EU-CIRCLE

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

D4.2 EU-CIRCLE RESILIENCE PRIORITIZATION MODULE

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This report develops and explains a methodology to elaborate the overall resilience of network assets or network parts. The methodology proposed can also be used in order to elaborate the importance of different resilience capacities and for the evaluation of strategies to strengthen resilience.	

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Executive Summary

The main purposes of D4.2 is to describe an approach for prioritisation of network assets for the resilience of an infrastructure system.

Basis for this are the specific resilience capacities introduced in D4.1 “resilience framework” – Anticipation, Absorption, Coping, Restoration, Adaptation. For all these capacities, D4.1 lists more detailed parameters which can be measured by means of concrete indicators.

The present D4.2 provides a first methodological approach to measure the overall resilience of network assets by aggregating factual information about assets characteristics (in the above mentioned resilience parameters) together with subjective valuation from stakeholders, such as relative weights and utility functions.

The approach proposed in this deliverable is mainly based on Multi-Attribute Utility Theory (MAUT) which is a well-established decision support approach (Keeney, Raiffa 1976). Depending from the actual situation – stakeholder engagement, data availability etc., the approach can be amended or complemented with further techniques, such as the pairwise comparison, known from the Analytic Hierarchy Process (AHP) (Saaty & Vargas 2001).

This report also describes, how different perspectives of various stakeholders can be taken and how to test the robustness of results.

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1 Introduction

A key objective of EU-CIRCLE and the tools that are developed within this project is the reduction of risk of interdependent networks against climate hazards by strengthening their resilience. The method that is presented here allows the decision maker to systematically decrease risk.

Taking into consideration the steps of risk management as explained in D3.4 Risk Assessment Framework, D4.2 addresses primarily the step "Assessment and evaluation of risks" (Figure 1, left hand side, red box). Crucial questions to be answered are: Which are the network assets[1] with the highest resilience? Which are the network assets with the highest risks?

The resilience prioritization aims to allow end-users to assess the overall resilience of a network of assets. Resilience measurement supports the decision making for different levels, from the level of infrastructure owners/operators up to the governmental level. Infrastructure owners/operators can compare their facilities and initiate measures to reduce risks (Petit 2013). The method helps the decision maker to structure the decision process by revealing facts and subjective valuations.

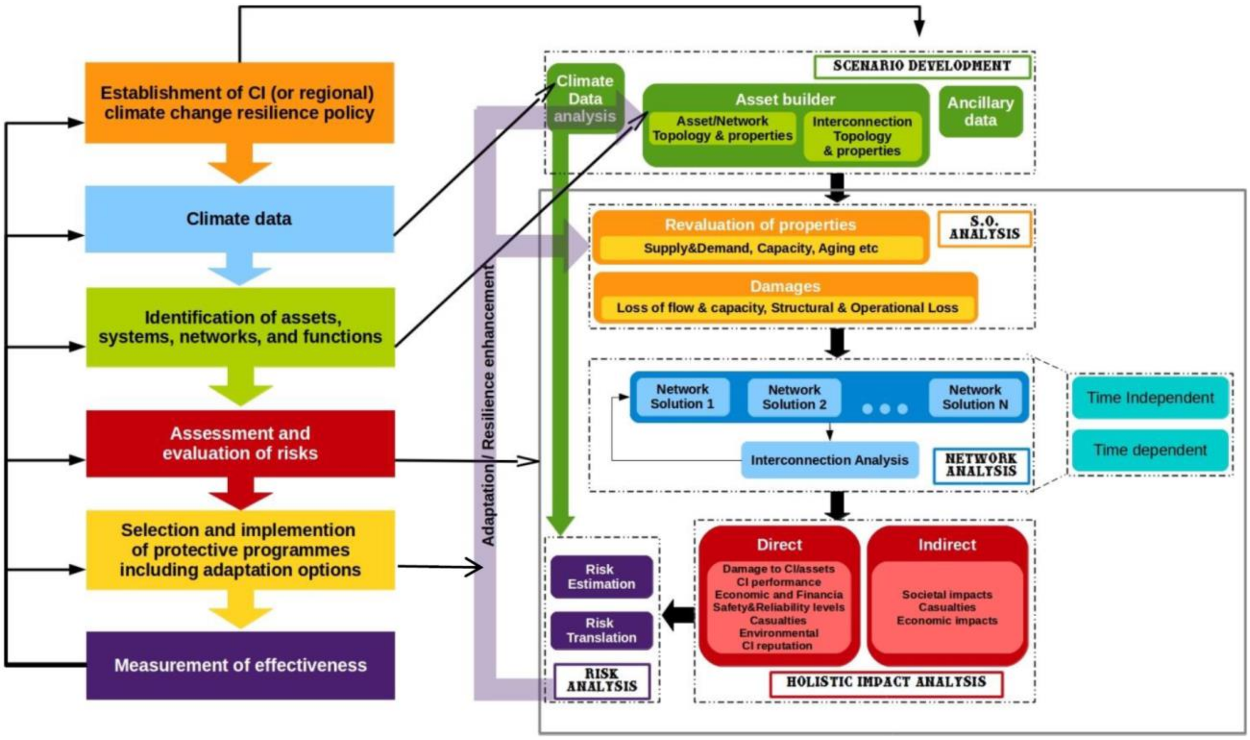

Figure 1: Risk management (left) and risk modelling process (right). Source: EU-CIRCLE D3.4

More in detail, the proposed set of methodologies facilitates three distinctive analytical directions:

[1] A draft catalogue of assets and networks has been developed within T3.1, Deliverable D3.1

1) The proposed methodology can be used to analyse the relative importance of the different resilience aspects, respectively resilience capacities. The following resilience capacities were introduced in D4.1 “resilience framework”:

- Anticipation,
- Absorption,
- Coping,
- Restoration,
- Adaptation.

2) The methods can also be used to compare network assets regarding overall resilience. This overall resilience is calculated as an aggregate (mean or lowest value) based on scores in specific resilience capacities. For all resilience capacities, D4.1 lists and explains detailed parameters that can be measured by means of concrete indicators. The selection of suitable indicators strongly depends from data availability and the specific case study.

3) Furthermore, the same methodology facilitates comparison of measures that address the unacceptable risks (USAID 2013). It supports the later steps of risk management, as there are “Selection and implementation of protective programs including adaptation options” and even “Measurement of effectiveness” (Figure 1, left hand side, yellow and dark blue boxes). Thus, it is also a part of the adaptation model. Measures are expected to contribute to aspects as:

- Socio-economics and environmental benefits
- Increased operational capacities
- Reduction of severity of disruption to connected networks
- Reduction of probability of failures
- Costs and benefits for operators/owners
- etc.

Deliverables D3.4 and D4.1 provide exhaustive descriptions of aspects associated to protective programs.

1.1 Methodology

The development of the resilience prioritisation module started with a discussion on *what* has to be compared, respectively prioritised. Following to that, *methodological approaches* for deriving an overall resilience metric have been screened, analysed and discussed among WP 4 partners together with the partners of WP 3 (Risk assessment framework), WP 5 (CIRP development) and WP 6 (case studies).

1.2 Structure of the deliverable

Chapter one informed briefly on *what* has to be prioritised or compared. The following chapter 2 introduces in the *methodological approaches* which are foreseen. Chapter 3 and 4 are devoted to discuss two methodological fields in detail: chapter 3 explains different approaches to elicit numerical weights from (verbal) decision maker opinions and chapter 4 explains the multi-attributive utility theory which can be used to aggregate subjective valuations and objective measurements. Chapter 5 concludes the deliverable with explanations on the next steps.

2 Methodological overview

The methodology presented hereafter aims to break down the decision problem into smaller components (USAID, 2013). Extensive literature reviews on multi-criteria decision analysis, guidelines for choice and explanations on their use are presented for example by Nijkamp et al. (1990), Schneeweiß (1991), Malczewski (1999), Figueira, Greco & Ehrgott (2005) and Roy & Slowinski (2013). The following table lists strengths and weaknesses of applications of multi-criteria decision analysis approaches.

Table 1: Strengths and weaknesses of multi-criteria approaches, taken from USAID 2013, based on Gamper & Turcanu 2007

Strengths	**Weaknesses**
Easy integration of different kinds of information.	Final results, particularly sorting and ranking of options, can be driven by stakeholder preferences, who is involved, and the timing of their participation.
Able to tackle a wide range of qualitative and intangible criteria together, including monetized and non-monetized costs.	Can become technically complex, particularly in regards to the identification of criteria and disaggregating the impact of an option on each criterion.
Supports broad stakeholder participation and helps stimulate discussions and a common understanding of the problem, potentially helping to resolve conflicts.	Difficult to compare results across different applications.
Systematic and transparent, thus more accountable.	Challenging to reach agreement on weighting of criteria.
Helps reveal and legitimize decision makers and other stakeholder preferences.	Can be time consuming when done thoroughly.
Open to different values and opinions that are formalized and can be revised as more information is made available	May strengthen power of groups with access to more information.

Multiple approaches with different capabilities have been developed in the last four decades. USAID 2013 describes the spectrum of approaches it as a continuum between simplicity and complexity (see following table).

Table 2: Key characteristics of simple and complex multi-criteria approaches (USAID 2013)

Simple → Complex			
Simple qualitative assessment of proposed options against a set of criteria. Often just a	Some quantitative work to assess options against set criteria with different weights	Significant amount of quantitative analysis for each criteria as well as development of specific weights for each criterion. Mathematical	Complex formula and computational resources used to derive best options, combine weights and

positive or a negative sign for each criteria.	and some sensitivity analysis.	functions used to rank options as well as conduct sensitivity analysis.	possible decision spaces, as well as to determine error bands.

The general procedure to conduct multi-criteria analyses typically comprises the following steps:

Step 1: Identify the decision context

Step 2: Identify adaptation options to prioritize

Step 3: Identify criteria

Step 4: Identify outcome and performance of options

Step 5: Assign weights to each criteria

Step 6: Examine results

Step 7: Conduct a sensitivity analysis

The EU-CIRCLE prioritization module is foreseen to facilitate and structure the decision making process, especially to support steps 5, 6 and 7. The approaches will become a vital component of the CIRP in order to allow the end-user to test and apply the methods multiple times,

- with varying conditions and assumptions,
- for different geographical regions,
- on different levels of decision making, from the level of infrastructure owners/operators up to the governmental level,
- on different time scales and
- on different climate change scenarios.

As mentioned in chapter 1, the evaluation may take three different analytical directions:

1) Elicitation of relative importance of *resilience capacities*, parameters and indicators,
2) Assessment of resilience of *network assets* (or alternatively: network parts) and
3) Comparison of *protective measures*.

Obviously, in all three analytical directions we prioritise different elements, marked in *italics*. However, the methods described in this deliverable can be deployed equally in all analytical directions.

The three analytical directions take primarily an ex-ante perspective. All three different analytical directions aim to prioritize or to compare things on different “nature”, thus, we will have to “compare apples and oranges”. Furthermore, we will have to deal with imperfect knowledge about characteristics or outcomes of alternatives.

All selected approaches should be characterized by:

- comprehensibility to all stakeholders, thus not too complex,
- “versatile” applicable - meaningful in many different contexts,
- practicability for implementation as software tool and
- realistic input data requirements.

Taking into consideration these requirements, we suggest to combine the following methodologies:

- **Analytical Hierarchy Process (AHP)**, respectively its core element “**pairwise comparison**” to elicit relative weights or - alternatively – further light-weight techniques for estimation of relative weights
- **Multi-attribute Utility Theory (MAUT)** for integration of analytical values and subjective valuations into overall scores
- **Sensitivity analysis** among **specific preference profiles**

In the following, we explain in short how we foresee to deploy the approaches in order to facilitate the three analytical directions. More detailed information is provided in the following chapters.

2.1 Alternatives, criteria, indicators and hierarchy

In order to compare the alternatives, in a first step, suitable criteria and indicators must be identified. The following requirements must be considered in the selection of indicator:

- Collectability for all alternatives,
- High expressiveness,
- Coverage of all decisive aspects,
- Low redundancy and
- (Preferably) a monotonic function.

Not all relevant criteria can be captured directly with an indicator. For example, if “improvement on the aspect withstanding” is a decisive criterion, then the achievement of this objective could be measured with the indicator “maximum possible water depth” where the network asset remains operational. In many publications and studies, the terms “criteria” and “indicators” are used in a synonymous way, however, in many evaluation context, criteria and indicator can be different.

Sets for criteria and indicator sets may vary between different decision makers. Also, indicator sets vary between ex-post and ex-ante context. In ex-ante evaluations, typically criteria that concern the implementation are important (costs, feasibility, political issues etc.), whereas in ex-post evaluations, the factual impacts are considered. Indicators can also be composed of multiple indicators. Such indicators are called aggregated indicators.

Turning to the different analytical direction.

- In case (1), *the elicitation of importance of resilience capacities*, parameters and indicators, if assess only capacities, it is not needed to define criteria and indicators. The alternatives (which are in this case the resilience capacities) could be directly ranked for example by means of pairwise comparison which is explained in chapter 3.

- In case (2), *the assessment of resilience of network assets*, the criteria are the resilience capacities. These criteria are in turn composed of sub-criteria, which are called "Generic resilience indicators" in D4.1 (see next table). The achievement of every network asset regarding each sub-criteria must be measured by an suitable indicator.

- In case (3), *the comparison of protective measures*, the criteria alternatives are the measures and the same hierarchy of indicators, sub-criteria, criteria can be applied.

We foresee the following hierarchy levels:

- Level 3 (highest): aggregation of the generic resilience indicators for each resilience capacity
- Level 2: generic resilience indicators
- Level 1 (lowest - not shown in the table, depends from case-study): network assets or protective measures (alternatives), and their objective attributes, measured by means of indicators

Table 3: Proposed generic resilience indicators

Crises management phase	**Resilience parameters (level 3)**	**Generic resilience indicators (level 2)**
Preparedness	**Anticipation**	1. Probability of failure 2. Quality of infrastructure 3. Pre-event functionality of the infrastructure 4. Quality/extent of mitigating features 5. Quality of disturbance planning/response 6. Quality of crisis communication/information sharing 7. Learnability
Mitigate	**Absorption**	1. Systems failure (Unavailability of assets) 2. Severity of failure 3. Just in time delivery - Reliability 4. Post-event functionality 5. Resistance 6. Robustness
	Coping	1. Withstanding 2. Redundancy 3. Resourcefulness 4. Response 5. Economic sustainability

		6. Interoperability
Response	**Restoration**	1. Post-event damage assessment 2. Recovery time post-event 3. Recovery/loss ratio 4. Cost of reinstating functionality post-event
	Adaptation	1. Substitutability (replacement of service) 2. Adaptability / flexibility 3. Impact reducing availability 4. Consequences reducing availability

2.2 Elicitation of relative importance of resilience capacities, parameters and indicators

The Analytical Hierarchy Process (AHP) has been initially designed as a structured and efficient technique for rank ordering alternatives. The overall aim is to structure the decision problem and to develop a mathematical model of the decision situation. The core element of the AHP are "**pairwise comparisons**", developed by Saaty in the 1970-ies and successfully deployed in many domains such as governmental decisions, architecture or investment. In this process, all "elements" are compared to each other "elements" with respect to preference or importance. A scale with 9 degrees is typically used to transfer the subjective valuations into a numerical value. AHP allows to "map" the decision hierarchy – in our case consisting of resilience capabilities, parameters, indicator values and physical network assets. The numerical values can be processed in a straightforward way. The scale for the comparison and the formulas applied to the results of the comparisons are provided and discussed in subsequent chapter. Thus, we can use this technique to elicit the relative importance of single resilience capacities, parameters and indicators and use the pairwise comparison to decompose the decision problem. The procedure also allows to evaluate the degree of consistency (or in-consistency) of the subjective valuations.

One drawback should be mentioned: pairwise comparison per se is a laborious technique. We therefore also consider to deploy simpler techniques such as **rank sum, equal weight, rank exponent** (Roszkowska, 2013). These techniques require as input from the decision maker either simply to rank the elements or to allocate scores. Based on that, weights are determined with a simple formula (explained in the following chapters).

2.3 Assessment of resilience of network assets

The assessment of the resilience of network assets requires to aggregate for each network asset the values of each element of the hierarchy of indicators, parameters and resilience capacity. Petit et al. (2013) proposes to deploy **Multi-Attribute Utility Theory (MAUT)** to determine a resilience index for assets or sites that is composed from achievements in the different resilience capacities.

MAUT is another well-established approach in the field of Multi-Criteria Decision Making (MCDM) and a competitor to AHP. The concept of MAUT was introduced by Keeney & Raiffa in 1976 and has been applied in many different decisions situations (Keeney 1982). In MAUT, a utility function has to be determined over the entire range of values for each criterion, as a first step. This utility function helps to transfer the actual measurement values (indicator values) into a “degree of desirability”. The function can be of linear or other form.

The expected overall utility (or in our case: the overall resilience) is often calculated as the weighted sum of the impacts in all criterion. However, it could be more appropriate to assess the overall resilience as the lowest (minimum) of the individual values since the overall system might be as resilient as its weakest part.

The network asset (or network parts) can be ranked according to this overall resilience index.

In case that pairwise comparisons are feasible, we may consider to use the aforementioned approach AHP to elaborate a ranking of network assets in terms of resilience.

Alternatively, we can directly compare each capacity (anticipation, absorption, coping, etc..) of network assets, without determining the overall resilience index. In this case we obtain partial orders which can be visualized by Hasse Diagramme Technique or other approaches.

2.4 Comparison of protective measures

The methodologies introduced can be applied also for prioritization of protective measures (alternatives). The focus is on measures that address unacceptable risks. Measures are characterized by indicators, that include aspects related to:

- Socio-economic outcomes and distribution to stakeholder groups
- Operational capacities
- Severity of disruption to connected networks
- Costs and benefits for operators/owners
- Environment etc.

Deliverable D3.4 provides more exhaustive description.

Again, we need to deploy an aggregative method and depending from feasibility of pairwise comparisons, the both approaches - AHP and MAUT – are considered. Aside from AHP and MAUT, further evaluation techniques such as cost-benefit analysis (CBA) and cost-effectiveness analysis (CEA) will be explained within the later deliverables.

It should be noted, that comparison of protective measures is the focus of T4.5 and T4.5 and will be elaborated in detail in pertinent deliverables D4.5 *CI adaptation to climate hazards model* and D4.6 *EU-CIRCLE Cost – effectiveness Analysis*.

2.5 Different and specific preference profiles

Any evaluation (in the case of EU-CIRCLE: resilience capacity importance, asset resilience, protective measures priority) comprises three components (Hill, 2002):

- **a) analytical model**, objective characterization of an element/alternative, such as measurements

- **b) subjective model**, consisting for example of system of valuations, preferences, hierarchy of indicators, utility functions, thresholds, relative weights and
- **c) result of evaluation**: aggregation of analytical model and subjective valuations.

With other words, evaluation means to complement factual measures with individual valuations. EU-CIRCLE aims to facilitate decision support from different viewpoints, such as:

- perspective of infrastructure owner/operator aiming to maximize enterprise profit or
- perspective of government to maximize benefit in equal measure for society, environment and economic development

We expect differences especially in selection of relevant criteria and indicators and notably in different weights of importance of criteria and indicators.

Therefore, the evaluation result (c) can vary when different subjective models (b) are applied to the analytical measurements (a). The EU-CIRCLE prioritization module will facilitate to elicit, store, retrieve and apply different preference profiles.

The resilience prioritisation module will allow end-users to store and retrieve individual preference profiles.

2.6 Sensitivity/robustness analysis

Sensitivity analysis helps to deal with uncertainty and to test the robustness of the results. Uncertainty can be introduced in both, in analytical values and in subjective valuations. For example, if criteria values are the result of forecasts. Also, it can be the case that a decision makers prefer to determine a range of a relative importance (weight), e.g. “something between 30—50 %” instead of deciding for a specific value.

Sensitivity analysis means to repeat the systematically the prioritization procedure and in every repetition to gradually vary one (or more) variables over a given range and to study the behavior of the evaluation result.

The EU-CIRCLE prioritization module facilitates this sensitivity analyses by giving the user the opportunity to select the “active” variables and to enter parameters for the systematic repetitions (number of repetitions, step width, direction etc.).

3 Analysis of criteria weights

Criteria within decision processes are often not equally important (Malczewski 1999). In order to elicit these differences in importance, multiple approaches have been developed, mainly in the field of economic research. These approaches allow for a transformation of verbal valuations into quantified, relative criteria weights. This quantification eases storage and processing of the valuations in computer based systems.

Also for the prioritization of resilience, evaluation of resilience and ranking of protective measures, all involved criteria need to be weighted.

The sum of all individual criteria weights must be 1. The interval of all possible individual criteria weights is between 0 and 1. A criterion with a weight of 0 does not influence the evaluation at all. The evaluation exclusively depends on one criteria, if its weight is 1. If all criteria are equally important, then the weight of each criteria is 1/n. From that follows: even if "no" specific weights are allocated to a criterion, this means also a certain (= equal) weighting.

In the following, different approaches for the analysis of relative weights are presented which are well-established and frequently deployed in multiple domains and could also be of use within EU-CIRCLE and should be introduced to the EU-CIRCLE prioritization module. The approaches explained here are only a subset of the approaches described in the literature, however, they are - due to low input requirements – frequently deployed and widely accepted. An extensive introduction and overview over approaches provide for example Malczewski (1999) and Roszkowska (2013).

3.1 Rank order approaches

The approaches explained in the following require as input from the decision maker only to order the criteria. Also in terms of mathematics, they belong to the simplest approaches to determine criteria weights.

Basically, one has to distinguish between ascending and descending ranking order. With ascending ranking order, the most important criterion receives rank 1, the second important criteria rank 2 etc., while as with descending ranking order, the least important criterion receives rank 1, the second least important receives rank 2 etc.

For the determination of relative weights from the ranking order, different mathematical models can be used.

In the following, the calculation with rank sum (RS), rank reciprocal (RR) and rank exponent (RE) is explained. The normalized, relative criteria weight w_j of the j^{th} criterion is calculated with the rank sum approach as follows:

$$w_j = \frac{n - r_j + 1}{\sum_{k=1}^{n} (n - r_k + 1)}$$

Here, n is the total number of involved criteria and r_j the rank of the criterion j. The ranking reciprocal approach calculates the normalized, relative criteria weights as follows:

$$w_j = \frac{1/r_j}{\sum_{k=1}^{n} 1/r_k}$$

The rank exponent approach can be seen as an extension or generalization of the ranking sum approaches.

$$w_j = \frac{(n - r_j + 1)^p}{\sum_{k=1}^{n} (n - r_k + 1)^p}$$

Additionally, a value p must be entered and leads to interesting behavior: p=0 leads to equal weights, p=1 leads to weights according to the rank sum formula. With increasing value, the weight distribution becomes more extreme (see following table).

Table 4: Criteria weights in rank exponent approach for 5 criteria.

Rank	p=0	p=1	p=2	.	p=10
1	0.2	0.33	0.45	.	0.9
2	0.2	0.27	0.29	.	0.1
3	0.2	0.2	0.16	.	
4	0.2	0.13	0.08	.	
5	0.2	0.07	0.02	.	
Sum	1	1	1	.	1

3.2 Direct quantitative valuation

In contrast to the determination of criteria weights based on ranking order, the determination of criteria weights is based on the allocation of a positive number (“score”) according to the criteria’s importance.

The ratio of the resulting criteria weights is the same as the ratio of the input values (scores). The best known approach is called direct scoring (DS).

In scoring models, a given number - for example 100 – are distributed by the decision maker among the involved criteria. The higher the score allocated to a criterion, the higher the relative importance. A score of 100 indicates, that the decision depends only from this criterion. A score of 0 means, the criterion not at all influences the decision. The approach is robust against stretching or compression of the overall score (Churgin & Peschel, 1989). Relative weights q for each criteria can be determined according to the following formulas:

$$q_j = \frac{x_j}{\max\{x_1, x_2, ..., x_n\}}$$, alternatively: $$q_j = \frac{x_j - \min\{x_1, x_2, ..., x_n\}}{\max\{x_1, x_2, ..., x_n\} - \min\{x_1, x_2, ..., x_n\}}$$

If multiple stakeholders are involved in the decision making process, arithmetic means of their individual scores could be used as an admittedly simple approach to aggregate diverse opinions.

An alternative to the direct scoring method is the method of ratio estimation. In this approach, the most important criterion receives a score of 100, all other criteria a score below according to their importance.

In contrast to direct scoring, the calculation of the relative weight is based on the scores of the *least* important criterion, according to the following formula:

$$q_j = \frac{x_j}{\min\{x_1, x_2, ..., x_n\}}$$

In order to obtain normalized relative weights, the individual relative weights must be divided by the sum of all criteria weights.

3.3 Pairwise comparison

"With redundancy and variety, even 'fuzzy' verbal judgments can produce accurate ratio scale priorities", Ernest Forman explains the main benefit of pairwise comparison (Forman 2016).

The method of pairwise comparison was developed in the 70-ies from the American mathematician and economist Thomas Saaty as the core element of the Analytic Hierarchy Process (AHP) and since then has been further developed (Poschmann et al. 1998).

The has been successfully deployed in various disciplines such as economics, politics, architecture (Saaty & Vargas 2001). Every criterion must be compared against every other criterion according to its importance. Usually, a nine-step scale is used for the transformation of the importance differences from verbal scale into numerical values; fewer applications are based on 5, 7 or 15 step scale (Poschmann et al. 1998).

Table 5: Nine-step scale according to Saaty

Numerical value	Meaning
1	equally important, indifferent
2	
3	slightly higher importance, light preference
4	
5	significant higher importance / preference
6	
7	strongly more important / strong preference
8	
9	absolutely dominant

The values 2, 4, 6 and 8 are used for intermediate valuations. In order to express an opposed valuation, inverse values between 1/9 and 1/1 are used. Thus, there are in total 18 possible steps to express importance or preferences.

By means of the fixed scale is it avoided, that extreme differences in importance/preference must be expressed by high numerical values. Saaty & Vargas (2001) justify the validity of the scale with the findings in the field of psychophysics from Weber and Fechner.

Usually, the values are entered into a matrix. In the following, the method of pairwise comparison is demonstrated at an hypothetical example of the resilience evaluation for network assets with three criteria: anticipation capacity, coping capacity, adaptation capacity (for the sake of simplicity, the two remaining resilience capacities are omitted in this example).

The following table shows the valuations. The criterion “Anticipation” has a slightly higher importance (3) than the criterion “Coping” and a significant higher importance (5) than the criterion “Adaptation”. The criterion “Coping” has a slightly higher importance (3) than “Adaptation”. The opposed relations – below the diagonal – can be determined as the inverse value.

Table 6: Example matrix for three criteria

Criteria	Anticipation	Coping	Adaptation
Anticipation	1	3	5
Coping	1/3	1	3
Adaption	1/5	1/3	1
Column sum	1.533	4.333	9

The procedure of criteria weight calculation comprises multiple steps. At first, the column sums are calculated. Next, in order to normalize the matrix, each element is divided by the column sum. The relative criteria weights are then calculated as the arithmetic mean of each line.

Table 7: Normalised matrix and relativ weights

	Normalised matrix			Relative weight
Criteria	**Anticipation**	**Coping**	**Adaptation**	
Anticipation	0.654	0.692	0.556	0.634
Coping	0.218	0.231	0.333	0.261
Adaption	0.131	0.077	0.111	0.106
Column sum	1	1	1	1

An important feature of pairwise comparison method is to detect inconsistent input data. The consistency ratio (CR) expresses the distance to complete consistency. If a certain inconsistency threshold is exceeded, it is recommended to correct the input data. It is recommended to fix the threshold at 0.1.

In a first step, for each criterion the sum of the products of criteria value and input value is calculated. In the following second step, the resulting values are divided by the criteria value. The result of step is denoted as consistency vector λ.

Table 8: Calculation of consistency vector

Criteria	**Step 1**	**Step 2**
Anticipation	1 * 0.634 + 3 * 0.261 + 5 * 0.106 = 1,947	1.947 / 0.634 = 3.072
Coping	1/3 * 0.634 + 1 * 0.261 + 3 * 0.106 = 0,790	0.790 / 0.261 = 3.032
Adaption	1/5 * 0.634 + 1/3 * 0.261 + 1 * 0.106 = 0,320	0.320 / 0.106 = 3.010

By means of consistency vector λ, respectively its arithmetic mean value:

$$\lambda = (3.072 + 3.032 + 3.010) / 3 = 3.038$$

and the number of the involved criteria, the consistency index CI can be calculated as follows:

$$CI = \frac{\lambda - n}{n - 1}$$

in our example:

$$CI = (3.038 - 3) / (3 - 1) = 0.019$$

The final calculation of the consistency ratio (CR) requires the random index (RI). The values of this RI has been determined in randomized experiments (Poschmann et al. 1998).

$$CR = \frac{CI}{RI}$$

Table 9: Random index for up to 15 criteria

N	RI	N	RI	N	RI
1	0.00	6	1.24	11	1.51
2	0.00	7	1.32	12	1.48
3	0.58	8	1.41	13	1.56
4	0.9	9	1.45	14	1.57
5	1.12	10	1.49	15	1.59

Values within the input matrix can be considered as consistent, if the consistency ratio is ≤ 0.1.

$$\mathrm{CR} = 0{,}19 / 0{,}58 = 0{,}03$$

In our hypothetical example of the resilience assessment, the consistency ratio is 0.03 and can therefore be considered as consistent.

Often, many criteria are involved in the evaluation. The decision/evaluation problem can and should be structured in a hierarchy consisting of multiple layers. The overall objective is at the top of the hierarchy and the alternatives with indicator values constitute the lowest level. The indicators itself can be allocated on intermediate levels. Pairwise comparisons are conducted on every layer individually.

With increasing number of criteria and hierarchical levels, the conduction of the analytical hierarchy process becomes more and complex. There are different software tools available to support the process. One example is “ExpertChoice”. The software allows to model the decision or evaluation problem in a top-down or bottom-up way over as many as needed hierarchical levels. It facilitates graphical modelling and sensitivity analyses and provides tools for visualization of results and group collaboration (Expertchoice 2016). Though, this tool does not allow to process geo data directly.

4 Multi-attributive utility theory

Another approach to aggregate subjective valuations and objective analysis results into one model is the well-known and well established Multi-Attributive Utility Theory (MAUT).

As AHP, MAUT is a methodology that structures the decision/evaluation process and helps to manage tradeoffs among multiple and sometimes conflicting objectives as for instance economic, social and environmental aspects. In contrast to AHP and its pairwise comparison, MAUT method requires significantly less input data.

The method was developed by Keeney & Raiffa in the early 1970-ies. Since then, MAUT is frequently deployed in decisions in public and private sector, for instance for the evaluation of tenders or investments. Early applications of MAUT involved an evaluation of alternative locations for a new airport in Mexico City.

Utility theory - and its most popular representative MAUT - is a systematic approach to for quantifying the preferences of an individual. The analytic values of every criterion are rescaled to an interval [0,1], where 0 represents the lowest importance or preference and 1 the highest importance or preference. Any form of mathematical function can be used for the transformation of the analytic values to utility values, such as linear, logistic or parabola function. The input values can be on cardinal or even on ordinal scale. The result of MAUT is a rank order of the alternatives.

The aggregation of rescaled values (often called “scores”) are typically conducted as a weighted multiplication or – even more frequent – as a weighted addition of the scores in each criterion multiplied by the relative weight of the criterion. The higher the overall utility, the more desirable or important the alternative. The criteria weight must be provided to the algorithm. All the approaches explained in the chapter 3 can be used. The rank order is determined according to the next formula. In this formula, a and b denote the hypothetical alternatives, j the number of involved criteria, w_j the relative importance and z_j the score of an alternative in each criterion.

$$(a \succ b) \Leftrightarrow \left(\sum_{1}^{j} w_j z_{ja} > \sum_{1}^{j} w_j z_{jb} \right)$$

With increasing number of alternatives and criteria, it becomes more and more unlikely, that alternatives have exactly the same overall utility value. This effect leads to a differentiation between alternatives on different ranks, that are factually not justified.

Similar to AHP and approaches based on monetisation (cost-benefit analysis, cost-effectiveness analysis), MAUT has a “compensatory behavior”, which means that shortcoming in one aspect can be balanced unboundedly through a better value at another value. With this character, MAUT belongs to the “American school of decision making”, in difference to the “French school”, which emphasize the aspect of non-compensatory character. However, one has to say, that the French approaches, among them are ELECTRE (Roy 1991) and PROMETHEE (Brans, Vincke & Mareschal 1986) and its various derivate have severe drawbacks in terms of comprehensibility. The obvious benefits of MAUT are:

- excellent comprehensibility to all stakeholders,
- simple transfer of analytic measureable values to values that can be processed by computer and
- low data requirements, measurements of different scales can be integrated within one framework.

5 Outlook

The initial version of this deliverable describes the analytical directions and furthermore versatile methods that appear to be suitable to conduct the analyses.

The next step is to discuss during the forthcoming EU-CIRCLE Mid-Term meeting in Exeter (UK), on 5th and 6th December 2016 again the selection of the methods and their suitability for the case-studies.

If the suitability is confirmed by the case study experts, we foresee to implement the methods as plug-ins for the EU-CIRCLE CIRP. The implementation will allow to deploy the methods for stakeholders with own data, assumptions etc.

Again, it should be noted, that the approach explained here are subject to discussion, further development and evaluation in the case studies.

The methods itself will be documented properly in the EU-CIRCLE online wiki in order to allow stakeholders to familiarize with.

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