

RISK-BASED DECISION MAKING FOR RESILIENT SYSTEMS

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Keywords: Risk Analysis, Decision Making, Resilient Systems, Innovation.

Abstract. *Resilient systems present an inherent ability of recovering from a certain damage state reached due to the application of a significant stress. The quantification of a system's resilience is a difficult task to perform because of: a) the system's complexity, b) the uncertain characteristics of the excitation force, c) the lack of specific elements to measure for an accurate assessment of a system's resilience, and d) the lack of robust tools for quantifying a system's resilience. Therefore, a decision maker requires both a methodology and the tools to decide for the most effective risk-response strategy. This paper presents such a methodology for a risk-based decision making for resilient systems. The proposed methodology involves the consideration of the following parameters: i) the variability of impact upon risk occurrence, ii) the available response strategies, and iii) the preference of the decision maker with regard to the criticality of the various impacts upon risk occurrence. The proposed methodology considers the four risk-response strategies defined by the Project Management-Body of Knowledge (5th ed.), namely: a) acceptance, b) mitigation, c) transfer, and d) avoidance. Three criteria are examined, in order to determine the preference margins between these strategies: i) compliance with regulations and specifications, ii) determination based on data elaboration (e.g. statistical, empirical, etc.), and c) subjective judgment. By applying any one of these criteria for a specific risk impact, the decision maker predetermines the boundary values between the risk-response strategies. Once, the value of the impact upon risk occurrence is estimated, the decision maker is capable to decide for the respective risk-response. The proposed methodology, then, integrates the various strategies decided for the various risk impacts to one single strategy that best confronts simultaneously all the different impacts on the system. The application of the proposed methodology is demonstrated through a case study that provides with numerical results. This paper introduces a new approach that successfully incorporates into the risk-based decision making problem, the critical issue of considering margins between damage states of resilient systems for various failures that occur simultaneously under a single stress.*

1 INTRODUCTION

Infrastructure systems are characterized of great interdependencies, which are mostly identifiable, yet difficult to model. Therefore, their efficiency in improving everyday's life for people, as well as their contribution to the economy and societal wealth can only partially be estimated by traditional tools and techniques. These estimations become even more difficult when risks of all kind of nature are considered. Natural hazards like floods become more intensive due to climate changes, while earthquakes still remain difficult to foresee. Infrastructure reliability and functionality are very critical and require appropriate risk response strategies, which can successfully ensure the long-term sustainability of infrastructure systems.

Introducing the concept of resilience for infrastructure systems is a new and evolving approach that provides a different perspective to the design and monitoring of infrastructure systems [1], [2]. Resilience may be, generally, considered as a system property that allows a quick recovery after a major risk occurrence [3], [4]. The recovery can be, generally, defined as a stable system's state that allows operation to a specific service level depending on the system. Therefore, resilience does not imply a full system recovery, but rather the necessary one that ensures continuity of the system's functionality to predetermined and required levels. A comprehensive analysis of the resilience concept can be found in [4].

Measuring resilience is a difficult task, because it requires a good insight of the system's structure and operation [5]. When the system is complex and prone to inherent uncertainties with regard to its function, measuring resilience becomes a, really, rough work to do. On the other hand, while resilience is inherent to the system, there is a definite interaction between the system and the system's environment that renders the process of recovery, not solely dependent on the system's resilience, but also on the actions that aim to alleviate the risk impact, which are normally decided in the framework of a risk response action plan. Therefore, a system's safety against stresses (occurred risks) is a combination between several parameters and hardly a system's property [6].

A complementary approach to resilience measurement for ensuring infrastructure system's functionality is the application of the proper risk-response strategies against anticipated risks. A properly designed and applied risk-response strategy that successfully corresponds to the system's requirements for recovery facilitates and accelerates the system's reaction against the damage from the occurred risk. Risk-response strategies can be decided through various decision making methods. However most of them present two serious limitations when they are considered for application in resilient systems: a) they do not address, in any way, the systems' characteristics to the decision making process and b) they treat systems' complexity in a rather descriptive, than analytic fashion. The following section presents some well-established and widely applied decision making methods and argues about their limitations for resilient systems.

This paper presents a risk-based decision making approach that aims at providing risk-response decision for resilient systems that consider both the systems' characteristics and the complexity. The first feature, i.e. the systems' characteristics, is introduced in an indirect way; a risk analysis that may be performed by any traditional or innovative method produces the values of risks that the system is prone to. However, since the risk value is considered as the expected value of a risk impact and this impact is directly related to the system's characteristics, it is inferred that in an indirect way these characteristics are addressed to the decision making process. The second feature, i.e. the system's complexity, is introduced by the comparison of the best risk-response decisions for different criteria and the homogenization of these decisions to one that optimally responds to all criteria simultaneously. The final output is a single decision for responding to a specific risk that the system faces.

The proposed methodology is presented in section 3 with an application example to facilitate understanding and demonstrate the mode of application.

2 DECISION – MAKING METHODS AND THEIR LIMITATIONS FOR RESILIENT SYSTEMS

Many decision making methods have been developed that present different levels of complexity and suitability for the various decision making problems. From basic methods that apply to everyday life's occasions to more sophisticated ones that are introduced in the cases of complex problems, there are two main approaches in the philosophy of the decision making: a) the decision is made based on the preference of the expected output compared to the expected outputs of other decision alternatives or b) the decision is made based on the problem's analysis that clearly suggests the best treatment for the problem in hand. In the following subsections some well-established methods that constitute the state-of-the-art in decision making are very briefly described, in order to provide the basis for consideration of their efficiency for resilient systems.

2.1 Elementary methods

Elementary methods are mostly applied to relatively simple decision making problems and they do not require either special knowledge or specific skills. "Pros and Cons" and "weighted Pros and Cons" methods rate the advantages and the disadvantages between alternative decisions and the alternative that presents the strongest pros and the weakest cons prevails [7].

Plus/Minus/Interesting method introduces except from pros and cons, the probable impact of the alternative decisions and through simple numerical rating it does not only suggest an optimum decision among alternatives, but also examines whether the selected alternative: a) shall improve the decision situation and b) is applicable or not [8].

Payoff matrices are used in combination with optimistic, realistic or pessimistic criteria (e.g. maximax - minimin, Hurwicz criterion, maximin – minimax) to identify the best tradeoff between a decision and its output [9].

Conjunctive and disjunctive methods evaluate decision alternatives by comparison to a given threshold and only those alternatives that reach a satisfactory level compared to the threshold are acceptable for implementation [10].

The above methods are not designed for complex problems; therefore their structure prevents their application to such problems. With the exception of conjunctive and disjunctive methods, the rest of the others fail to address the system's characteristics to the decision making process in a systematic or quantified way.

2.2 Graphical methods

Graphical methods comprise influence diagrams (fault-trees, event-trees, and cause and effect diagrams) and decision-trees. They incorporate uncertainty by assigning probabilities to the different decision nodes and they can map system's processes. However, there are two major limitations for application to infrastructure systems: a) they are highly impractical for complex systems and b) the system is mapped in a rather deterministic way, i.e. each branch of a tree describes a "road map" from the initial event (decision) to the final output, which is stable and independent from interdependencies and unexpected events. Both limitations render graphical decision making methods inappropriate for application to infrastructure systems' decision situations.

2.3 Multi-Attribute Utility Theory (MAUT) methods

MAUT is a theoretical framework that can deal with complex decision problems that feature a large number of criteria and decision alternatives. MAUT methods are characterized from the use of utility functions that express the preference of the decision maker over the various decision criteria for different decision alternatives. The final decision is selected through a process that utilizes dimensions-free scales that allow for comparison between different, in nature, criteria. A great number of methods and techniques are based on MAUT such as SMART, Generalized means, UTA, AHP, etc. The main limitation of these methods, which is systemic and related to the methodological approach, is that the decision criteria are weighted according to the preference of the decision maker and the final decision is made based on the aggregate of the products between these weights and the expected values of the decision's output for the criteria. This approach overlooks the actual impact of a decision and instead it correlates it with the factual (quantitative) or judgmental (qualitative and mostly subjective) preference of the decision maker. The importance of this limitation can be understood by the following examples:

- Example A: Tom decides to go to the movies and he has to choose between two options (AL_1 and AL_2) based on the criteria of distance from home (DH) and time of the movies start off (TS). According to his preferences by using any MAUT method, the final decision will come up to a problem generally described in the following equations:

$$AL_1 = w_{DH} \times DH_1 + w_{TS} \times TS_1 \quad (1)$$

$$AL_2 = w_{DH} \times DH_2 + w_{TS} \times TS_2 \quad (2)$$

In equations (1) and (2), w_{DH} and w_{TS} are Tom's weights (preferences) for each decision he used. The maximum value between AL_1 and AL_2 indicates the optimum decision for Tom. However, this optimum decision does not, in fact, consider the real values of the criteria (i.e. real distance, real start off time), but, only, some weighted values that reduce or increase the real ones according to Tom's preferences.

- Example B: A public authority decides to take measures to increase the safety of a bridge against earthquake. The appropriate measures result to two options and they are evaluated based on the criteria of bridge functionality and technical reliability (after the application of the measures). In this example, the relativity, which is an inherent feature in decisions drawn through MAUT methods may easily alter the real data and result to doubtful decisions.

The systemic limitation of MAUT methods that has been identified and described above, along with certain other limitations that each one of the methods discretely suffers from, renders them questionable for application to infrastructure systems, where real values of impact from a risk or stress should not be altered for the process of decision making.

2.4 Outranking methods

Outranking methods may also be applied to complex systems and they also use weights for the different decision criteria. However, they are significantly different to MAUT methods. The most important difference is that outranking methods do not evaluate the alternatives based on a maximum score over certain criteria with different preferences, but, instead, they make pair wise comparisons between alternatives based on actual measurements. Outranking methods, such as ELECTRE and PROMETHEE methods, are able to compare any two different alternatives fully or partially, in the case where there are no available data or information for all the criteria used. Application of these methods results to a ranking between them and the first alternative in this ranking is the selected decision. The main limitations of outranking

methods are: a) complexity, b) requirement of a strong mathematical background for application, and c) computational limits, i.e. these methods are not applicable for decision problems with many alternatives. These limitations render outranking methods questionable for application to infrastructure systems.

3 A NEW APPROACH FOR RISK-BASED DECISION MAKING FOR RESILIENT SYSTEMS

In the previous section the current practice in decision making was briefly discussed and the main findings were that for various reasons the existing methods present significant limitations for application to infrastructure systems. Such limitations become more significant when considered for application with regard to the resilience of infrastructure systems. Therefore, a new approach that can be free of these limitations and applicable to these systems is required. In this section such an approach is presented and demonstrated through an application example.

3.1 Risk-based decision making process

Risk – based decision making is a process that should follow certain steps (sub-processes) as illustrated in Figure 1.

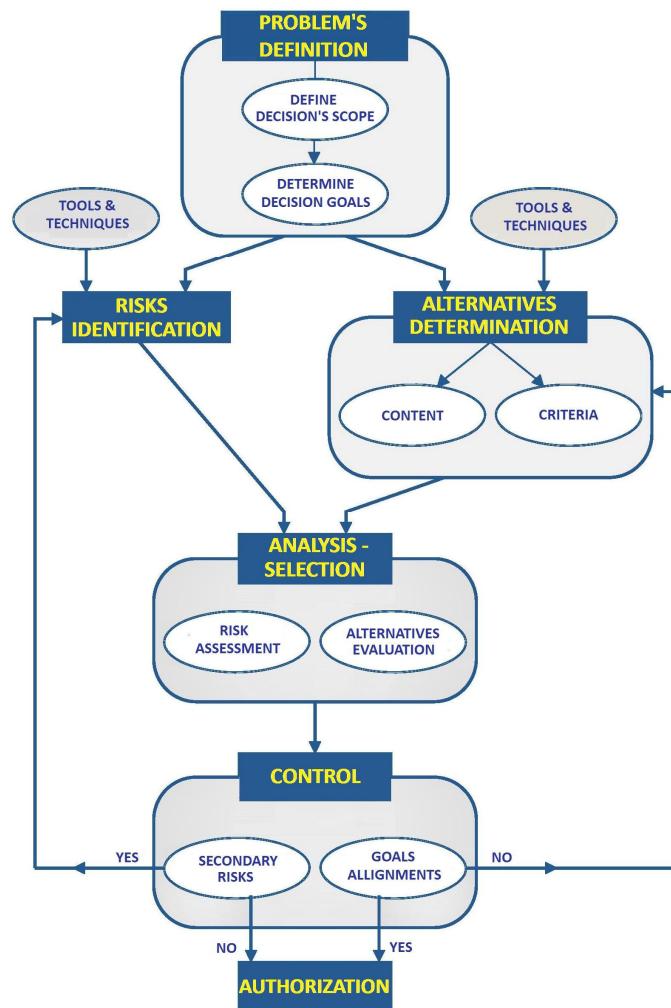


Figure 1: Risk-based decision making process flowchart

The first step is the problem’s definition, which includes the clear and concise determination of the involved stakeholders’ requirements. Given these requirements, the scope of the decision is defined and the determination of the respective goals to attain is achieved. Once, the decision situation problem is clearly defined, the next steps are to identify both the involved risks and the alternative decisions that can potentially serve the achievement of the goals set in the previous step. The alternative decisions must be well described in terms of their content, i.e. required processes, expected impact, etc., as well as criteria that are, one by one, associated to the predetermined goals. Both processes are performed through appropriate tools and techniques, which are extensively used in risk analysis and scenario analysis (e.g. Delphi method, SWOT analysis, information gathering techniques, etc.). The analysis that considers, simultaneously, the outputs of the previous steps, i.e. the risks and the alternative decisions, results through risk assessment and alternatives evaluation to the selection of the best decision in terms of satisfaction of the stakeholders’ requirements. This decision is then checked for goals alignment and secondary risks that may arise upon its application and if the control results are acceptable then it is approved, while if not, the whole process is repeated from step 2, until it reaches acceptance.

In this paper, a new methodology is proposed that complies with the generic risk-based decision making process, as described above, and achieves to integrate the various strategies that are optimum for each different impact upon the occurrence of a specific risk to one single strategy that best confronts simultaneously all the different impacts on the system. In order to facilitate understanding, the methodology is presented through an application example.

3.2 The proposed methodology through an example of application

Suppose an infrastructure system that is of critical importance for the economic and social life of a specific area. Such a system may be a highway road, an airport, a wind farm, a public service building, etc. Infrastructure systems during their life – cycle are prone to several and different risks that can cause severe damages once they occur. Examples of such risks are all the types of failure caused by a natural hazard (earthquake, flood, fire, etc.), material failure, terrorist act, etc. The potential occurrence of one of these risks results to certain damages that are evaluated in a different way among those affected (stakeholders) by the risk event. Therefore, at every stage when a decision is required for the determination of the appropriate risk response strategy, the latter depends on the requirements and specifications set by these stakeholders.

In the case of a power plant, for example, the main priority is set to supply energy with a steady rate through an environmental friendly production process. The achievement of these goals must be ensured against a wide range of risks during the operation of the power plant. An example of one of these risks is recorded in Table 1.

Code	TECH 1.1
Name	Risk of failure due to earthquake
Class	Technical
Factors	Heavy earthquake loads that exceed the facilities’ structural strength
Components	Cracks in walls, deformations, production fall
Impact	Repair costs, loss of revenue, injuries, fatalities, pollutants emissions

Table 1: A record of a risk for a power plant

Table 1 presents a hypothetical record in a risk inventory used for risk identification. The identified risk, given in the second row of the table, is classified and analyzed in terms of: a)

the factors that lead to its occurrence, b) the symptoms (components) that are visible in different levels of risk occurrence and c) the impact, which is the result of the risk event upon occurrence. This type of inventory along with certain innovative notions such as the “component” term is based on current research performed by Angelides et al. [11].

The alternative decisions that need to be investigated, in relation to the identified risk, in order to determine the optimum among them that ensures the achievement of the decision’s goals (i.e. constant energy supply in an environmental friendly mode) are: a) risk acceptance, b) risk mitigation, c) risk transfer, and d) risk avoidance. These alternatives are essentially the recommended risk response strategies proposed by the Project Management Body of Knowledge [12], which are apply, in general, to all types of projects or situations. Table 2 provides a detailed description of the alternative decisions in terms of content, required processes, and expected impact adjusted to the example of application.

Alternative decision	Risk acceptance	Risk mitigation	Risk transfer	Risk avoidance
Content Description	A decision that aims at assuming responsibility and liability for the negative impact upon risk occurrence. Recommended for insignificant risks	A decision that aims at the reduction of the risk to an acceptable threshold.	A decision that aims at shifting to a third party, the negative risk impact, along with ownership of the response. Risk transfer only indirectly deals with risk.	A drastic decision that aims to eliminate either the risk factors or the risk impact. It involves even project cancellation. Recommended for very significant risks.
Application mode	A. Establish a contingency reserve to use in case of failure.	A. Simplify the energy supply process. B. Reinforce critical elements of the structure. C. Design an action plan for quick – response.	A. Insurance. B. Performance bonds. C. Guarantees. D. Risk transfer contracts.	A. Establishment of the facilities to a non-seismic area. B. Change of goals.
Expected impact	Undertake the cost for the system’s recovery after the occurrence of the risk	Limit the negative effect to an acceptable level	Ensure compensations from a third party for the harmed stakeholders in case of failure	Eliminate risk

Table 2: Alternative decisions for dealing with the risk of failure due to earthquake for a power plant

The alternative risk response strategies analyzed in Table 2 may be quantified either according to regulations, specifications, and legal frameworks or based on the strategy and policy of the organization that operates the power plant.

The criteria over which the alternative decisions are evaluated need to be consistent with the final decision’s goals. They also need to be of quantitative nature, in order to define the thresholds that will constitute the boundaries of transition between the alternative decisions.

These boundaries, in fact, define the ranges that correspond to the respective risk response strategies or, in other words, all the estimated risks define a range from zero value to a maximum value, which is further divided to smaller ranges that each one of them corresponds to the respective decision alternative. A generic example of the quantified relation between the risks and the risk response strategies is illustrated in Figure 2 (AD: Alternative Decision).



Figure 2: Quantification of the alternative decisions for one decision criterion

For the example under study, the following criteria are set:

- Minimization of the system's recovery cost (SRC). This cost includes maintenance costs, repair/replacement costs, and loss of revenue due to the temporary halt of the energy production and supply process. The quantification of the alternative decisions with regard to the SRC criterion is based on: a) the risk analysis that is conducted by the facility's administration, and b) the attitude towards risks that the facility's administration adopts. Figure 3 illustrates a numerical example for this criterion. In Figure 3, "Ac" stands for "Risk acceptance", "M" stands for "Risk mitigation", "T" stands for "Risk transfer", and "Av" stands for "Risk avoidance". It should be noted that the ranking of the alternatives is consistent with the risk impact. Therefore, it is assumed that the smaller impact is manageable for the decision maker (risk acceptance), while the larger impact is intolerable for both the decision maker and any third party (risk avoidance).



Figure 3: Quantification of the alternative decisions for the SRC decision criterion

Any risk R that has a value R_{C_i} with regard to the SRC criterion results to the respective alternative decision according to the following relations:

$$[0, 10^6] = \Theta^C, C_i \in \Theta^C \quad (3)$$

$$\forall R_{C_i} \in [0, 20.000] \rightarrow \text{Risk acceptance} \quad (4)$$

$$\forall R_{C_i} \in [20.000, 100.000] \rightarrow \text{Risk mitigation} \quad (5)$$

$$\forall R_{C_i} \in [100.000, 250.000] \rightarrow \text{Risk transfer} \quad (6)$$

$$\forall R_{C_i} \in [250.000, 1.000.000] \rightarrow \text{Risk avoidance} \quad (7)$$

- Prevention of human injury or fatality (HIF). The quantification of the alternative decisions with regard to the HIF criterion depends on the legal framework that regulates the health and safety issues in each case. An established approach to evaluate the severity of a non-fatal accident is according to the hours or days of absence from work [13]. Specific thresholds stand to differentiate between non-injuries, light injuries, fair, and

severe injuries. The case of human loss is, of course, the worst scenario and the upper boundary in the HIF criterion. This quantification approach is adopted in the case of the example and Figure 4 illustrates the numerical output for this criterion. The notations in Figure 4 are identical to the respective in Figure 3.



Figure 4: Quantification of the alternative decisions for the HIF decision criterion

Any risk R that has a value R_{HL_i} with regard to the HIF criterion results to the respective alternative decision according to the following relations:

$$[0, 25.000] = \Theta^{HL}, HL_i \in \Theta^{HL} \quad (8)$$

$$\forall R_{HL_i} \in [0, 60] \rightarrow \text{Risk acceptance} \quad (9)$$

$$\forall R_{HL_i} \in [60, 365] \rightarrow \text{Risk mitigation} \quad (10)$$

$$\forall R_{HL_i} \in [365, 5.000] \rightarrow \text{Risk transfer} \quad (11)$$

$$\forall R_{HL_i} \in [5.000, 25.000] \rightarrow \text{Risk avoidance} \quad (12)$$

The intervals in equations 9-12 describe respectively the following situations: a) no injury to light injury, b) light to fair injury, c) fair to severe injury, and d) severe injury to death. Again, as in the case of the SRC criterion, the ranking of the alternatives is consistent with the risk impact. Therefore, it is assumed that the smaller impact is manageable for the decision maker (risk acceptance), while the larger impact is intolerable for both the decision maker and any third party (risk avoidance).

- Prevention of environmental pollution (ENP). The quantification of the alternative decisions with regard to the ENP criterion can be based on regulations and respective legal frameworks. Another approach, which is adopted for the example, is to consider the severity of the pollution with regard to the magnitude of the area which is affected [14]. Figure 5 illustrates a numerical example for this criterion (values refer to acres). The notations in Figure 5 are identical to the respective in figures 3 and 4.



Figure 5: Quantification of the alternative decisions for the ENP decision criterion

Any risk R that has a value R_{E_i} with regard to the ENP criterion results to the respective alternative decision according to the following relations:

$$[0, 10^7] = \Theta^E, E_i \in \Theta^E \quad (13)$$

$$\forall R_{E_i} \in [0, 10^4] \rightarrow \text{Risk acceptance} \quad (14)$$

$$\forall R_{E_i} \in [10^4, 10^5] \rightarrow \text{Risk mitigation} \quad (15)$$

$$\forall R_{E_i} \in [10^5, 5 \times 10^5] \rightarrow \text{Risk transfer} \quad (16)$$

$$\forall R_{E_i} \in [5 \times 10^5, 10^7] \rightarrow \text{Risk avoidance} \quad (17)$$

The same assumption made in the previous two criteria concerning the ranking of the alternatives stands for this criterion as well.

Once, the evaluation criteria of the alternative decisions are determined, the risk-based decision making process steps to the next stage, which is the analysis, based on actual risk estimations and the evaluation of the decision alternatives. It is important to notice that the process assumes the interdependency of the criteria. This assumption, although not always valid, does not reduce the effectiveness of the methodology, since the integration to one decision is independent of the interdependency between the criteria.

Risk quantification can be generally performed by the equation (18).

$$\text{Risk} = E [h] = \int h(\theta) \times p(\theta) d\theta \quad (18)$$

, where θ , denotes the uncertainty that characterizes the risk occurrence, which is expressed by a probability density function $p(\theta)$, while the overall impact upon risk occurrence can be measured by a Risk Consequence Measure $h(\theta)$. Equation (18) expresses the expected value of the risk, which is a well – established approach on the field for risk quantification. This expected value in the case of the example under study must be estimated for the three different criteria. Therefore, the identified risk (Risk of failure due to earthquake) must be quantified in terms of impact to the system's recovery costs, the human losses and the environmental pollution. This quantification is performed by proper adjustment of equation (18). The mathematical expression for each case is given in equations (19) – (21):

$$R_{C_i} = \int h_{C_i}(\theta) \times p(\theta) d\theta \quad (19)$$

$$R_{HL_i} = \int h_{HL_i}(\theta) \times p(\theta) d\theta \quad (20)$$

$$R_{E_i} = \int h_{E_i}(\theta) \times p(\theta) d\theta \quad (21)$$

In equations (19) – (21), h_{C_i} measures in monetary terms the impact of the risk occurrence with regard to the SRC criterion, h_{HL_i} measures the impact of the risk occurrence with regard to the HIF criterion (the measurement is hours), and h_{E_i} measures the impact of the risk occurrence with regard to the ENP criterion (the measurement is acres). Provided that the necessary data to estimate the Risk Consequence Measures for each criterion and the probability of the risk event are available, equations (19) - (21) produce specific values that can be placed in the respective ranges of the previously defined alternative decisions for each criterion. Figure 6 illustrates graphically an example of this step of the process. As shown there, for the example under study, the same risk requires three different decisions, one for each one of the three different decision criteria: a) the proper decision with regard to the SRC criterion is “Risk acceptance”, b) the proper decision with regard to the HIF criterion is “Risk avoidance”, and c) the proper decision with regard to the ENP criterion is, again, “Risk acceptance”. It is obvious that if the analysis would indicate, also, “Risk acceptance” for the HIF criterion, then the decision maker would decide this alternative for the specific risk. However, in this case the decision maker needs to compare the alternative decisions for each criterion and select the most appropriate one that satisfies simultaneously all the criteria. While in the case of the example,

the selection of “Risk avoidance” may be considered “an easy choice”, since preventing human loss is a top priority, the general approach requires an objective way to compare all the alternatives for all the criteria between them. A graphical representation of all possible comparisons between any four decision alternatives for three criteria is illustrated in Figure 7.

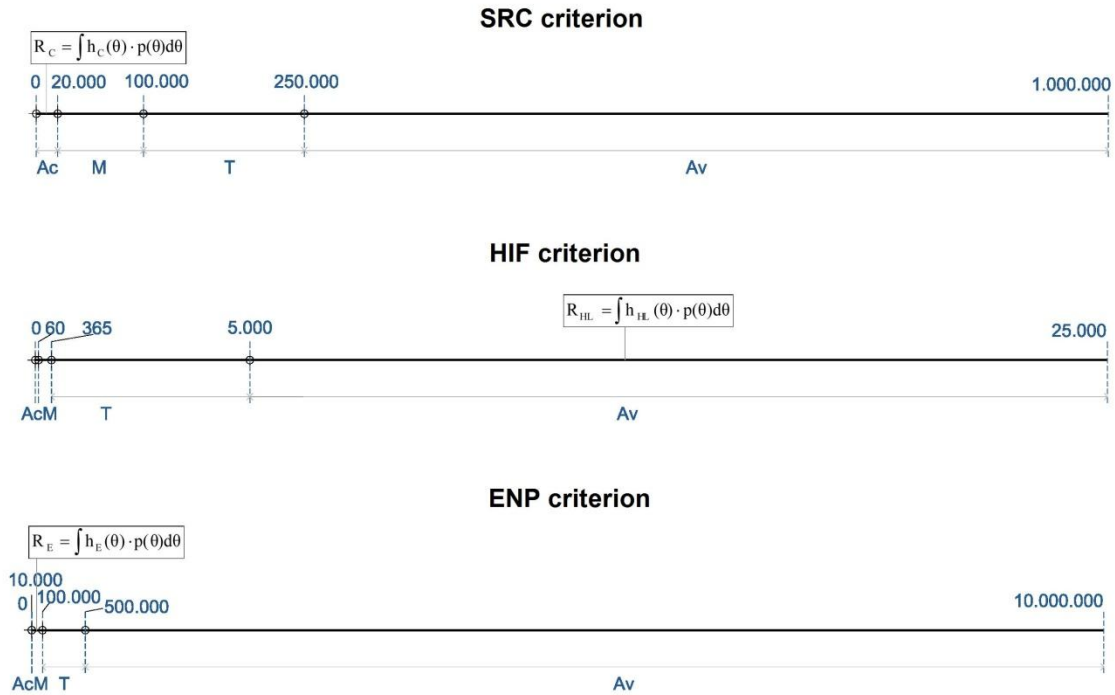


Figure 6: Assignment of risk values to the alternative decisions ranges per criterion

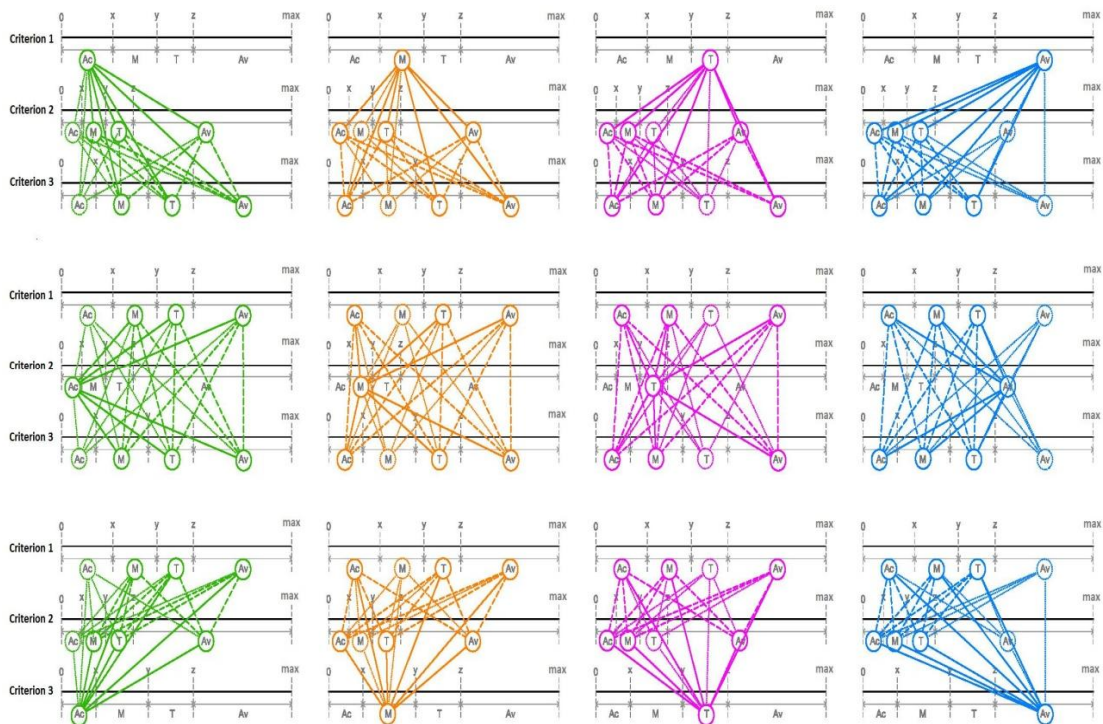


Figure 7: The possible comparisons between the alternative decisions of each criterion to the alternative decisions of the other criteria for the example under study

Due to the fact that different measures are used for each criterion, it is essential to transform the different scales from the three criteria to one single scale, in order to allow comparison between the alternative decisions. This can be easily achieved by dividing the values of the boundaries between the alternative decisions to the maximum value of the risk for each criterion. Essentially, the original scales are transformed to dimensions-free scales in the interval $[0, 1]$, where 0 corresponds to the minimum value of the risk, 1 corresponds to the maximum value of the risk, and the values in between correspond to the boundaries of the alternative decisions. Figure 8 graphically illustrates the dimensions-free scales for each criterion.

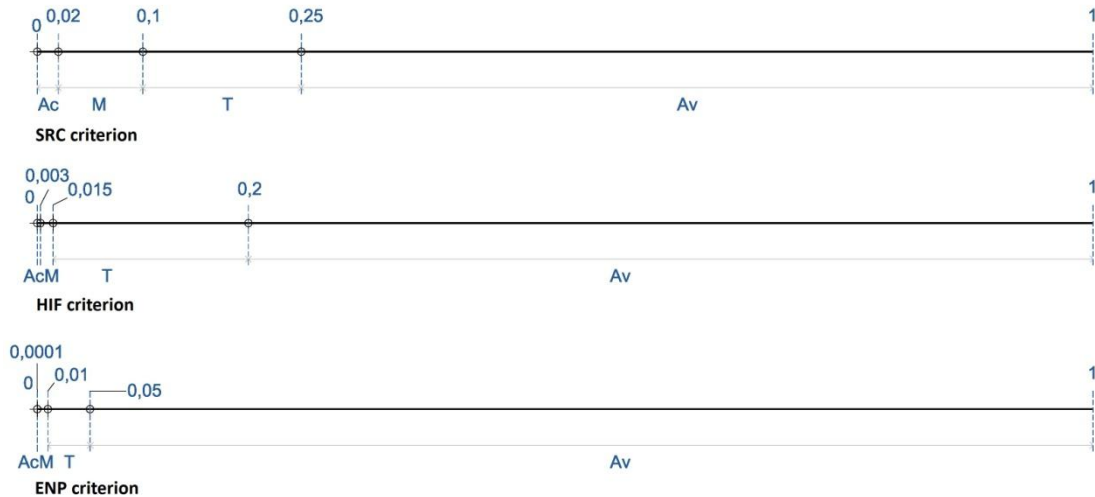


Figure 8: The dimensions-free scales for each criterion for the example under study

Another critical issue, which should be considered for the appropriate comparison between the alternative decisions, is the preference of the decision maker for the various alternatives for each criterion. For example, as stated above, it can be, generally, expected that there is a stronger preference to avoid human loss compared to the preference of spending a large amount for maintenance costs to reduce the risk of failure due to earthquake. However, it is not easy to generalize a preference, e.g. of taking measures for environmental protection (risk mitigation for the ENP criterion) compared to a fair amount of equipment replacement costs (risk acceptance for the SRC criterion). Therefore, a systematic way that will denote preference of the decision maker of the alternative decisions evaluated over different criteria is required. The proposed approach is based on the concept of utility, which addresses the preference of the decision maker between different alternative decisions. Utility theory has been used extensively with many variations in the field of decision making [15], [16], [17].

For each criterion of the alternative decisions, the decision maker defines the appropriate utility function that best represents his preference considering the parameter of risk. Figure 9 illustrates a graphical example of such functions that were selected for the example under study.

The utility functions in Figure 9 are defined in the set $[0, 1]$ as they are in concordance with the dimensions – free scales for each criterion. Since the boundaries for each alternative decision are known from the previous steps, the overall preference of each different alternative is calculated by the area defined by the function’s curve, the x axis and the utility values for each boundary value of the alternative decision. Figure 10 illustrates a graphical example of this calculation and the numerical results are presented in Table 3.

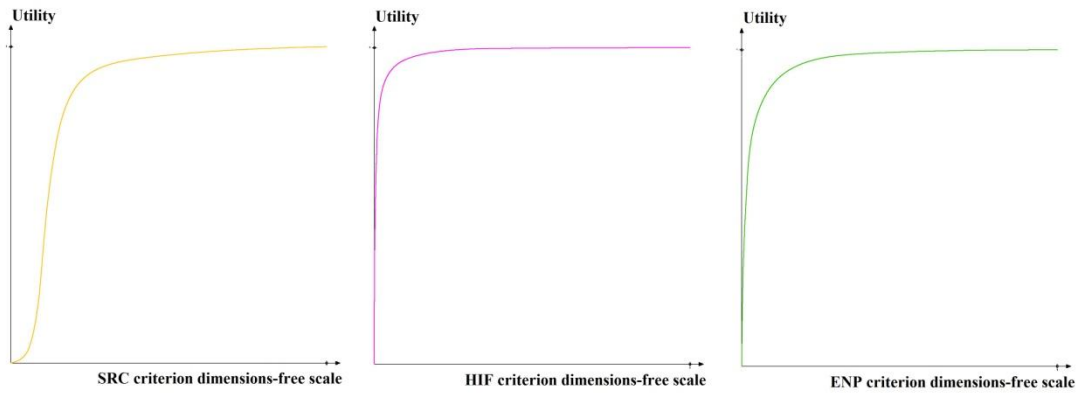


Figure 9: Utility functions for each decision criterion

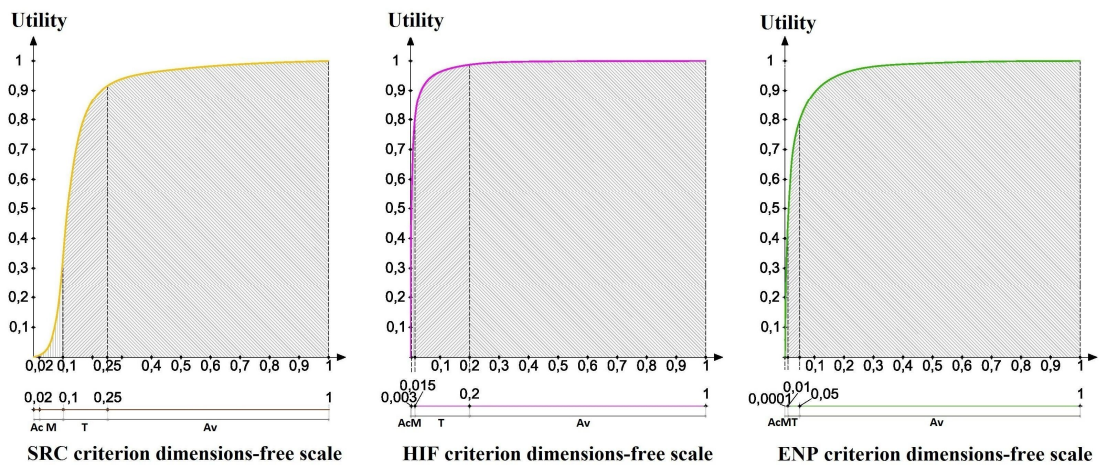


Figure 10: Calculations of the utilities of the alternative decisions for each criterion

Criterion	Alternative Decision	Utility
SRC	Risk acceptance	0.00058
	Risk mitigation	0.07361
	Risk transfer	1.13112
	Risk avoidance	7.33324
HIF	Risk acceptance	0.01106
	Risk mitigation	0.08325
	Risk transfer	1.76021
	Risk avoidance	7.98551
ENP	Risk acceptance	0.00001
	Risk mitigation	0.02922
	Risk transfer	0.27364
	Risk avoidance	9.29736

Table 3: Utility values for the alternative decisions for each criterion

The calculation of utilities for each alternative decision per criterion facilitates the comparison of the alternatives and consequently the decision making process for the decision maker. Concerning the example under study, the risk analysis indicated a risk acceptance for the SRC and ENP criteria, and risk avoidance for the HIF criterion (see Figure 6). An objective comparison between the two alternative decisions, which is based on the numerical results that are

presented in Table 3, clearly suggests the “risk avoidance” decision as the most preferable (the one that corresponds to the maximum utility value).

Some interesting observations of the numerical results in Table 3 prove the logical consistency of the approach:

- In the case where each of the three criteria corresponds to a different alternative decision the most risk averse decision of all three always predominates.
- The HIF criterion, compared to the other two criteria consistently presents greater utility values for the same alternative decision. This is not the case only for the “risk avoidance” decision between the HIF and ENP criteria; however it is not unreasonable to consider a human injury or fatality as less important compared to an incident of major environmental pollution with long-term catastrophic effects on every form of life.

4 CONCLUSIONS

Infrastructure systems are very critical for the society and the economy. In a challenging situation with severe risks of different nature and magnitude, it becomes crucial to define those limit states of the systems that will ensure functionality and serviceability right after the occurrence of a risk and a fast system recovery to the operational levels before the occurrence of the risk.

Resilience is a concept that responds to the above requirements. However, due to the high complexity of infrastructure systems and their interdependencies both between the system’s parameters and between the system and its environment, the measurement of resilience becomes a very difficult task to perform. A complementary approach, which indirectly provides estimation for the system’s resilience is the application of the proper risk-response strategies against anticipated risks. Therefore, appropriate decision making is required.

Currently, several decision making methods and techniques exist that are well-established and in some cases, they are very sophisticated, in terms of methodological approach or mathematical background. However, they all present various limitations both in general and for application to infrastructure systems, in particular.

This paper presents a methodology for risk-based decision making that is characterized by the following features:

- It considers the variability of impact upon risk occurrence by using appropriate risk values, which are estimated for each criterion under study. Instead of the traditional approach, that of integrating different risk values to a single one that, allegedly, denotes an overall risk value, the proposed methodology utilizes actual risk values that correspond to the different decision criteria.
- It involves the preference of the decision maker not in a way that alters the evaluation criteria of the decision as is done in MAUT methods, but, rather, in a way that is restricted to the expression of tolerance of certain risk events in case they occur. This means that the boundaries for the alternative decisions with regard to different stresses are predefined and constant, regardless of the risk event and any per case variation of the preference of the decision maker.
- It compares preference of decisions instead of preference of alternatives. This means that the risk analysis that precedes the decision making process provides results that directly indicate the appropriate decision regarding a specific criterion and then these decisions are compared and the most preferred is selected.
- It involves risk-response strategies for which the decision maker has decided that they respond to the system’s requirements for increasing resilience.

The proposed methodology allows the overcoming of some limitations of well-established decision making methods in the problem of deciding the appropriate risk-response strategies for infrastructure systems. In this way, it becomes a potentially valuable tool for an indirect definition of resilience in these highly complex systems, which are prone to various failures that occur simultaneously under a single or multiple stresses.

ACKNOWLEDGEMENTS

This work has been supported by the Project “Integrated European Industrial Risk Reduction System (IRIS)”, Nr: CP-IP 213968-2, funded by the European Union FP7.

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