard Probabilistic Network Analysis flow chart.

This operation creates a value for each node that expresses the service loss of a node due to a hazard. Then, a network analysis solution takes place, as described below:

1. Determine which nodes are going to change state.
2. Calculate new flow and cost values of the network creating thus a new network affected by the hazard.
3. Solve a minimum cost and maximum flow optimization problem for each type of network.
4. Conduct an interdependency analysis.
5. Repeat steps 1 to 4 for a predefined number of steps.
6. Perform impact analysis.

A very useful information for the CI operation, is the time that the network will gain back part or total operation, after the extreme event. In order to assess that, CIRP introduces a restoration time value for each asset, that can be utilized in the impact analysis and calculate the average time that the network will be fully operational.

Time Dependent Network Analysis (TD)

The spatial evolution of an exteme event can affect the types of CI networks differently and thus, the solution may differ from an "instant" enforcement of the hazard. In addition, it is very useful and interesting to know the behavior of the CI over the duration of extreme events. In order to take into account time evolution scenarios, a Time Dependent Network Analysis is proposed.

The first step in the TD analysis is to discretize time according to the evolution of the hazard. Then, the different time periods are inserted as inputs, in the Scenario Development step. CIRP calculates the maximum intensity during the event for each asset and the time step that is reached. That value is used in order to assess the point that the recovery process can start. Each type of asset has a recovery time value as described in introduction of Section 4.If the maximum value of the hazard has been reached, the asset begins to recover during the next time steps based on a restoration curve/function that is defined using the recovery time value of the asset. That method incorporates the recovery process in the Network analysis step, and permits a dynamic function of the nodes of the network over time, where nodes can lose or restore service. The analysis begins sequentialy from the first time step by performing a network analysis as described in introduction of Section 4 taking into account the restoration process of the asset.

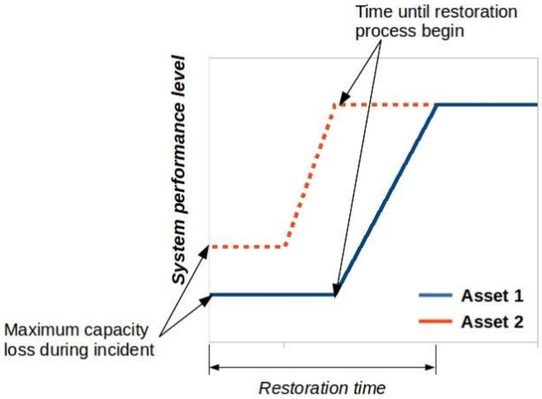


Figure 20: Restoration curve

The result is a new network state matching the hazard at a specific time period. The next time period initializes with the new network state together with the next time step of the hazard. The procedure is repeated sequentialy for all the time periods that were determined in the first step.

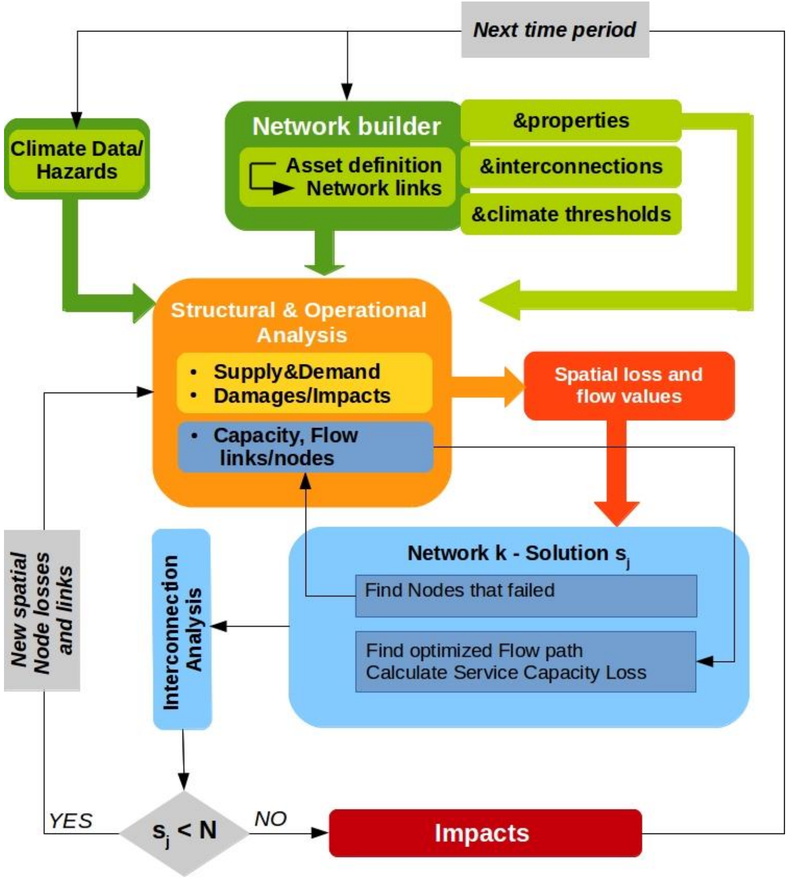


Figure 21: Resilience Factor Network Analysis flow chart.

The steps that TD follows are:

1. Discretization of time according to hazard
2. Solve as TI
3. Perform impact analysis
4. A new network state is determined
5. Run the next time period with the new state of network as initial step
6. Repeat for all time periods (N in total)

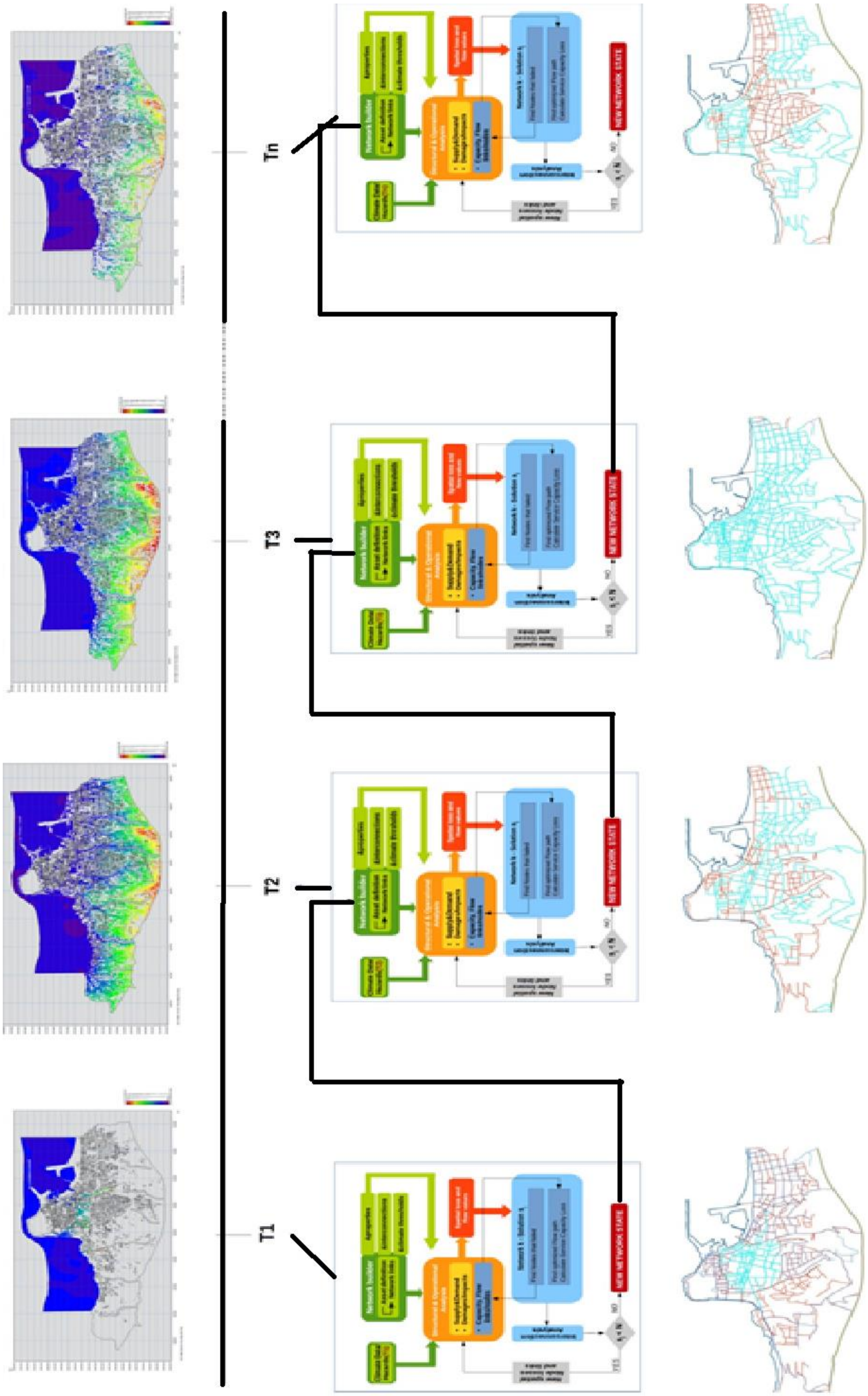


Figure 22: Time Dependent Network Analysis example

5 Defining impacts/consequences

5.1 Direct

This category of impacts corresponds to **Level 1** of the risk quantification methodology (see Figure 88) and directly affects the CI (or the interconnected network of CI), in multiple pathways which are presented in the following points:

Damages to CI assets (Level 2)

Assets that are completely or partially damaged (significant destruction from its as-built state) due to a climate hazard. The enumeration of this category could be through different indices and each one corresponds to a Level 3 impact of risk quantification methodology (see Figure 88). Below the categories used are referenced:

- number of assets fully damaged (beyond reparability)
- number of assets partially damaged
- number of assets with a [over] certain per cent (%) or range of damages
- highest per cent (%) of damage per network
- average damage per network
- Enumerated damage per [asset / network]. Value depending on network specific properties (e.g. km of roads destroyed, km of railways, km of water pipelines, km of electricity transmission network, etc.)

CI performance (Level 2)

This category refers to the change of the capacity of the CI network (or interconnected networks) to maintain its fully functional performance level, as identified in the baseline category of normal operation. The following parameters correspond to a Level 3 impact of risk quantification methodology (see Figure 88):

- Flow reduction in network asset (node / link)
- Changes in network generation capacity
- Changes in network demand capacity
- Changes in network links capacities due to climate hazards
- Time that CI/asset/ is not able to serve its intended function

The network simulation solutions could be used to derive performance related indicators as follows:

- **Connectivity Loss (CL)**

Connectivity Loss is a measure of the ability of every distribution node to receive from a generation node and it is defined as:

Equation 3
$$\mathrm{CL} = 1 - \sum_{\mathrm{j}=1}^{N} \frac{G_j^{\mathrm{ap}}}{G_j^{\mathrm{af}}}$$

where N is the number of distribution nodes, G_j^{af} denotes the number of generation nodes able to feed flow to the j distribution node, and G_j^{ap} denotes the number of generation nodes able to supply power to the j distribution node.

- **Service Flow Reduction (SFR)**

Service Flow Reduction (SFR) determines the amount of flow that the system can provide compared to what it provided before the "event". SFR is defined as:

Equation 4

$$\mathrm{SFR} = 1 - \sum_{\mathrm{j}=1}^{N} \frac{\mathrm{PR}_j}{\mathrm{CS}_j}$$

where PR_j denotes the actual flow at the j distribution node, and the CS_j represents the demand of j distribution node.

Casualties (Level 2)

Casualties include fatalities and injuries to employees of the CI operation and also to those using the infrastructure at the time of the incident (related only to transportation networks and governmental services, health sector). Casualties can be quantified using two approaches:

- **Numerically**, in an absolute manner, such as the number of people exposed,
- **Person years lost.** (Klaver, et al., 2008) define this index as the sum of: a) Half the life expectancies of the people who lost their lives, b) The total period that people are hospitalized and in recovery, the percentage unable to live a normal life times the period affected, and the decrease in life expectancy

Economic and Financial Perspectives (Level 2)

Economic losses are estimated on the network (and/or interconnected networks) where the incident occurred and accounts for the following elements:

- Costs of damaged assets
- Loss of income as a result of not servicing demand
- Loss due to possible penalties from violating service level agreements with buyers
- Costs for replacements of services
- Restoration and recovery costs
- Maintenance costs after hazard

Total economic costs and losses can be calculated as follows, with reference to the intervals identified in 4.1:

total economic costs & losses =
[cost of economic losses & costs damaged assets] at (the damage absorption stage A2, see Section 4.4) +
[cost of economic losses + cost of response + cost of replacement] at (the response stage A3, see Section 4.4) + [economic losses + recovery cost] at (recovery stage A4, see Section 4.4) +

[loss of income from not servicing + maintenance costs] at (all stages of this inciden, see Section 4.4)

Additionally, the risk premiums to a specific CI maybe alternated in the light of changing climatic conditions and exposure to increasing levels of risk.

All economic effects shall use the same metric, preferably in a common currency. Furthermore, due to the change of the monetary value over time all losses that last more than a year should be annualized using the Net Present Value (NPV) method.

Environmental Losses (Level 2)

As CI operation is expected to have an impact on future climate, especially the operation of highly susceptible infrastructures such as energy, the production of Greenhouse Gases can also be considered as an impact within the proposed approach. The following types of pollutants are considered, the estimation of which will be done based on emission factors from existing international databases

- Air pollutants affecting local air quality (NOx,SOx, CO, PM of various dimensions, VOC) and toxics (EMEP/EEA air pollutant emission inventory guidebook 2013)
- Green house gases (http://www.ghgprotocol.org/Third-Party-Databases/IPCC-Emissions-Factor-Database)
- Hazardous materials & toxics, that may be classified according to the chemicals danger classification obtained from the related web site of the Globally Harmonized System of Classification and Labelling of Chemicals (http://www.unece.org/trans/danger/publi/ghs/ghs_rev01/01files_e.html)

In case of spills and leak of chemicals and hazardous materals involved in the incident a series of indices can be used to stress the impact of the substance on the environment. Once the amount of the material is quantified then a dispersion model (from the simplest Gaussian one and towards more complex models) could be applied to define the impacted area.

Environmental/ecological effects can be expressed in terms of the size of the impacted area, an indication of severity based on recovery time needed to fully restore the state of the environment in its previous state and as an indicator of the ecosystem and biodiversity that is at-risk. The latter is critically important if the location of the natural hazard on the CI network is under a protected area (NATURA 2000, RAMSAR treaty etc.).

CI reputation (Level 2)

This type of impact is related to the reputation of the CI (can be classified in a categorical way) in a subjective-quantitative estimate from subject matter experts-CI operators.

5.2 Indirect

This category corresponds to **Level 1** and pertains to the impacts affecting society that is served by the CI. As such they correspond to impacts on diverse groups of people accounting for a holistic assessment and quantification of the role of CI.

Impact on societal groups (Level 2)

This category accounts for the part of society whose demand for CI services is not (or is partially) met due to the CI not being able to meet the required demand. This can be further expanded into the following elements

- Number of people exposed / affected
- Number of in-need societal groups (in people) not-served, such as infants, elderly, patients, etc.
- Number of houses not-served
- Number of enterprises not-served
- Number of special facilities not-served (elderly care, kindergarten, schools, etc.)

Additionally, psychological effects can be accounted for, as a measure of the citizen confidence in the CI network and is directly related to their motivation in continuing using the network in the future. The psychological impacts are classified as:

- Inconvenient: Irritating for the individual, but not disruptive to his/her daily routine
- Disruptive: The individual will have to modify his/her daily routine
- Very disruptive: The individual will have to make significant modifications to his/her daily routine
- Interrupting: the individual is no longer able to continue his/her daily routine

Considering risk assessment of **political** effects, it is obvious that only those political aspects can be considered that can be assessed beforehand. Risk assessment cannot and shall not take into account heightened political sensitivities between parties such as that during an election period or sequences of events which may have led to a political change, unless it considers the re-evaluation during or just after an incident. The only political effects that can be qualitatively assessed are the risk of policy changes that affect the process or structure of the business or the sector after an incident and the continuation of governmental operations at all levels of government.

Casualties (Level 2)

Casualties include fatalities and injuries to the society caused due to the CI not being able to perform an agreed level of operation. Casualties can be quantified using the same two approaches as for the direct impacts. Also accounting for possibly displaced people.

Economic impacts (Level 2)

Economic losses are estimated for the economic activity of the society that is affected by the climate hazards on the network. The Critical Infrastructure Network (CIN) is considered as an integrated production system consisting of different assembly lines/economic activities. In other words the CIN is an economic entity composed by distinct economic activities while it is incorporated in a total economic system at regional or/and national level. The time dimension will be taken into account by implementing ex-post and ex-ante (hazard/disaster) methodologies in order to cover at highest level the risk assessment and management in CI.

The impact of the security incident on the economic system of a country, region or area may be defined from the Input – Output Matrix, using the Leontieff framework. The fundamental information used in input–output analysis concerns the flows of products from each industrial sector, considered as a producer, to each of the sectors, itself and others, considered as consumers. This basic information from which an input– output model is developed is contained in an interindustry transactions table. The rows of such a table describe the distribution of a producer's output throughout the economy. The columns describe the composition of inputs required by a particular industry to produce its output (Miller, et al., 2009).

		PRODUCERS AS CONSUMERS								FINAL DEMAND			
		Agric.	Mining	Const.	Manuf.	Trade	Transp.	Services	Other	Personal Consumption Expenditures	Gross Private Domestic Investment	Govt. Purchases of Goods & Services	Net Exports of Goods & Services
PRODUCERS	Agriculture												
	Mining												
	Construction												
	Manufacturing												
	Trade												
	Transportation												
	Services												
	Other Industry												
VALUE ADDED	Employees	Employee compensation								GROSS DOMESTIC PRODUCT			
	Business Owners and Capital	Profit-type income and capital consumption allowances											
	Government	Indirect business taxes											

Figure 23: Input-Output Matrix.

Input-Output Model:

X=Ax+Y,

Where: X= Production Y= Final Demand, A=Technical Coefficient Matrix

Each element of A (Technical Coefficient Matrix) represents the quota of each sector's production:

$a_{ij} = X_{ij} / X_j$

I.e, the technological factor a_{ij} shows the share of x_i industry in the total output of industry j.

Assuming each CI of the network (system) as a productive sector of this system that is interdependent with other CIs (sectors) we could find the extension of this direct and indirect interdependency across all CIs. This assumption is not far from reality, taking into account that according to EUROSTAT's National Accounts (based on I-O framework) most of CI are separate economic sectors (i.e. Energy Sector, Transport Service Sector). More specifically, a unitary impact on the CI network activity class (input) **y**, would result in an analogous impact estimate $\mathbf{x} = (\mathbf{I}-\mathbf{A})^{-1}\mathbf{y}$, where x (output) are economic values on an economic activity level, and $(I-A)^{-1}$ is the inverse Leontief Matrix which shows the direct, indirect and induced interdependencies of all production sectors.

Therefore, the system's solution is:

$X = (I-A)^{-1}Y$

Under the proposed scheme, the economic costs account not only for the costs of the public sector or the infrastructure operator, which is currently practice, but will also account for the economic costs to the private sector.

Again, all Economic effects shall use the same metric, preferably in a common currency. Furthermore, due to the change of the monetary value over time all losses that last more than a year should be annualized for instance by means of using the Net Present Value (NPV) method.

6 Uncertainty estimation in the EU-CIRCLE risk assessment

The EU-CIRCLE framework results in a new network state by using the CI description, interconnection and network analysis. The new state is the basis of which indicators are calculated and describe the damage of the infrastructure. Nonetheless, the framework is a computational approach and as such the solution comes with a confidence interval. The lack of data, the use of theoretical ones or the use of data from the literature etc, makes the solution of the system uncertain in a way that the effect of a small variance of an input value to the solution is unknown. CIRP takes into account these parameters and incorporates them in the calculation of the overall error (see Figure 264). A two level process is implemented for the error estimation. The first is the use of (a) input data uncertainty in order to generate a distribution of input values and the second is (b) the sampling of the generated values efficiently and calculation of the overall error of the method.

6.1 Generation of distribution of solutions

Initially, EU-CIRCLE analysis results in a new state of the network and the calculated indicators demonstrate the effect of the CI from a hazard. The first stage of the error estimation approach is the generation of the distribution of inputs. The steps are:

1. Generation of distribution: Assuming a Gaussian distribution generation, the initial value of data is used as the mean value, μ, and an interval around that value is chosen as a variance, σ^2. A Gaussian distribution of inputs (N(μ ,σ^2)), is produced. Any kind of distribution can be used (Gaussian, Median, Weibull etc).
2. The step 2 is repeated for each type of input.

Each type of input (a distribution) represents a sample (strata) to which a stochastic method, like Monte Carlo, can be performed.

6.2 Stratified Monte Carlo

In case of different groups samples (strata), a method of variance reduction is the Stratified Sampling Monte Carlo (SSMC)[4]. The latter produce a weighted mean that has less variability than the arithmetic mean of a simple random sample of the overall population. The equations used are presented below:

Equation 5
$$x_{overall} = \frac{1}{G}\sum_i N_i x_i$$

Equation 6
$$\sigma^2_{overall} = \sum_i \left(\frac{N_i}{G}\right)^2 \left(\frac{N_i - n_i}{N_i}\right)\frac{\sigma_i^2}{n_i}$$

Where G is the number of stratas, N_i is the size of strata i, n_i is the number of values used from strata i, and x_i and σ_i is the mean value and the variance of strata i accordingly. Moreover, except from the overall mean value and variance, the sampling of the strata is independent and for each strata a mean value and variance are calculated, thus, the effect of the perturbation of the data

[4] W. H. Press and G. R. Farrar, "Recursive Stratified Sampling for Multidimensional Monte Carlo Integration," Comput. Phys., vol. 4, no. 2, p. 190, 1990.

values of each group in the solution, is derived. The error estimation process is illustrated in Figure 24.

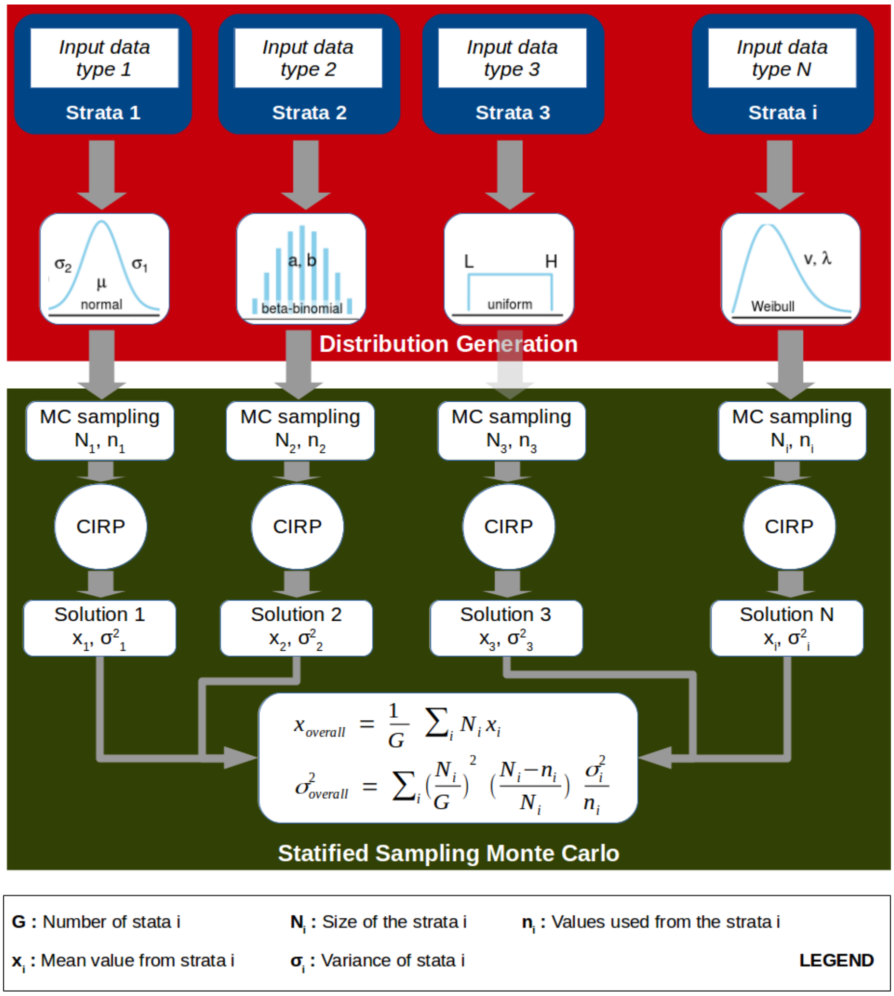


Figure 24: illustration of error estimation of CIRP framework

6.3 CIRP implementation

The flow-process, described in the previous paragraphs, will be implemented in CIRP framework in order to estimate the error of the solution. For better understanding the SSMC method in EU-CIRCLE framework, a simple example is presented below. It is assumed that three types of input are given (a) the climate data, (b) the CI description: asset, connections, interconnections, capacities, demand etc, and (c) the reaction of the asset to a hazard (aka damage function). The result of the analysis is a specific indicator that the user wants to assess. Following the SSMC method, type (b) is taken as a detailed description of the CI network with no uncertainty and the (a) and (c) inputs comprise the two types that introduce the uncertainty of the solution to our system. The user can choose the uncertainty (variance of the initial value) from a cardinal scale (see Figure 26) that corresponds to a predefined value of variance, in-line with the process described in D3.4. For each input ((a) and (c)), a generation of distribution is applied, a MC sampling is performed and a solution is calculated for each type of input separately. The solutions are summed up in weighted average alongside the variance of the calculation. That way the uncertainty of the input data and the sensitivity of the solution to a small perturbation of the input values, are taken into consideration. Analytically the steps are presented in Table 5.

Steps	Climate Data - Input type (a)	Damage function - Input type (c)
0	Identify input data that introduce uncertainty (type (a) and (c) in our case)	
1	Choose Gaussian distribution	Choose Gaussian distribution
2	Give mean value, $\mu_{(a)}$, and an interval around that value as variance, $\sigma^2_{(a)}$ As $\mu_{(a)}$ is the initial value of input data and $\sigma^2_{(a)}$ is chosen by the user	Give mean value, $\mu_{(c)}$, and an interval around that value as variance, $\sigma^2_{(c)}$ As $\mu_{(c)}$ is the initial value of input data and $\sigma^2_{(c)}$ is chosen by the user
3	Sample randomly (MC) a value, **i**, from the distribution	Sample randomly (MC) a value, **j**, from the distribution
4	Perform CIRP analysis with the new value	Perform CIRP analysis with the new value
5	Calculate the indicator of interest, $\mathbf{IN_{(a),i}}$	Calculate the indicator of interest, $\mathbf{IN_{(a),j}}$
6	Repeat **N** time the steps 3 to 5	Repeat **N** time the steps 3 to 5
7	Calculate mean value of the solution, $IN\_\mu_{(a)}$ and $IN\_\sigma^2_{(a)}$	Calculate mean value of the solution $IN\_\mu_{(c)}$ and $IN\_\sigma^2_{(c)}$
8	Calculate the $IN\_\mu_{overall}$ and $IN\_\sigma^2_{overall}$ (Equation 5 & Equation 6)	

Table 5: Steps of SSMC followed in EU-CIRCLE framework in order to incorporate the uncertainty of input data and estimate the variance of the solution.

In the end of all model phases, the whole uncertainty of the process may be calculated as a number but also a category from a scale that consists of five (5) classes from very low to very high.

VERY LOW	LOW	MEDIUM	HIGH	VERY HIGH

Figure 25: Categorization of uncertainty of EU-CIRCLE process

The different levels of uncertainty can be broadly expressed as:

- Very High: high modeling error >80% or relative terms & estimate based upon no supporting scientific evidence.
- High: Expert view based on limited information, e.g. anecdotal evidence, & modeling outcomes with important error 60-80% on relative terms.
- Medium: Estimation of potential impacts or consequences, grounded in theory, using accepted methods and with some agreement across the sector, quantified modeling error between 40-60% in relative terms
- Low: Reliable analysis and methods, with a strong theoretical basis, subject to peer review and accepted within a sector as 'fit for purpose', quantified modeling error for a specific process between 20-40% in relative terms
- Very Low: Comprehensive evidence using the best practice and published in the peer reviewed literature; accepted as an ideal approach (no risks, received a very high confidence score)

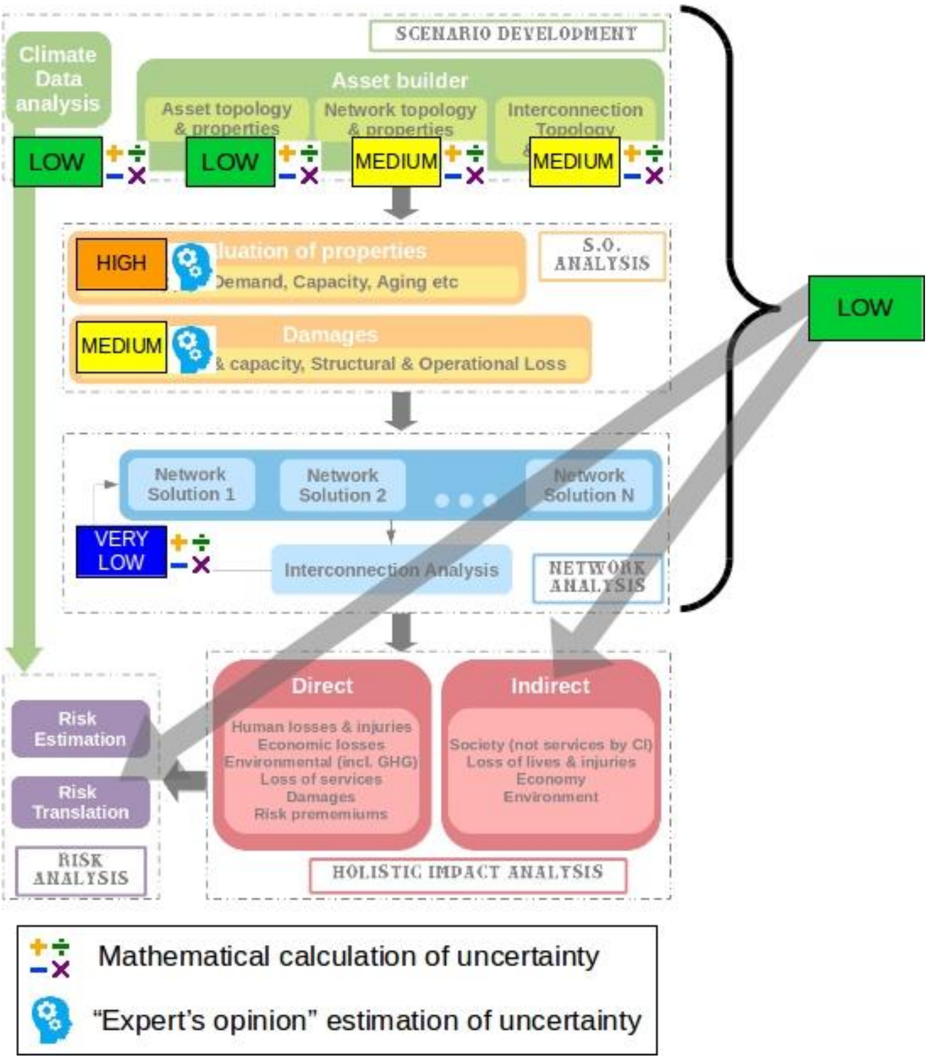


Figure 26: Process to assess uncertainty

7 Closing remarks

It is obvious, that climate change amplifies risks and creates new risks for people, infrastructure and nature. Within this deliverable, we have drafted a generic approach for holistic risk assessment which is based on scientific validated methods. In the development of our risk assessment framework we took into consideration national and international frameworks on risk assessment, risk management and resilience. Our approach is generic in the sense that it is intended to be applicable to various assessment situations; it is holistic in the sense that it includes a wide variety of direct and indirect impacts.

We have augmented the classic understanding of risk assessment and risk management with aspects of resilience and suggest the following steps which operationalize the approach:

- Determine which hazard and CIs are under study
- From hazard, estimate:
  - Exposure
  - Likelihood
- Utilize various models and methodologies to estimate:
  - CI assets and network damages
  - Network interdependency analysis
  - Impacts
- The results of models is a variety of indicators (depending on the analysis) that represent the consequences of the hazard to the CIs

For all the steps, respectively components, we describe a potential analytical approach and foresee an implementation of these steps within a geographic information system. This analytical approach has been implemented and demonstrated in the five case studies.

At the end of the process, several indicators are produced and need to be combined to an overall risk. Hence, we propose an overall risk framework, based on a set of mixing rules, that takes into account all impacts and the hazard likelihood. Finally, a method to estimate the uncertainty of the EU-CIRCLE framework is presented.

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Annex 1: Description of mixing rules

In order to combine different consequence categories at a categorical level, different approaches can be applied. The different levels need to be mapped to numbers (1 to 5) before making the actual calculations. The method that can be used are:

- **Mode**: We assign an impact level equal to the category level that occurs most often in the analysis.
- **Maximum**: This can be thought of as the most "precautious" ("risk-fearing") total impact assessment method since it attributes the highest observed risk rating among all categorical categories to the total impact.
- **Median**: This method calculates the Median value of the categories impact ratings as the value standing in the middle of the impact ratings when we sort them by their impact severity.
- **Weighted Mean**: This is the most flexible method of total assessment and is due to the fact that we can apply weights (0-100% with a sum of 100%) to each categorical category based on their relative significance, map their individual impact rating to ordered numbers and sum them to calculate their weighted mean
- **Average**: This is the same method with Weighted Mean but with equal weights assignment to each categorical category.
- **Majority Rule**: This rule implies that the final metric is estimated as the class that appears the most times within a predefined number of alternatives.
- **At least k times**: This rule is used to define a final class if the corresponding class appears at least k times in the predefined number of alternatives. This rule is considered very useful in the definition of critical events.

For each level a single number is extract by means of rounding to the closest integer representing that category. Having estimated the impact and likelihood (Level 0) the same procedure is applied in order to calculate the overall risk.

Annex 2: Impacts classification table

LEVEL 3						LEVEL 2	LEVEL 1	LEVEL 0
	NEGLIGIBLE	SMALL	MEDIUM	HIGH	SEVERE			
IMPACT/CLASS	1	2	3	4	5			
Damage to CI assets						Physical damage to CI assets	DIRECT	IMPACT
Number of assets fully damaged over all assets (physical)	value< 10%	25% > value > 10%	50% > value > 25%	75%> value > 50%	value > 75%			
Number of assets partially damaged over all assets (physical)	value< 10%	25% > value > 10%	50% > value > 25%	75%> value > 50%	value > 75%			
Number of assets with a certain per cent (%) or range of damages (recommended threshold = 30% or 50%)	value< 10%	25% > value > 10%	50% > value > 25%	75%> value > 50%	value > 75%			
Highest per cent (%) of physical damage of asset per network	value< 10%	25% > value > 10%	50% > value > 25%	75%> value > 50%	value > 75%			
Average damage per network [%]	value< 10%	25% > value > 10%	50% > value > 25%	75%> value > 50%	value > 75%			
Percentag of damaged assets over specific threshold over total number of assets *	property < 0.02 x MAX threshold	0.05 x MAX threshold > property > 0.02 x MAX threshold	0.15 x MAX threshold > property > 0.05 x MAX threshold	0.40 x MAX threshold > property > 0.15 x MAX threshold	property > 0.40 x MAX threshold			

*** Value depending on network specific properties (e.g. km of roads destroyed, km of railways, km of water pipelines, km of electricity transmission network,**

etc.)								
			Damage to CI performamce					
Flow reduction in network asset (node / link)	% value < 2%	5% > % value > 2%	15% > % value > 5%	40%> % value > 15%	% value > 40%	**Damage to CI performamce**		
Changes in network generation capacity	% value < 2%	5% > % value > 2%	15% > % value > 5%	40%> % value > 15%	% value > 40%			
Changes in network demand capacity	% value < 2%	5% > % value > 2%	15% > % value > 5%	40%> % value > 15%	% value > 40%			
Changes in network links capacities due to climate variability	% value < 2%	5% > % value > 2%	15% > % value > 5%	40%> % value > 15%	% value > 40%			
Time that CI/asset/ is not able to serve its intended function	value < 0.5 days	1 days > value > 0.5 days	4 days > value > 1 days	7 days > value > 4 days	value > 7 days			
Connectivity Loss (CL)	% value < 2%	5% > % value > 2%	15% > % value > 5%	40%> % value > 15%	% value > 40%			
Service Flow Reduction	% value < 2%	5% > % value > 2%	15% > % value > 5%	40%> % value > 15%	% value > 40%			
			Casualties					

Number of people affected over total (region) population	value< 2%	5% > value > 2%	15% > value > 5%	40%> value > 15%	value > 40%	**Casualties**		
Person years lost over affected population	10	100	250	500	1000			
Economic & Finance						**Economic & Finance**		
Costs of damaged assets	value < 0.5% of total value of CI	0.5% > value > 2% of total value of CI	2% > value > 10% of total value of CI	10% > value > 20% of total value of CI	20% > value > 30% of total value of CI			
Loss of total income as a result of not servicing demand	% value < 0,5%	0,5% > % value > 2%	2% > % value > 10%	10% > % value > 30%	30% > % value > 40%			
Costs for replacements, restoration & recovery	value < 0,35% of regional GDP	0,35% > value > 0,5% of regional GDP	0,5% > value > 1% of regional GDP	1 % > value > 5 % of regional GDP	5% > value > 15% of regional GDP			
Maintenance costs after hazard	value < 0,02 % of regional GDP	0,02 % > value > 0,05 % of regional GDP	0,05 % > value > 0,1 % of regional GDP	0,1 % > value > 0,3 % of regional GDP	0,3 % > value > 0,5 % of regional GDP			
Enviromental						**Environmental**		
Max concentration of pollutant over region's threshold (data provided for daily pm10 concetration – μg/m^3)	< 35	35 < value < 50	50 < value < 100	100 < value < 200	200 < value			

			CI reputation			**CI reputation**	
CI reputation (user defined according to the provided category)							
			To societal groups			**To societal groups**	**INDIRECT**
Percentage of people exposed / affected	% value < 2%	5% > % value > 2%	15% > % value > 5%	40%> % value > 15%	% value > 40%		
Percentage of in-need societal groups (in people) not-served	% value < 2%	5% > % value > 2%	15% > % value > 5%	40%> % value > 15%	% value > 40%		
Percentage of houses not-served	% value < 2%	5% > % value > 2%	15% > % value > 5%	40%> % value > 15%	% value > 40%		
Percentage of enterprises not-served	% value < 2%	5% > % value > 2%	15% > % value > 5%	40%> % value > 15%	% value > 40%		
Percentage of special facilities not-served (including emergency services)	% value < 2%	5% > % value > 2%	15% > % value > 5%	40%> % value > 15%	% value > 40%		
Percentage of people inconvenienced (see Section 5)	% value < 2%	5% > % value > 2%	15% > % value > 5%	40%> % value > 15%	% value > 40%		
Percentage of people disrupted	% value < 2%	5% > % value > 2%	15% > % value > 5%	40%> % value > 15%	% value > 40%		
Percentage of people very disrupted	% value < 2%	5% > % value > 2%	15% > % value > 5%	40%> % value > 15%	% value > 40%		

Percentage of peopleinterrupted	% value < 2%	5% > % value > 2%	15% > % value > 5%	40%> % value > 15%	% value > 40%			
			Casualties			**Casualties**		
% of number of casualties ove total population of region	value < 2%	5% > value > 2%	15% > value > 5%	40%> value > 15%	value > 40%			
			Economic & Finance			**Economic & Finance**		
Cost of damage for the entire economy (national/regional level)	value < 0.1 %	0.1 < value < 0.3 %	0.3 < value < 0.6 %	0.6 < value < 1%	1% < value			

Figure 27: EU-CIRCLE proposed aggregation method

Annex 3: Likelihood classification table

	VERY LOW	LOW	MEDIUM	HIGH	VERY HIGH
LIKELIHOOD/CLASS	1	2	3	4	5
Return Period	Occurs less than once in 100 years	Occurs once in 50 – 100 years	Occurs once in 10 – 50 years	Occurs once in 1– 10 years	Occurs more than once in 1 year
			or		
Probability of occurence	Probability within 1 year: 0.005% to 0.05%	Probability within 1 year: 0.05% to 0.5%	Probability within 1 year: 0.5% to 5%	Probability within 1 year: 5% to 50%	Probability within 1 year: 50% +

Annex 4: Combination table of Impact and Likelihood

LIKELIHOOD/IMPACT	**NEGLIGIBLE**	**SMALL**	**MEDIUM**	**HIGH**	**SEVERE**
VERY HIGH	LOW	MEDIUM	HIGH	CRITICAL	CRITICAL
HIGH	VERY LOW	MEDIUM	MEDIUM	HIGH	CRITICAL
MEDIUM	VERY LOW	LOW	MEDIUM	MEDIUM	HIGH
LOW	VERY LOW	VERY LOW	LOW	LOW	MEDIUM
VERY LOW	VERY LOW	VERY LOW	VERY LOW	VERY LOW	LOW