RAIN PROJECT

Security Sensitivity Committee Deliverable Evaluation

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The evaluation is:

- **The content is not related to general project management**
- **The content is not related to general outcomes as dissemination and communication**
- **The content is not related to critical infrastructure vulnerability or sensitivity**

Diagram path 1-2-3. Therefor the evaluation is Public.

Decision of Evaluation	**Public**	~~**Confidential**~~
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RAIN – Risk Analysis of Infrastructure Networks in Response to Extreme Weather

Project Reference: 608166

FP7-SEC-2013-1 Impact of extreme weather on critical infrastructure

Project Duration: 1 May 2014 – 30 April 2017

D5.5 RAIN Workflow Integration

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Table of Contents

Executive Summary

Deliverable D5.5 has the following objectives:

a) To ensure the compliance of all inputs from WP2, WP3, WP4, and WP7 deliverables that feed D5.1's risk based decision making framework,

b) To effectively elaborate, adjust and modify the outputs of WP2, WP3, WP4, and WP7, in order to provide D5.1's risk based decision making framework with robust input, and

c) To successfully integrate the outputs of WP2, WP3, WP4, and WP7, into D5.1's risk based decision making framework.

In this deliverable we present the integration between the WP2, WP3, WP4, and WP7 deliverables. This work package integration pivots around the WP6 case studies, as it is these case studies which, on the one hand, bring together (elements of) all the work package contributions and, on the other hand, will provide the show cases for the proposed risk based decision making framework in the RAIN project. This deliverable furthermore consists of 2 non-trivial inference models informed by WP3 and WP4, to illustrate the workflow. Both represent non-trivial proofs of concept of the proposed inference phase of the risk based decision making framework. Finally, the role of WP5 in the RAIN project is discussed as well as the WP's recommendation that the Bayesian probability theory be used in the inference phase of the proposed risk based decision making framework.

1 Introduction

This deliverable D5.5 is about (a) improving of the internal project communications between WP's 2, 3, 4, 6 & 7, (b) aligning WP outputs, and (c) re-defining/broadening WP5's role within the RAIN project.

We quote from the consolidated review report (pp.3-4):

1. Overall the project has achieved its objectives; however, some corrective actions are required, in order to ensure quality of outputs and a strong scientific co-ordination that will constitute the base for real innovation.

2. Improve scientific co-operation to ensure high quality of research outputs. This improvement does not imply lack of communication between the project's partners or a weak organizational structure that needs to be revised. On the contrary, since both are judged as sufficient, it is rather an issue of more in depth collaboration with more synergies and integrations between approaches.

3. Plan and perform a new deliverable or broaden appropriately an existing one (e.g. 6.3) to include testing and modifications of the outputs of all submitted deliverables, in order to align them towards a robust methodology for managing extreme weather risks for critical infrastructure.

4. Re-tune the objective of WP5 from developing a risk analysis framework to developing a risk-based decision making framework that will successfully integrate the outputs of WP2, WP3, and WP4 into D5.1 and provide a clear link between WP5 and WP6, WP7 that will ensure developments beyond the State of the Art. This re-tuning is closely related to the recommendation for a new deliverable that will effectively align all outputs from the deliverables that feed D5.1.

Recommendation (3) can be interpreted as stating that a plan should be put to paper by the relevant RAIN consortium members, which will guarantee this more in depth collaboration with more synergies and integrations between the various approaches, in order that a better alignment of the proposed methodologies may be achieved. The challenge of facilitating better communications and collaborations between the project members should be shared equally between WP1, WP5, and WP6; WP1 as the general communications facilitator; WP5 as the framework owners; and WP6 as the case study owners.

Recommendation (4) is interpreted as stating that WP5 should be actively involved in the integration of the various WP contributions, in order that a better alignment of the proposed methodologies may be achieved. In order to accommodate recommendation (4), it is proposed by WP5 that it will provide methodological support to the case study owner WP6, in order to guarantee/manage the alignment of the proposed methodologies of the case-study-content deliverers WP2, WP3, WP4, and WP7. Apart from presenting the common risk definitions, D5.1 clearly makes a distinction between the analysis (or inference) phase, where outcome probability distributions are constructed, and a decision making phase, where the present risk in these outcome probability distributions is being evaluated and compared to new risk levels after interventions have been made in the system. Hence the RAIN framework presented in D5.1 is in essence a '*risk-based decision making framework'.*

RAIN integration pivots around the two main WP6 case studies, the Alpine case, where rainfall induced landslides and flooding affected a region in North-East Italy, and the Finnish case, where high sea levels during a storm affected Helsinki and it surroundings. There are two smaller case studies included in RAIN, in order to broaden the geographical coverage throughout the EU (as requested by the mid-term review), especially with regards to East and South Europe and the most frequent extreme weather events the countries in these regions face. One of them is a case on the heatwave of Greece in July 2004. Two power plants in Lavrio (Laurium) and Megalopolis, Greece, shut down due to malfunction within 12 hours of each other, during a period of high demand due to a heat wave. That led to a cascading failure causing the collapse of the entire Southern (Power) System, affecting several million people in southern Greece. The other case is the heavy rainfall event in the Zilina region, of Slovakia, in 2014. The transport infrastructure was affected heavily by this triggering event, leading to landslides and debris flow with a total damage of €4 million. The difference between the main case studies and the smaller case studies is that the main case studies will be treated more comprehensively than the smaller ones.

2 WP5's Quantitative Risk Based Decision Making Framework and Its Implementation

In order to quantify both single and multi-mode risks and the impacts of extreme weather events on interconnected critical (infrastructure) systems, a risk analysis framework is proposed in WP5. In its *inference phase*, the framework quantifies the probabilities of the possible outcomes as a function of the actions that a risk manager might be contemplating to take and then – in the decision phase – it helps in choosing that action that promises to minimize the pertinent risks.

The necessity of reasoning as best we can in situations where our information is incomplete is faced by risk managers of infrastructures. They have to ask themselves, for example: do we improve the transport infrastructure or the E&TC infrastructure, and if so how much are we willing to spend on these improvements, or do we leave the flood surge defences as they are?

As a rule, we must decide what to do next, even though we cannot be certain what the consequences will be. Introspection would suggest that, before deciding what action to take, our intuition organizes the preliminary reasoning in the following stages (Jaynes, 1985):

1. Try to foresee all the possibilities that might arise

2. Judge how likely each is, based on everything you can see and all your past experience

3. In this light, judge what the probable consequences of various actions would be

4. Now make your decision

In Figure 2.1 an outline of a mathematical model of such reasoning/stages – the here proposed quantitative risk based decision analysis framework – is given; where the inference phase corresponds with the first three rows and the decision making phase corresponds with the last two rows.

The inference phase of any non-trivial risk analysis is where, for a project such as RAIN, the initial bulk of all the effort, ingenuity, and man-months will be spent, as it is in this phase that the current status quo of the case study reality will have to be captured in some kind of probability model. In the decision phase, possible protection and mitigation actions have to be formulated and their projected effects on the current reality of the case study have to be incorporated in the initial, status quo probability model. In order to incorporate these effects, re-iterations of the inference steps have to be performed for each proposed protection and mitigation action, or combination thereof. By way of example, Appendices A and B the outlines of completed inference phases are given for, respectively, WP3 (transportation systems) and WP4 (electricity infrastructure systems).

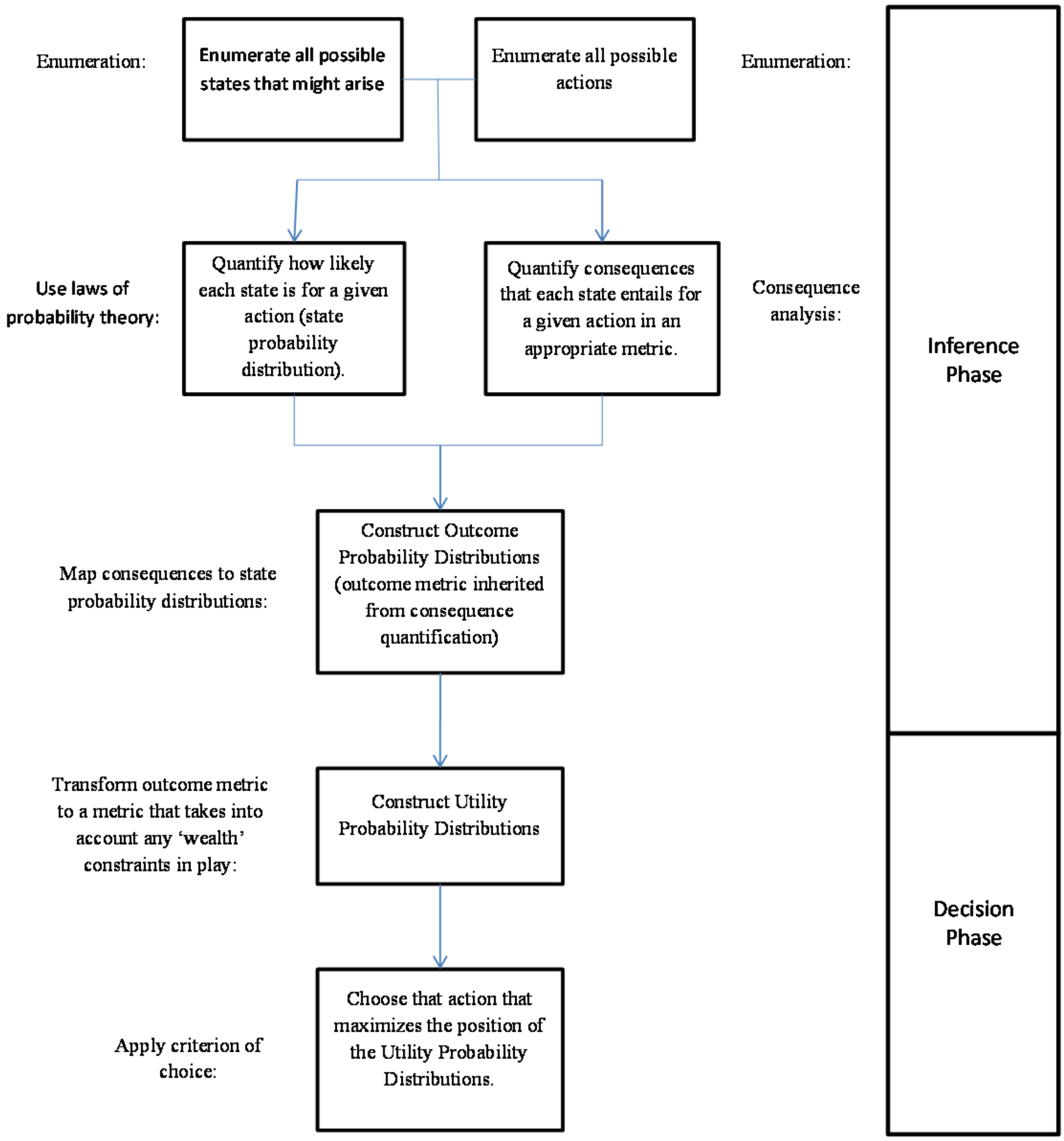


Figure 2.1: Quantitative Risk Based Decision Analysis Framework

In D5.1 it has been outlined that the laws of probability theory, that is, the product and the sum rules, are to be adhered to in the inference phase[1] (see also Figure 2.1). We now give the inference flow chart from Appendix B, Figure 2.2.

[1] Those which strictly adhere to the product and sum rules, as the only admissible operators on probability distributions, are typically called Bayesians.

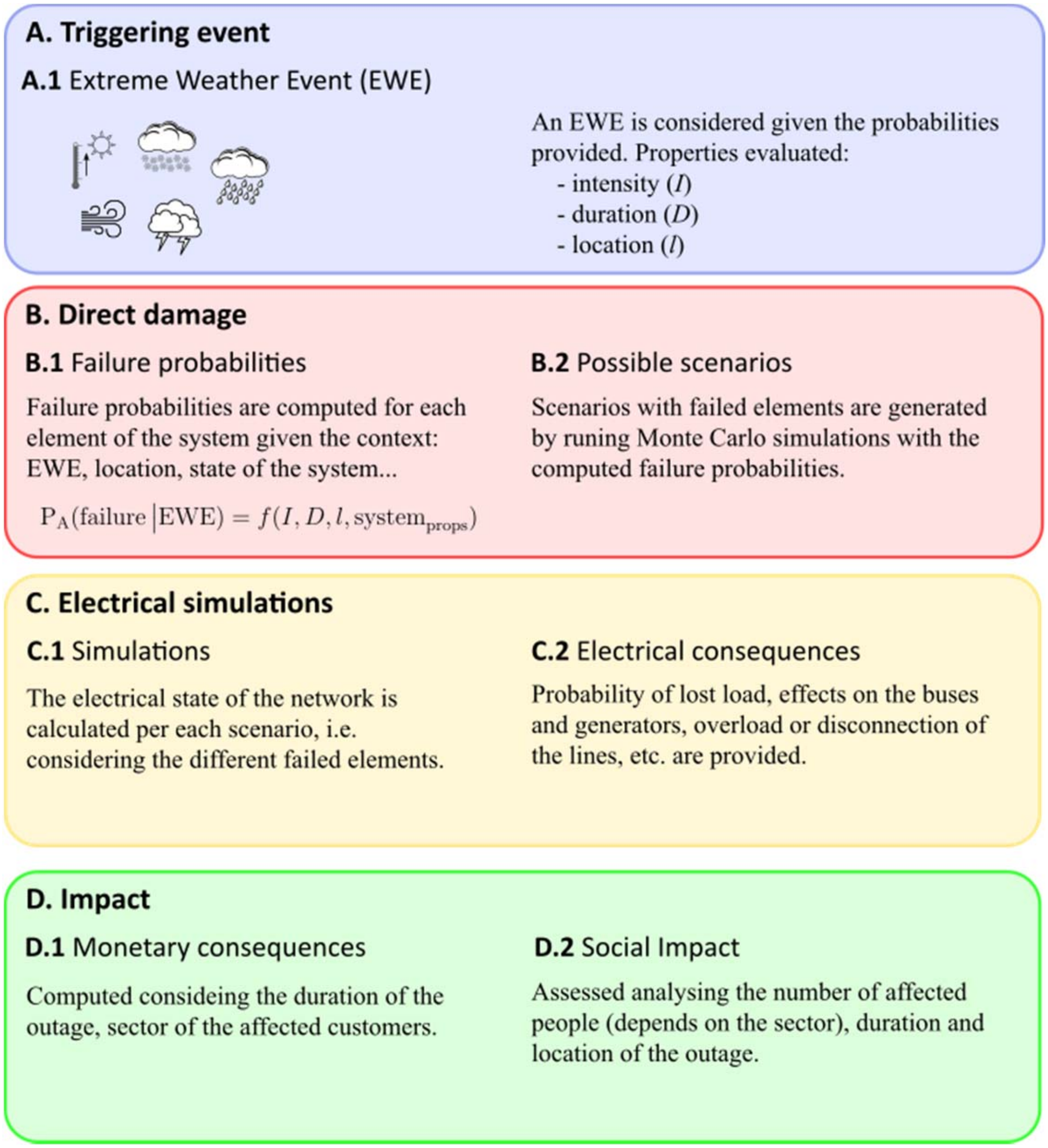


Figure 2.2: Inference Flow Chart from Appendix B

The inference flow charts presented in both Appendices A and B are in compliance with these laws, as we have that Extreme Weather Event (EWE) probability distributions are linked to system's damage state probability distributions, where damage states are mapped to relevant outcome metrics. These metrics include, e.g., monetary costs, waiting times, infrastructure capacity and ultimately yield outcome probability distributions, which are the needed inputs for the decision phase. Moreover, WP3 and WP4 have provided WP5, as a proof of concept, with outcome probability distributions, in both monetary and infrastructure outcome metrics. By way of example we now will demonstrate how WP4 has constructed these outcome probability distributions.

Let E_i be some EWE variable, say, 4-day precipitation values, or any other EWE variable which has been modelled in WP2. Let $\mathbf{x}_j = (x_1, \ldots, x_n)$ be the damage state vector of some system which consists of n objects, each object having m possible damage states, then we have that the number of damage states is given as m^n, or equivalently, $j = 1,2,\ldots,m^n$. Let O_j, for $j = 1,2,\ldots,m^n$, be some outcome/consequence that is associated with the damage state $\mathbf{x}_j$.

For the RAIN project, in their Deliverables, WP3 and WP4 have developed a methodology by which the conditional damage state probability distribution $p(\mathbf{x}_j \mid E_i)$, that is, the probability distribution of the damage state $\mathbf{x}_j$ given, say, the 4-day precipitation value E_i. By mapping the damage states $\mathbf{x}_j$ to their corresponding outcomes O_j, by way of the consequence model which has been developed by WP3 & WP4, the conditional damage state probability distribution $p(\mathbf{x}_j \mid E_i)$ may be mapped to its corresponding conditional outcome probability distribution $p(O_j \mid E_i)$. WP2 has delivered, via its Deliverables, a set of EWE probability distributions $p(E_i)$.

WP3 & WP4, by way of the aforementioned product rule of probability theory, combine the probability distributions $p(E_i)$ together with $p(O_j \mid E_i)$, as:

$$p(E_i, O_j) = p(E_i)\,p(O_j \mid E_i) \tag{2.1}$$

where $p(E_i, O_j)$ is the bivariate probability distribution of the EWE variable E_i and the outcome variable O_j. WP3 & WP4, by way of the sum rule of probability theory, then summates/integrates out the unwanted EWE variable E_i (where E_i may be any kind/combination of EWE):

$$p(O_j) = \sum_i p(E_i, O_j), \tag{2.2}$$

which leaves us with the outcome probability distribution $p(O_j)$. By way of example, WP4 has provided WP5 with probability distribution in Eqn. (2.2) for both monetary and electrical outputs O_j's.

Now, in order to be able to proceed to the decision phase in Figure 2.1, WP7 develops together with WP3 and WP4 conditional probability distributions $p(O_j \mid E_i, A_k)$, which are WP3 & WP4 conditional outcome probability distribution $p(O_j \mid E_i)$ under additional mitigation actions A_k, where it is understood A_k may either influence the underlying damage state probabilities $p(\mathbf{x}_j \mid E_i)$ or the consequence mappings $\mathbf{x}_j \to O_j$. The first action is known as a probability-reducing (or preventive) measure, and the second action as a consequence-reduction (or repressive) measure.

With these mitigation conditional probability distributions $p(O_j \mid E_i, A_k)$, we then compute the outcome probability distribution under the different mitigation actions A_k, using both the product and sum rules of probability theory:

$$p(O_j \mid A_k) = \sum_i p(E_i, O_j \mid A_k) = \sum_i p(E_i) p(O_j \mid E_i, A_k). \tag{2.3}$$

In the decision phase of the quantitative risk based decision making framework the mitigation outcome probability distributions, $p(O_j \mid A_k)$, are compared to the status quo outcome probability distribution, $p(O_j)$. Based on this comparison, either no action or the optimal mitigation action is chosen, which then concludes the decision phase in Figure 2.1.

With WP3 and WP4, WP7 has discussed the conversion of the current status quo outcome probability distributions (2.2) to the mitigation outcome probability distributions (2.3).

By way of example, WP4 generates outcome probability distributions (2.2) for electricity infrastructure systems. WP3 performs a similar task for land based transportation networks. WP6 and WP5 interact with WP2 in order to implement the EWE in the case studies, whilst WP7 provides information on possible mitigation strategies and their impact on the outcome probability distributions (2.3).

3 Structure – Methodology – Content

In order facilitate the implementation of the inference phase of the risk framework in Figure 2.1, the following taxonomy is offered up by WP5:

Structure – Methodology – Content

On the highest level of abstraction, the structure level, it is prescribed in WP5's risk based decision making framework that the information carriers of the inference phase, Figure 2.1, are probability distributions and that these probability distributions are to be connected by way of the product and sum rules (i.e. Bayes' theorem and the law of total probability). This structural requirement is as simple as it is non-negotiable.

On the middle level of abstraction, the methodological level, it is thought desirable that in the inference phase, the pertinent physical and sociological mechanisms are translated to probability distributions in the optimal manner. There are several methodological models by which one may obtain such probability distributions (e.g. linear regression model, logistic regression model, GEVs, POTs, BN models, neural networks, etc.). Now, what constitutes is that statistical sophistication is very relative. This inherent relativity notwithstanding, WP5 chooses to adopt the Bayesian data-analysis methodology for RAIN's implementation of the inference phase[2].

On the lowest level of abstraction, the content level, it is prescribed in WP5's risk based decision making framework of D5.1 that in the inference phase the pertinent physical and sociological mechanisms are to be translated to probability distributions. What is deemed to be the pertinent physical and sociological mechanisms is a matter of content. It follows that in the RAIN project the content is provided by content domain owners (i.e. WP2, WP3, WP4, and WP7). These content domain owners are typically natural scientists and engineers. Note that the content may vary from case study to case study; that is, content generation within the quantitative risk based decision analysis framework is an open-ended research challenge (whereas the structural requirements of the quantitative risk based decision analysis framework are firmly fixed, as described in D5.1).

The Structure-Methodology-Content taxonomy also suggests for WP5, the Bayesian experts who have adopted the Bayesian data-analysis methodology and, as a consequence, are the framework owners, a trajectory which is perfectly parallel to WP6's case study trajectory. The case study owner WP6 interacts with the content domain owners WP2, WP3, WP4, and WP7, in order to capture as accurately as possible in a probability model the physics of that what happened in the case studies. During this interaction process methodological support is provided by WP5 to WP6 in order to see if WP2, WP3, WP4, and WP7's suggestions can be couched in alternative, more optimal probability models. Such an approach allows WP5 to help WP6 articulate its probability modelling needs, on a technical, non-content, methodological level, to the content domain owners WP2, WP3, WP4, and WP7.

[2] In the D5.1 "Annex On The Bayesian Probability Theory" a case is made for the Bayesian data-analysis methodology, as it is juxtaposes Bayesian probability with both the alternative Bayesian Network (BN) methodology (which is currently very popular) and orthodox statistics (the dominant data-analysis methodology in the period 1920-1990).

4 WP5's role as an aggregator and assembler

RAIN models the extreme weather events, which are the triggering events. This means that WP2 is at the beginning of the chain of inference in Figure 2.1. Nonetheless, it is WP3, WP4, and WP7 that, for a specific WP6 case study, specify to WP2 the needed probabilities of the weather intensity thresholds, as the physical features, that is, structural and maintenance status (under possible mitigation actions), of given critical elements are dependent on the specific weather conditions to which these elements are subjected to.

WP5 does not specify WP2 what kind of threshold exceedance values/ probability distributions are needed for WP6's case study. This is not for WP5 to answer, as this is a matter of "content". The only ones who, for a given case study, can provide WP2 with meaningful structural failure threshold exceedance values/ probability distributions specifications are WP3, WP4, and WP7, as it is only those WPs that can gauge the effect of a given EWE intensity on the structural integrity of some infrastructural object. This is the basis of the RAIN methodology.

As a case in point, the probability of damage due to floods (mainly on substations and pylons) is highly dependent on the specific circumstances (example: towers' foundation, type of terrain, type of tower, location of substation). Considering the case (study) of the Susitna river flooding in 2009 where two 230 kV transmission towers failed structurally, the probability of failure of a pylon under an estimated thresholds of a 4-days period amount of precipitation is provided by WP4 in Table 4.1.

Precipitation (mm)	x < 70	70 < x < 150	150 < x < 220	x > 220
P (failure)	0	0.4	0.8	1.0

Table 4.1: Thresholds for amount of precipitation in a 4-days period

In Table 4.1, we see that WP4 has (implicitly) defined the kind of rainfall event that can lead to pylon failure. WP3, WP4, and WP7 consist of the engineers that can specify what kind of weather related hazard events will lead to what probability of a structural failure. WP2 consists of natural scientists that put probabilities on the weather related hazard events that may lead to structural failures. So WP3, WP4, and WP7 specify, in principle, to WP2 what kind of weather intensity thresholds are needed. Again this is the basis of the RAIN methodology.

In concert with this process, WP5 safeguards that the structural requirements of the quantitative risk based decision making framework are met (as described in D5.1), by making sure that all the WP deliverables are either in the form of, or translatable to, (conditional) probability distributions. Similarly WP5 provides methodological support, as is proposed in the previous chapter.

Furthermore it is reiterated that the RAIN 'engine', i.e. the **risk based analysis/decision making framework for single and multiple hazards** is delivered in D5.1. This framework consists of two phases:

1. Inference Phase:
    a. Use the laws of probability theory

i. Product Rule
ii. Sum Rule
2. Decision Phase:
   a. Use the Bayesian decision theory
      i. Utility mappings by way of Bernoulli's utility function
      ii. Risk as a position measure of an outcome probability distribution

The "inference engine" proposed in D5.1 is a strict adherence to the product and sum rules of probability theory:

$$P(A \mid B)\, P(B) = P(AB) = P(B \mid A)\, P(A), \tag{4.1}$$

and

$$P(\bar{A}) = 1 - P(A), \tag{4.2}$$

from which flows forth the generalized sum rule:

$$P(A + B) = P(A) + P(B) - P(AB). \tag{4.3}$$

WP3 and WP4 outputs/deliverables have been required to conform to this "inference engine", by providing probability distributions that may be connected in a meaningful way through the product rule (4.1) into joint probability distributions, the methodology followed in these processes is demonstrated via Appendices A & B. These joint probability distributions then allow us to evaluate the outcome probability distributions, as we marginalize over all variables other than the outcome variable, by way of the generalized sum rule (4.3). Basically, the following de-aggregation takes place in this process (Figure 4.1):

1. Weather hazards developed in connection with work performed in WP2 (this can be on either a low or high resolution spatio-temporal scale, and it may assume either the present or future climate triggering events).
2. WP6 identifies infrastructure components in considered system and their current condition.
3. WP3 & WP4 provided with information on EWE – to facilitate determination of consequences of event (i.e. outcome probability distribution).
4. Lookup tables returned to WP5 & WP6 from which risk metrics are derived.
5. Steps 1-4 represent first iterative loop.
6. WP7 provides input on mitigation measures employed in 2nd loop to identify/prescribe mitigation measures.
7. 2nd loop repeats steps 1-4.
8. Risk reduction quantified. Risk Based Decision Making Framework is complete.

Steps 1 to 8 may seem straightforward, but the aggregation processes are quite complex as is demonstrated in the RAIN case studies.

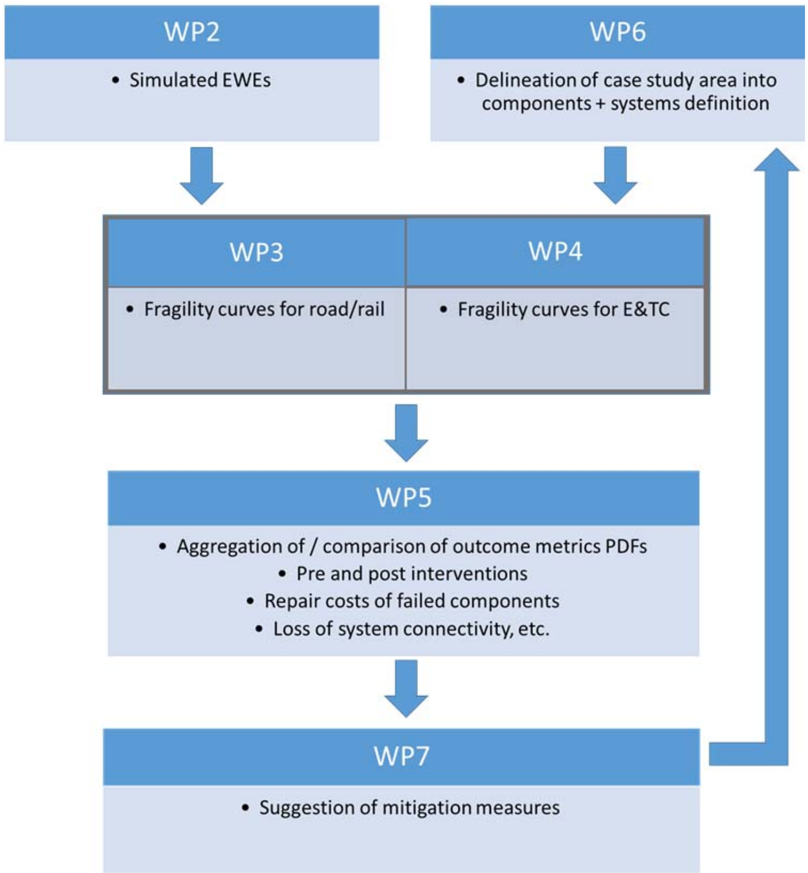


Figure 4.1: Chart of Work Flow associated with Risk Based Decision Making Framework

The steps in Figure 4.1 will not be affected by the choice of the EWE resolution (in time and space). Of course, the results (outcome metric probability distributions) are more biased in the case of a low resolution, but the workflow in itself does not change. The current WP2 output (D2.4) can be used for a rapid but rough risk assessment neglecting localized effects on a spatial scale < 25 km and temporal scale < 1 day. If we need higher accuracies we need to fine tune and develop detailed risk assessments such as presented by the RAIN case studies.

Apart from the comparison between different resolutions, a comparison of the outcome PDFs resulting from assuming the present or future climate triggering events, can be made to assess the effect of climate change on risk. The availability of simulations, provided in D2.5, addressing both the RCP4.5 and RCP8.5 scenarios in the middle and at the end of the 21st century (Figure 4.2) allows the effects of climate change mitigation on the effect of infrastructure risk to be estimated. The shifts of probability threshold exceedances on higher spatial and temporal scales might be larger than on the coarse scales, but we can take some appropriate hypotheses here.

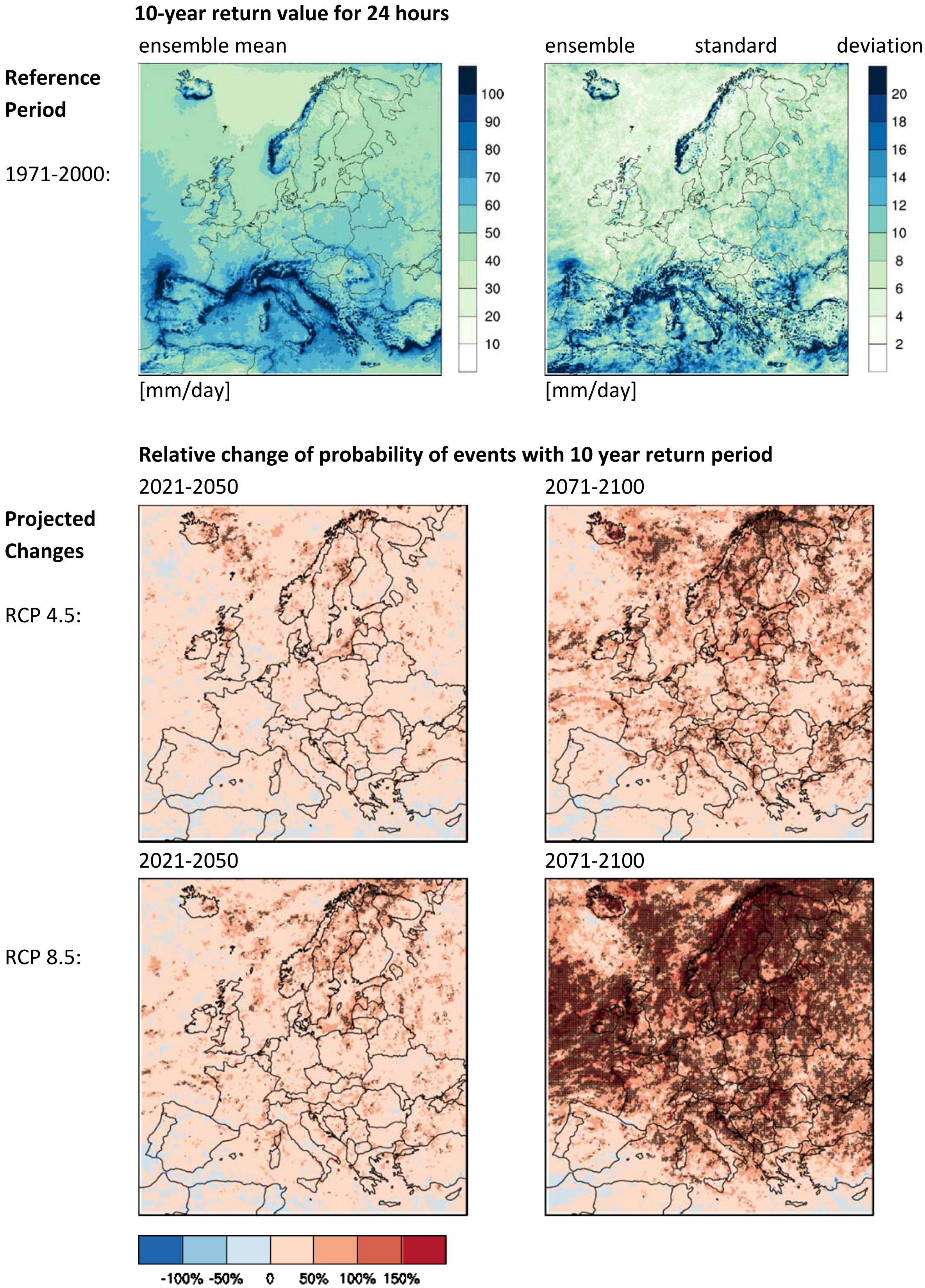


Figure 4.2: Top row: 10-year return value for daily precipitation in the historical simulation (1971-2000). Other panels: Change in the occurrence probability for heavy precipitation events between the historical period and the scenario simulations. Ensemble mean detected using daily data. (RAIN Deliverable 2.5).

5 Conclusion

As a part of the projects mid-term review, the reviewers requested that a new deliverable be produced, D5.5 as a Roadmap for Work Package Integration. The objectives of this deliverable were to:

a) To ensure the compliance of all inputs from WP2, WP3, WP4, and WP7 deliverables that feed D5.1’s risk based decision making framework,

b) To effectively elaborate, adjust and modify the outputs of WP2, WP3, WP4, and WP7, in order to provide D5.1’s risk based decision making framework with robust input, and

c) To successfully integrate the outputs of WP2, WP3, WP4, and WP7, into D5.1’s risk based decision making framework.

This deliverable has presented in detail the process of integration between WP2, 3, 4, 5, 6 & 7 in the context of their work flow and produced deliverables. Ultimately the integration of this work is demonstrated in the project via the RAIN case studies. In the interim this deliverable serves as an important roadmap for the integration process.

Appendix A: WP3 Inference Phase Demonstration

Diagram of interaction of WPs within RAIN for road – and rail transport infrastructures

The steps to be followed are summarized in the diagram below for the case of incidents in the transport infrastructure:

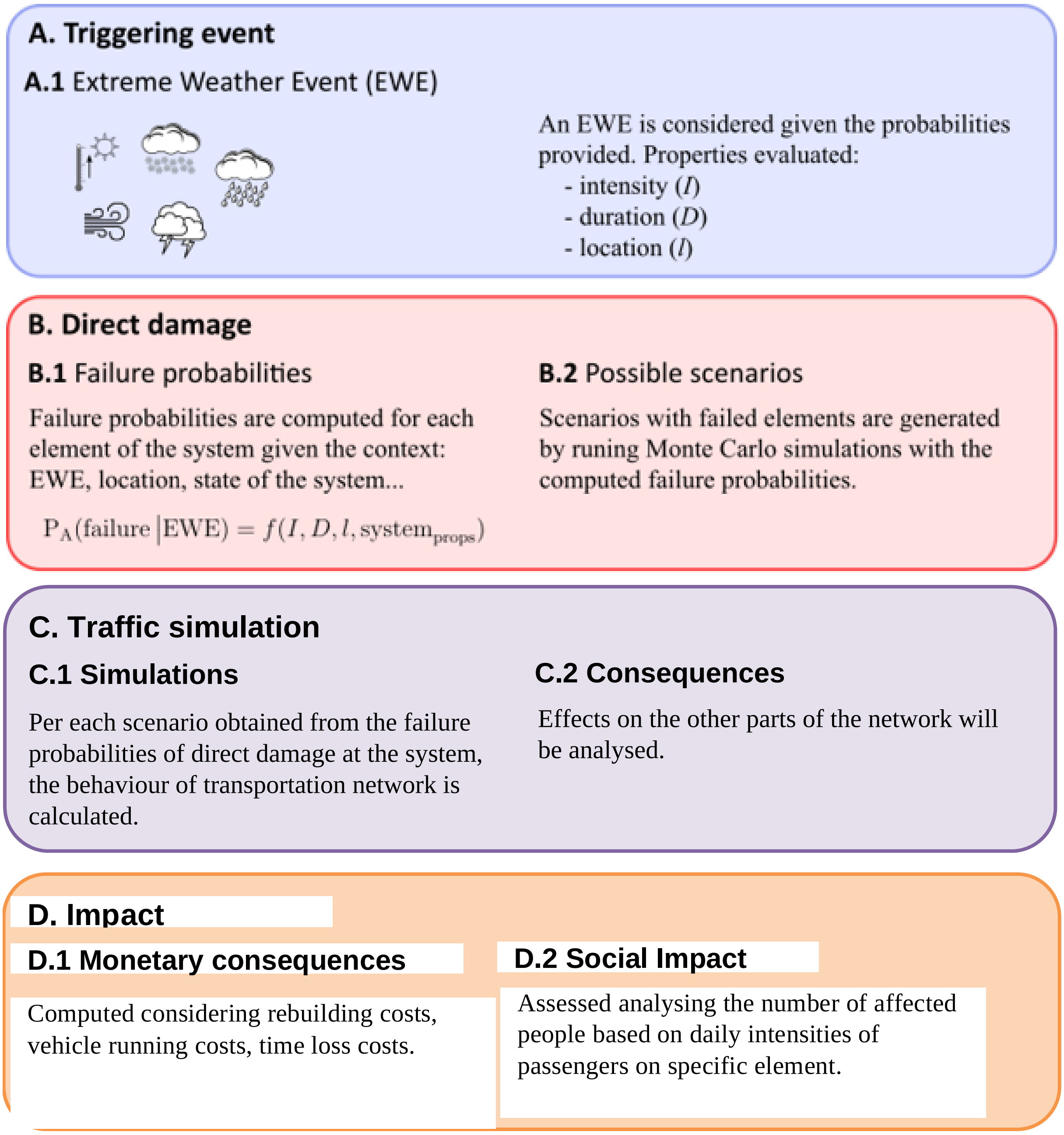


Figure A.1: Inference Flow Chart WP3

EXAMPLE:

Example of the workflow followed by WP3 for a particular *Bridge case study* under the effect of *heavy wind and rain*.

Step A: Triggering Event

The triggering event is described by a probability density function, delivered by WP2.

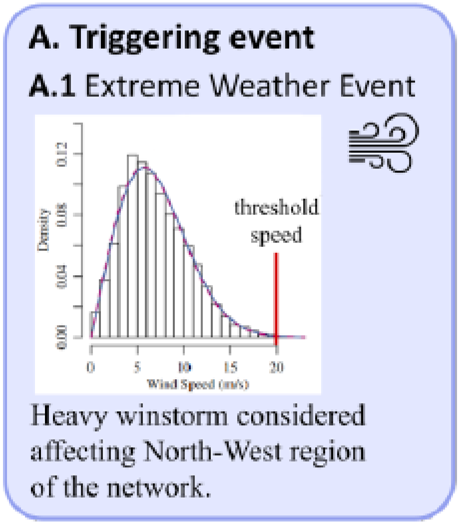


Figure A.2: Triggering event

Step B: Critical infrastructure element failure probability

Probability of CI element failure will be computed for each CI element separately taking into account their physical features (structural and maintenance status), engineering empirical formulae with respect to specific weather conditions, considering its intensity. For each element and for each relevant extreme weather event the probability of failure is produced.

Step B1: Possible scenario: Bridge under the effect of heavy wind and rain
e.g. Windstorm with speed 81km/h + Heavy Rainfall with precipitation more than 220mm/h

Windstorm and Heavy Rainfall has occurred and affected the bridge and adjacent roads.

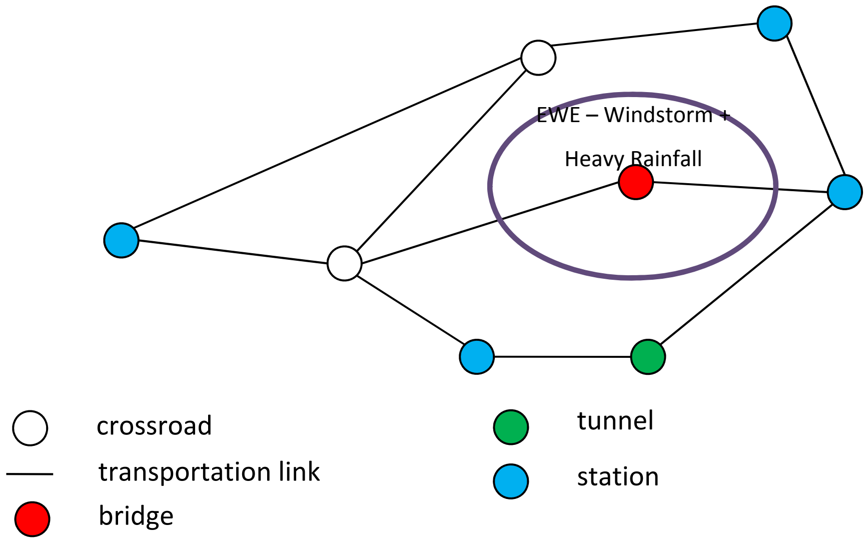


Figure A.3: Example of Road/rail Network

Failure Definition

Following the guideline of Danish Roads Directorate (2004), we distinguish between 3 types of failure (see Table A.1) with corresponding values of probability failure. This table is based on existing recommendation for loading- and safety regulations for structural design (NKB 1978, ISO 1999, EN 1990:2002). Related probabilities of failure are designated for High Safety Class structures (in other words Consequences Class CC3 (Table A.2)).

Failure Consequences (Safety Class)	Failure Type I: Ductile failure with remaining capacity	Failure Type II: Ductile failure without remaining capacity	Failure Type III: Brittle failure
Very Serious: High Safety Class	$P_f \leq 10^{-5}$	$P_f \leq 10^{-6}$	$P_f \leq 10^{-7}$
	$\beta \geq 4{,}26$	$\beta \geq 4{,}75$	$\beta \geq 5{,}20$

Table A.1: Guideline Requirements

The safety index, β, is formally defined in terms of the probability of failure P_f: $\beta = -\Phi^{-1}(P_f)$ for which $\Phi^{-1}(\cdot)$ is the inverse function of the standardised normal distribution.

Consequence Class	Description Related to Consequences	Reliability Class
CC1	Low consequence for loss of human life; economic, social, or environmental consequences small or negligible	RC1
CC2	Moderate consequence for loss of human life; economic, social, or environmental consequences considerable	RC1
CC3	Serious consequence for loss of human life or for economic, social or environmental concerns	RC1

Table A.2: Eurocode consequence classes

The vast majority of bridges are designed to CC2 (or RC2), with CC3 (RC3) a possibility only for bridges with very high consequences of failure, such as a signature bridge. In this example it is assumed that CC3 bridges represent CI elements due to possible very high consequences associated with failure.

In Table A.1 the potential of EWEs to cause damage on the CI element is not included. Therefore, additional probabilities need to be produced. They should be produced separately taking into account:
(1) physical features of the specific structure and
(2) specific characteristic of a EWE.

Step B2: Probabilities of failure

B2.1 Probabilities of failure - Engineering studies

In the case of bridge under the effect of heavy wind and rain, we start using the standard EN 1990 – Eurocode: Basis of Structural Design and EN 1990 –Eurocode 1: Actions on Structures (Part 1.4. and Part 1.6.) to compute the load (formulas below) produced by wind (actions caused by wind) and rain (actions caused by water mainly due to rain) respectively:

Rain:

$$F_{wa} = \frac{1}{2} k \rho_{wa} h b v_{wa}^2 \quad \text{(A.1)}$$

where:

F_{wa} is the water load in N;

v_{wa} is the mean speed of the water averaged over the depth, in m/s;

ρ_{wa} is density of water, in kg/m^3;

h is the water depth, but not including local scour depth, in m;

b is the width of the object, in m;

k is the shape factor, where

k = 1,44 for an object of square or rectangular horizontal cross-section, and

k=0,70 for an object of circular horizontal cross-section.

Wind:

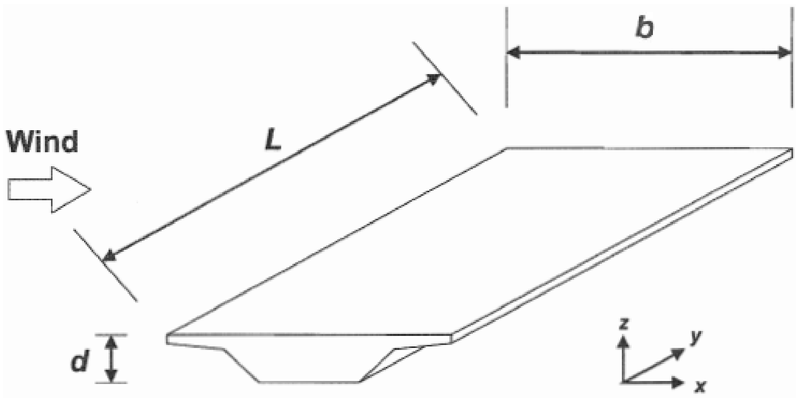


Figure A.4: Bridge under wind load

Wind force in x-direction:

$$F_w = \frac{1}{2} \cdot \rho \cdot v_b^2 \cdot C \cdot A_{ref,x} \quad \text{(A.2)}$$

where:

F_w is the wind load in N;

v_b is the basic wind speed in m/s;

ρ is the density of air in kg/m^3;

$A_{ref,x}$ is the reference area in m^2;

C is the wind load factor. $C = c_e \cdot c_{f,x}$.

These values should be compared with the resistance of a particular element in order to capture the specific physical features of the structure. Afterwards the probability of failure can be computed. This approach is very time consuming and requires a precise knowledge of the technical details of each structure and partly environmental conditions especially with regard to water (scour vulnerability, soil, etc.).

B2.2: Probabilities of failure - Historical analysis

The probability of failure may also be based on analysis of historical data. See for example the statistical evidence of bridges failure in United States, Table A.3 (Cook, 2014).

Mode of Failure	Partial Collapse	Total Collapse	Not Indicated	Total Count	Percentage of Total	Proportion of Failure Rate
Hydraulic Total	82	115	182	379	54.85%	1.17E-04
Flood	26	56	116	198	28.65%	6.10E-05
Scour	46	41	44	131	18.96%	4.03E-05
Debris	1	5	17	23	3.33%	7.08E-06
Hydraulic	6	8	0	14	2.03%	4.31E-06
Ice	3	3	5	11	1.59%	3.39E-06
Drift	0	2	0	2	0.29%	6.16E-07
Collision Total	47	24	18	89	12.88%	2.74E-05
Collision	35	13	14	62	8.97%	1.91E-05
Auto/truck	9	4	1	14	2.03%	4.31E-06
Barge/Ship	3	5	3	11	1.59%	3.39E-06
Train	0	2	0	2	0.29%	6.16E-07
Overload	11	44	23	78	11.29%	2.40E-05
Deterioration Total	25	12	24	61	8.83%	1.88E-05
Deterioration	23	11	15	49	7.09%	1.51E-05
Steel-deterioration	2	1	9	12	1.74%	3.69E-06
Fire	6	9	4	19	2.75%	5.85E-06
Storm/Hurricane	1	16	0	17	2.46%	5.23E-06
Geotechnical	7	4	1	12	1.74%	3.69E-06
Construction	3	7	0	10	1.45%	3.08E-06
Miscellaneous	1	2	4	7	1.01%	2.16E-06
Earthquake	0	5	1	6	0.87%	1.85E-06
Fatigue-steel	4	0	1	5	0.72%	1.54E-06
Design Error	2	1	1	4	0.58%	1.23E-06
Tree Fall	0	0	2	2	0.29%	6.16E-07
Bearing	1	1	0	2	0.29%	6.16E-07
Sum	190	240	261	691	100.00%	2.13E-04

Table A.3: Cause-proportioned failure rate for bridges in the United States (1987-2011)

In the example case, there is important information about the failure probability related to the category of (1) hydraulic type of failure (caused by the water) and (2) storm/hurricane category of failure.

The above may be employed to generate fragility curves, showing the probability of damage state *i* of an infrastructural component, as a function of the intensity measure (such as inundation depth, flow velocity, debris percentage of the flow, etc.).

B2.3: Probability of Failure and Expected Bridge Life

In the research of the HYRISK project (Stein et al., 2009), the model of probability of failure due to expected bridge life is combined with the probability of failure due to other fail causes e.g. flood, windstorm, etc. The HYRISK project was oriented towards the probability of failure due to scour effects but other failure probabilities can be computed by the developed approaches. In our case it could be probabilities obtained from the analysis above.

This combination of probabilities can be done using:

$$P_L = 1 - (1 - P_A)^L \tag{A.3}$$

where

P_L probability of failure over the expected life of the bridge,

P_A annual probability of failure calculated by HYRISK or supplied by the modeller,

L the expected life of the bridge in years.

Example: failure analysis indicates that a bridge will fail due to hydraulic or water causes with probability of 1.17E-04 and due to storm/hurricane with probability of 5.23E-06 which is together probability P_A = 1.22E-04. For such a bridge, the graph shown in Figure A.5 gives the probability of failure in any year between the present and 100 years hence.

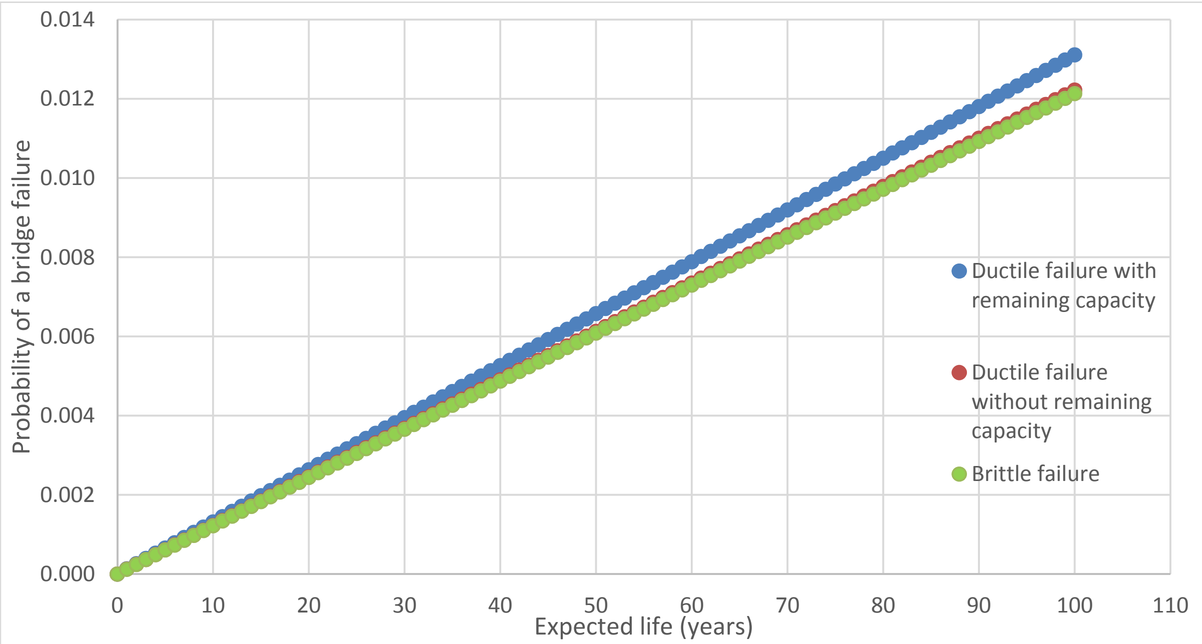


Figure A.5: Probability of failure versus expected life

Step C: Simulation of impact of CI element failure on Transportation Network (TN)

Per each scenario obtained from the failure probabilities of direct damage at the system, the behaviour of transportation network is calculated.

C1: Simulation of the impact of different failure states of the bridge on other elements of the TN and Society:

For such simulations a traffic simulation program can be employed (e.g. OmniTrans).

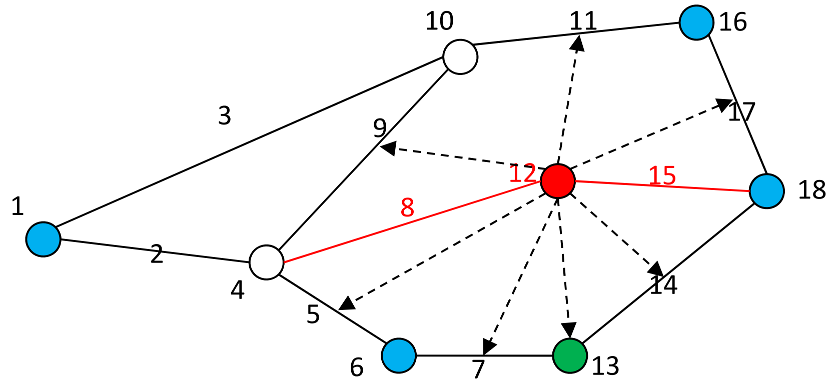


Figure A.6: Influence of the bridge failure on other elements of the transportation network

Step D: Impacts on economy and population in the case of transport CI element failure

Except from the direct extreme weather impacts on transport infrastructure, there are also consequential negative societal and economic impacts on the population which are caused by the dysfunctionality of transport infrastructure. They include e.g. the economic loss due to a necessary detour, indirect societal impact expressed in the form of the number of affected population, economic loss due to failure of transportation element, economic loss due to non-loading/non-unloading transported goods, etc. These consequences could vary depending on particular type of element (e.g. bridge or cargo station, etc.)

The economic loss/year due to necessary detour within the road infrastructure can be calculated (TRI, 2014):

$$EL = 365 * AADIT * DL * N \tag{A.4}$$

where:

EL economic loss, in €/year;

$AADIT$ annual average of daily intensities of trucks on specific element, in vehicle/day;

DL detour length which is necessary to pass in order to provide the service (delivery of goods), in km;

N price per 1 km of freight and commercial passenger transport, in €/(vehicle km).

The number of affected population per year due to failure of transport infrastructure can be calculated (TRI, 2014):

$$AP = 365 * (AADIP * AOP + AADIT * AOT) \tag{A.5}$$

where:

AP number of population affected per year, users/year;

$AADIP$ annual average of daily intensities of passenger cars on specific element, in vehicle/day;

AOP average occupancy of passenger car, in users/vehicle;

AOT average occupancy of truck, in users/vehicle.

In railway transportation the economic losses are based on the value of the effects caused by failure /destruction of the element (e.g. railway bridge, tunnel) which are calculated based on the transport capacity over the track section and the value of the average price €/tkm. In case of quantifying the economic losses in the railway transport the worst scenario, when destruction of the object caused termination of provided services (goods) on said track, is considered. Therefore, no economic loss due to detour was calculated. The economic loss can be calculated (TRI, 2014):

$$EL = TC * AvP \tag{A.6}$$

where:

EL economic loss, in €;

TC transport capacity over the track section for a period of time of 365 days, in tkm (tonne-kilometre),

AvP average price, in €/tkm.

In the case of cargo rail stations the consequences of their destruction are determined on the basis of economic losses due to non-loading/non-unloading transported goods which results in no transportation to the destination. Determination of economic losses is based on the assumption that if there are no goods loaded, there is no transportation what results in a decrease in revenues of carriers. The economic loss can be calculated (TRI, 2014):

$$EL = Q * AvP \tag{A.7}$$

where:

Q amount of manipulated material for period of 365 days, in t;

AvP average price, in €/t.

For the complex quantification of economic losses due to a bridge failure models such as those developed in HYRISK can be employed. According to this model the losses include four components: rebuilding costs, vehicle running costs, time loss costs, and the cost of a lost life (see formula A.8) (Khelifa et al., 2013).

$$Economic\ loss = (C_0 + C_1)eWL + \left[C_2\left(1 - \frac{T}{100}\right) + C_3\frac{T}{100}\right]DAd + \left[C_4\,O\left(1 - \frac{T}{100}\right) + C_5\frac{T}{100}\right]\frac{DAd}{S} + C_6X \tag{A.8}$$

where: rebuilding costs:

C_0 demolition cost, in €/m^2;

C_1 rebuilding cost, in €/m^2;

W bridge width, in m;

L bridge length, in m;

e cost multiplier for early replacement estimated from average daily traffic;

vehicle running cost (Stein et al, 2009):

C_2 cost of running vehicle, in €/(km vh);

C_3 cost of running trucks, in €/(km vh);

D detour length, in km;

A average daily traffic, in vh/day;

T average daily truck traffic, as a percentage of the total traffic;

d duration of detour, in days;

for time loss costs (Stein et al, 2009):

C_4 value of time per adult; [€/ (h user)],

O occupancy rate; [user/vh]

C_5 value of time for truck; [€ / (h vh)],

S average detour speed, in km/h;

for cost of lost life (Khelifa et al, 2013):

C_6 cost for each life lost is assumed 6 million USD;

X number of deaths.

Appendix B: WP 4 Inference Phase Demonstration

Diagram of interaction of WPs within RAIN for E&TC infrastructures

WP4 is developing the models to quantify risks in electric and telecommunication in relation to extreme weather events. The inputs are:

- A given geographical area
- Power grid and telecommunication infrastructure configuration
- Some context (including damage states and maintenance states)
- Some extreme weather event

The outputs are based on power flow equations and include:

- Outcome probability distributions
- What-if scenarios
- Worst case scenarios
- Monetary and social impact for given groups (Industry, commercial, residential)

The above allows incorporating the effect of some preventive actions (like replacing pylons, or clearing the right of way) and some mitigation measures, like the placement of mobile generation units (diesel). This appendix discusses all the steps to be followed, as summarized in the diagram below, and it shows how the steps fit in the framework provided by D5.1:

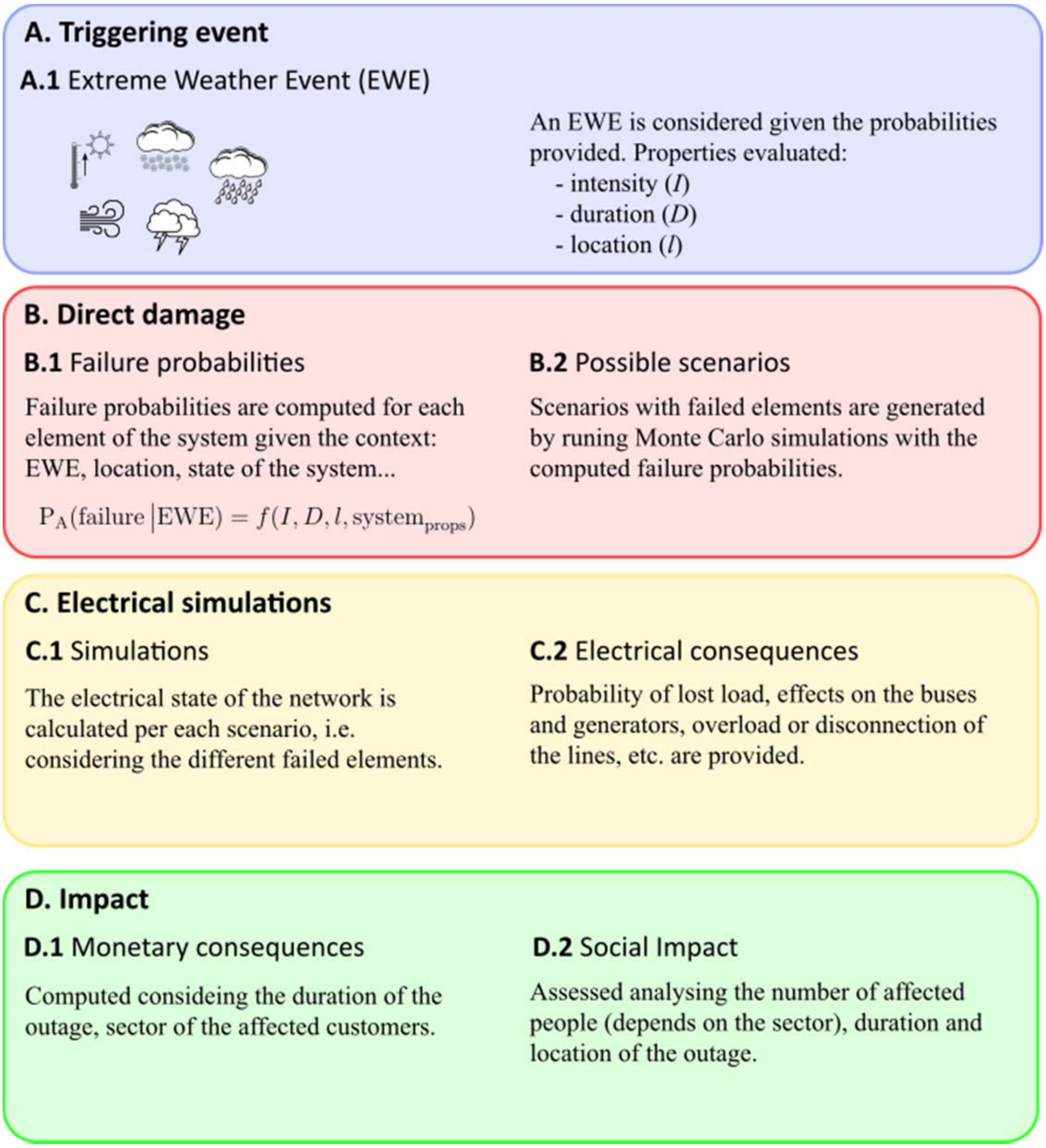


Figure B.1. Inference Flow Chart WP4

In the same general wordings as the flow chart of WP3, we may repeat:

The probabilities and properties of the triggering event are provided by **WP2** (weather). This information is used by **WP3** & **WP4** (infrastructures) to assess the direct damage. The direct consequences on transportation (**WP3**) or electrical and telecommunications network (**WP4**) are analysed. The impact in monetary and social terms is assessed per kind of infrastructure (**WP3** & **WP4**). The preventive measures that affect direct damage at Step B, or mitigation measures affecting the final impacts at Steps C and D are provided by **WP7**. **WP5** provides the structure to integrate the results from **WP2**, **WP3**, **WP4**, and **WP7**. Results from **WP5** integration are analysed and discussed in **WP6** (in particular in relation to the use cases).

The meteorological WP2 data gathered and computed (in case of forecasts and trends) feeds into WP4 in several points:

1. **Define intensity thresholds.**
   For each type of extreme weather, they provide a reference against which the potential damage of different component is evaluated.

2. **Provide relative relevance among types of extreme weather events per region.**
   This information is used to decide which EWEs are analysed in each particular case. For instance, it may be more interesting to study in depth the effects of a heat wave affecting Seville (located in the South of Spain) than a snowstorm in the same city.

3. **Provide trends**.
   For the optimal investment computation it is relevant to estimate if in mid-long term the intensity and frequency of such events is expected to increase or decrease and the rate.

4. **Expected frequency of rare events**.
   Knowing the probability of suffering a given EWE within the following 5, 10, 25 years is useful to determine the worthiness of an investment by the company

A number of WP7 mitigation actions specific to the Electrical and Telecommunications sectors were already provided by WP4 in deliverable D4.2. These actions are readily implemented within the framework. In addition to those, engineering solutions for mitigation proposed by WP7 can also be taken into account and applied in the case of E&TC to assess their effectiveness, and produce a benchmarking based strictly on simulation.

Example
Example of the workflow followed by WP4 in a particular EWE (from deliverable D4.4): *High Voltage Transmission Lines* under the effect of *heavy wind and rain*.

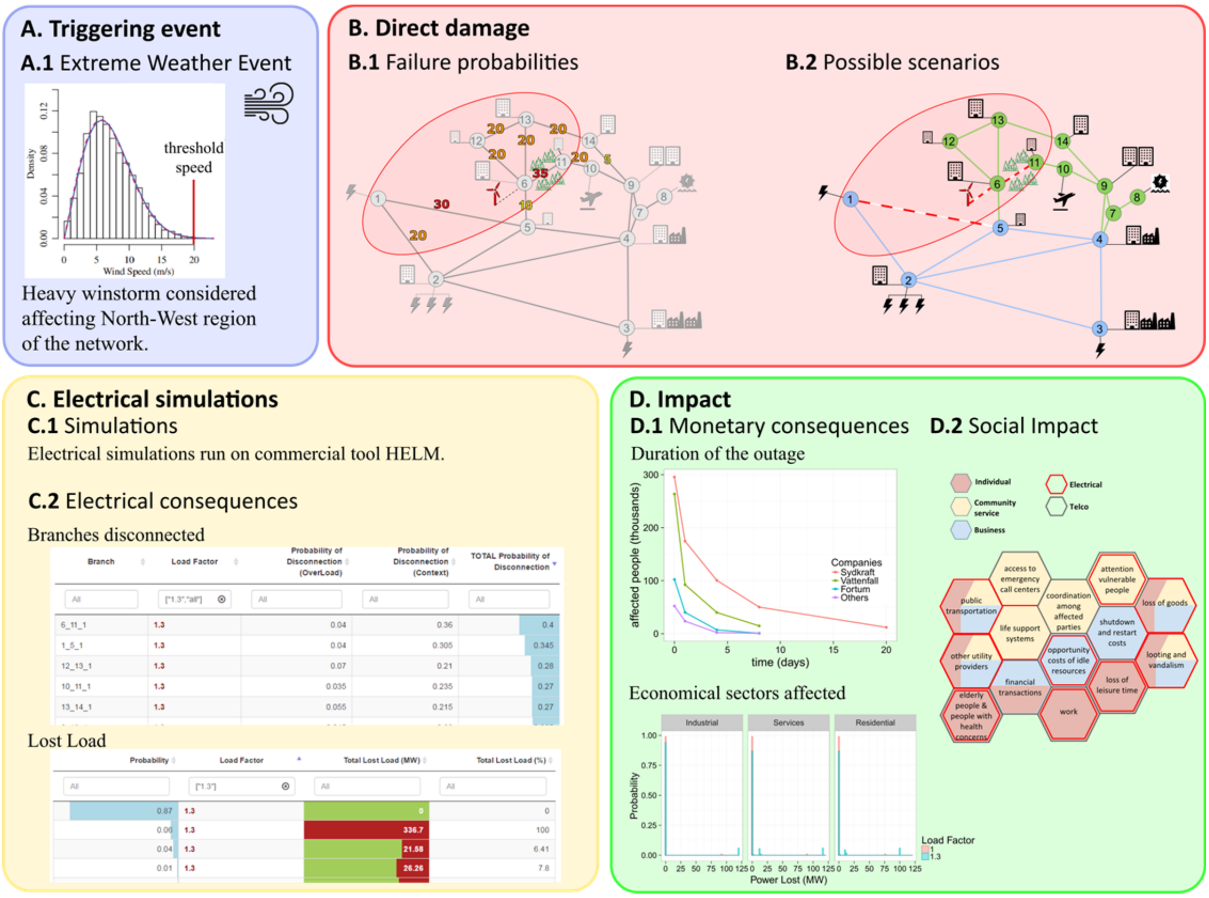


Figure B.2 Inference Flow Chart WP3

Direct damage

B1. **Element failure probability.** Computed for *each type for critical element* taking into account their physical features (structural and maintenance status), engineering empirical formulae respect to *specific weather conditions*, considering its intensity (in principle by using a predefined set of thresholds). In the assessment of each of these pairs (element - weather event) we have prioritized by criticality (i.e. more vulnerable and which failure causes more impact).

In the case of *High Voltage Transmission Lines* under the effect of *heavy wind and rain*, we start using the standard IEC60826 (design criteria of overhead transmission lines) to compute the load produced by wind and rain respectively:

Wind and rain

The load over the transmission lines due to **wind** is given by the formula

$$F_w(t) = \alpha \cdot \frac{V^2(t)}{1600} \cdot \mu_z \mu_{sc} \beta_c d L_v B \sin^2 \theta \tag{B.1}$$

where V(t) is the wind speed, θ is the angle between the line and wind direction, and the rest are constructive line parameters. In the case of **rainfall,** the load over lines is:

$$F_r(t) = \frac{2}{9} \pi d^3 n b V_s^2 \tag{B.2}$$

where V_S is the final velocity of raindrops, d is their mean diameter, n the number of them per unit of volume and b is the area.

Then, following the analysis of Wei et al, 2014, we can compute the probability of line failure in different scenarios. The probability is evaluated for segments between two towers; the probability for an electrical segment (usually several kilometres long) is

$$P_{f(n)}(t) = P_{f(n-1)}(t) + p_{f(n)}(t) - P_{f(n-1)}(t) \cdot p_{f(n)}(t),\ n \geq 2 \tag{B.3}$$

where $P_{f(n-1)}(t)$ is equivalent probability of failure of n − 1 series lines at time t, $p_{f(n)}(t)$ is the probability of failure of the n^{th} line at time t.

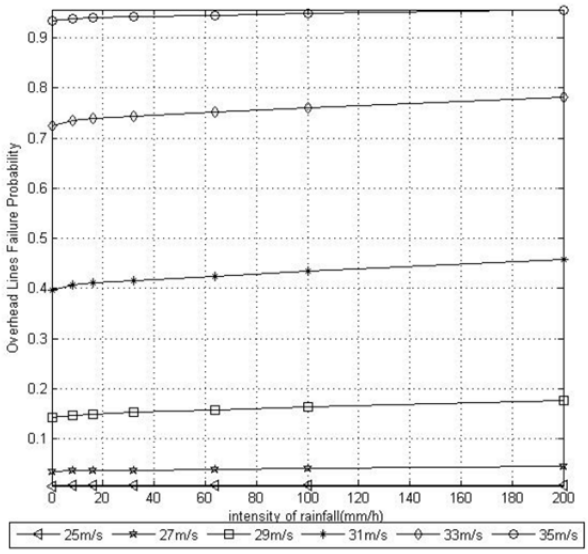


Figure B.3: Probabilities of overhead line failure given some rainfall and wind intensities

The following table shows the thresholds for **rain**:

Level	Moderate rain	Heavy rain	Rainstorm	Downpour		
				Weak	Middle	Strong
Intensity of rainfall (mm/h)	8	16	32	64	100	200

Table B.1: Thresholds for rain

The thresholds for **wind** intensity range is assumed from 25 to 35 m/s.

Floods (precipitation effect) in Electrical & Telecommunications

The probability of damage due to floods (mainly on substations and pylons) is highly dependent on the specific circumstances (example: towers' foundation, type of terrain, type of tower, location of substation). Nevertheless some general historical data can provide some estimations. Consider for instance the case of Susitna river flooding in 2009 where two 230 kV transmission towers crumbled down. This was the effect of **4 days** of precipitations; about **4-to-9 inches** of rain fell.

Estimated thresholds (probability of failure of pylon under this amount of precipitation in a 4-days period.

Precipitation (mm)	x < 70	70 < x < 150	150 < x < 220	x > 220
P (failure)	0	0.4	0.8	1.0

Table B.2: Thresholds for rain in 4 days period

Threats to grid include electrical clearances (scheduled maintenance), tower erosion, landslides, flood debris build-up around tower bases, interruption to substation auxiliary power supplies, flooded access. The input data for the failure probability computation are not directly weather variables in this case (as precipitation intensities) but flood probabilities computed through simulation on specific geographical areas.

Electrical simulations

Per each scenario obtained from the failure probabilities of direct damage at the system, the behaviour of the electric network is calculated and the consequences in terms of **probabilities** of **lost load**, and **disconnection** of lines is provided.

Impact

Lost loads are transformed into monetary costs (**probabilities of € lost**) per sector (industrial, services, and residential). Social impact is assessed by analysing the (**distribution of probability of) number of affected people** and the (**distribution of probability of) duration** of the outage.

Prevention and mitigation measures

These measures will be incorporated at the moment of assessing the failure probabilities (in case of prevention measures) or at the moment of assessing the final impact (monetary costs and social impact).

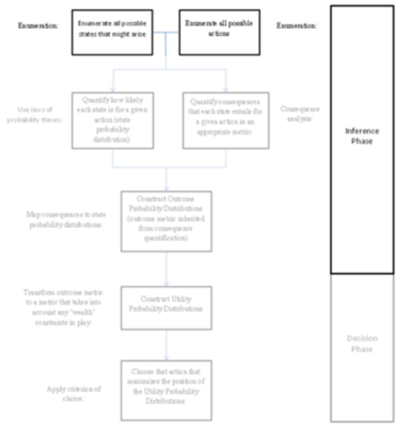
Following the framework for quantitative risk analysis proposed by WP5 in deliverable D5.1, the different required elements in the inference and decision phases (states, actions, consequences, outcomes, and utility distributions) are identified in relation to Electrical and Telco infrastructures.

Inference phase

Enumeration

The first sub-phase of the inference phase is the **enumeration of states**. For the analysis carried on in WP4, the states are defined primarily as the **different topological configurations** of the power grid, considering that one main disturbance to the power grid is the change of the network topology due to direct damage on transmission lines (or equivalently, structural transmission assets, like pylons). In principle this could generate a combinatorial explosion for large systems with many nodes and edges. In the computation this issue is overcome considering only the most relevant configurations, where relevance is given by their relative occurrence probability. To avoid the complexity of a continuous set of states (there are continuous quantities on place, like the consumption level), the definition of states can be complemented with "high level of abstraction" states that gather continuous sets (by defining ranges) and physically different states by their global features, using de facto the impact markers.

The possible **actions are enumerated** selecting those modeled for protection and mitigation strategies. In terms of the simulation environment, the protection actions are those that modify the *context*, for instance, the clearance of the right of way of lines, the reinforce or replacement of pylons and the deployment of backup batteries for telecommunication antennas. Among the mitigation action we count with the deployment of portable diesel generators in locations where the power supply has been interrupted, the electrical operation actions over the grid to ensure robustness in stressed situations (like meshing, connection of shunt devices for reactive power control).



Use of laws of probability theory and consequence analysis

The direct use of Monte Carlo-like approach allows translating single element failure probabilities into *configuration probabilities*, that is, the **probability of each defined state to occur**.

The following table shows an example of the state space and its probability: cases with a given probability of occurrence (first column) are numbered (second column). For each case, a number of branches of the electrical grid can be in failed condition (third column). The state of each branch (the remaining columns) is shown in green if functioning or red if failed.

Scenarios

Prob.	Case	Num.Open	1_2_1	1_5_1	2_3_1	2_4_1	2_5_1
0.085	3	0					
0.07	22	1					
0.05	8	1					
0.045	28	1					
0.04	38	1					
0.03	21	1					
0.025	33	1					
0.02	15	2					
0.02	79	3					
0.015	9	2					

Showing 1 to 10 of 97 entries Previous 1 2

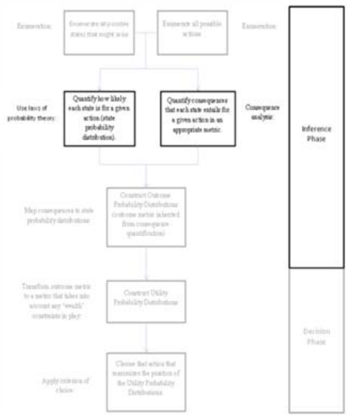
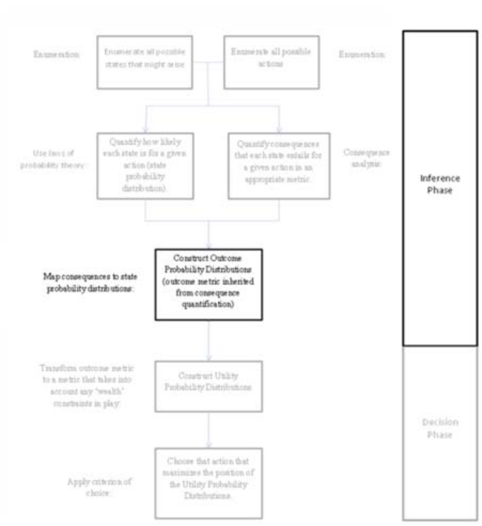


Figure B.4: State space

Computing the electrical state of the grid given each circumstance allows assessing the impact (if any) over the population activity. The metrics designed to quantify the impact involves the classification of consumers. In this way, the electrically modeled "load", which is an aggregation of an electrically connected consumption points, is broken into 3 different types according to the social /economic mixture of the area[3]. In other words, the consequences are assessed in terms of the electrical load lost that translates into economical losses and social impact. The outcome probability distributions are built using the costs associated to the consequences and the probability of each state-action combination.

Map consequences to state probability distributions

Having quantified the consequences through the defined metrics and the probabilities of occurrence of each state, the outcome probability distribution is computed separately for each social group, since it is estimated that the same physical event (for instance "one day without electricity") affects them differently (see figure below). In the case of electrical and telecommunication infrastructures, the measure of the impact rely mainly on the duration of the supply interruption and the clients affected (number and "size"). In this sense, the supply is almost "binary" on both cases (with or without supply) since the "bad quality supply" is intentionally avoided by the infrastructure operators[4].



[3] An approximation to this information is nowadays available on open platforms like www.openstreetmaps.com, which allow the automatic processing of geographical information (use of land or building tags in this case) through scripting.

[4] There are some exceptions, like voltage drops that could damage some electronic appliances.

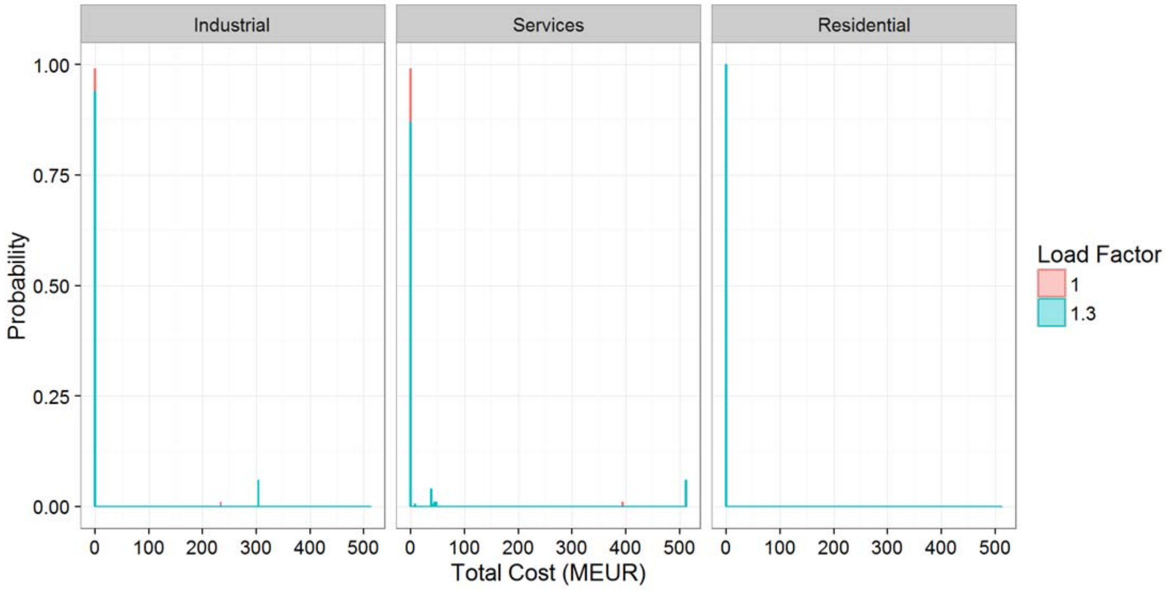


Fig. B.5: Probability distribution of costs of a EWE affecting a model network in two cases: close to peak hour (load factor = 1.3) and day non-peak hour (load factor = 1). The consumers are grouped by type (industrial, services, and residential), that allows discriminating the economic impact per sector.

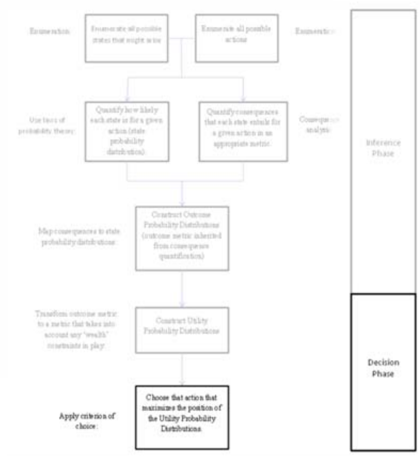
Decision phase

Construction of utility distributions

As explained in D5.1, [section 5.1] we have that we may "normalize", as a matter of modelling sophistication, the observed outcome values to the decision makers' wealth. In the workflow of WP4 this is done assuming typical investment capacity of the electric / telecommunication company.

Criterion of choice

Among the three methodologies take an optimal decision (*expected outcome, expected utility* and *Bayesian decision theory)*. WP5 has developed proper decision criteria for this purpose.



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