Spatially-Distributed Multi-Hazard Risk Analysis

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Abstract

The paper dwells on the problem of multi-hazard risk analysis and management. The authors identify some gaps in existing disaster risk reduction research projects. To overcome these gaps a comprehensive approach to multi-hazard risk analysis is needed that considers all components of multi-hazard risk in dynamics with a spatial reference. The development of such an approach is the purpose of the article.

The risk is presented in the form of the following components: hazard characteristics (danger, intensity, area affected by hazard), vulnerable object characteristics (location, vulnerability, speed of recovery), as well as spatio-temporal threat measured in time it takes for the hazard to reach the object. It's proposed to present hazard risk in dynamics as passing through the following three stages: potential risk, risk of threat, and risk of destruction. Individual risk is presented as a trajectory in n-dimensional space of its parameters, multi-risk is assessed using operation of taking maximum.

The proposed approach to risk analysis allows diagnosing the situation and making decisions throughout the entire disaster risk management cycle. Potential risk assessment can serve as a basis for long-term adaptation, active risk assessment can serve as a basis for early warning and response actions.

Keywords

Multi-hazard risk analysis, threat, danger.

1. Introduction & Related Works

Infrastructure owners and operators are increasingly faced with the challenge of delivering resilient infrastructure and mitigating the effects of multiple hazards and climate change effects. Therefore, multi-hazard risk analysis methodologies are critical for infrastructure protection.

The risk from a hazard, especially from multiple hazards, is a broad concept that depends on many components characterizing both the source of risk, namely hazard (or hazards), and risk receiver, namely assets or community affected by hazards.

Currently, there is no single definition for the notion of risk itself and its components such as vulnerability, resilience, et cetera.

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In the simplest case, hazard risk describes the combination of the probability of hazard occurrence and potential impact on an asset or community (object of risk) [1]. So, variables that determine risk can be related to hazard or object.

When it comes to hazard, risk analysis can include one hazard or multiple hazards, either dependent or correlated. However, analyzing the risk from several interacting hazards in the same area is one of the most challenging issues.

There are also different understandings of risk components related to the objects at risk, such as vulnerability, resilience, adaptation, and the correlation between them [2].

The term “resilience” is critical to understand hazard impact on the object. Resilience describes the emergent properties that the objects have, which allows them to withstand, respond and/or adapt to a vast range of hazards by maintaining and/or enhancing their functionality [3].

The concept of resilience has gone through a series of transformations. For example, in [4,5], resilience and vulnerability are considered two opposing conceptions. Namely, vulnerability is considered the flip side of resilience. When a social or ecological system loses resilience, it becomes vulnerable to change that previously could be absorbed [2].

According to the most comprehensive current approach [3], resilience originates from the interaction of some adverse event (such as hazard) and some object to which the property of resiliency is ascribed (it can be a single asset, infrastructure, people, communities, et cetera). Thus, resilience has a form of a process of transformation and adaptation of the object exposed to hazards.

Resilience is a wide-ranging dynamic concept described by two groups of parameters relating to vulnerability and recovery of the object affected by hazards. In practice, the dependence of these parameters on hazard intensity is described by functions, e.g., functions of dependence of fragility or vulnerability on intensity.

Currently, hazard risk is being considered on different levels (Table 1). There are such levels as a single asset, infrastructure, or community-country when it comes to the object of risk. Different risk measurement metrics are qualitative (descriptive) or quantitative, static, or time-dependent. Risk analysis can take into account one hazard or multiple hazards, either independent or correlated. If we consider hazards of different nature, restoring the damage due to one hazard is not expected to improve the performance against another hazard.

Table 1

Levels of risk analysis

<table>
<tr><td>Object of risk</td><td colspan="2">Asset
Infrastructure network
Community-country</td></tr>
<tr><td>Risk metrics and criteria</td><td colspan="2">Qualitative (descriptive) or quantitative
Static or time-dependent</td></tr>
<tr><td rowspan="2">Disruptive events</td><td colspan="2">One hazard</td></tr>
<tr><td>Multiple hazards</td><td>Independent hazards of different nature
Correlated or cascading hazards of the same nature
Correlated or independent hazards of different nature</td></tr>
</table>

The problem of multi-hazard risk analysis and management is tackled in several disaster risk reduction research projects. Table 2 shows some of the limitations found in these projects and how they could be overcome.

Table 2
Gaps in the existing disaster risk related projects

Limitations	Examples	How to overcome the gap
Considering independent hazards.	Hyogo Framework for Action 2005-2015 [6].	Risk should be related to multi-hazards, their interactions with climate drivers, and their cascade/simultaneous effects on the object.
Static risk assessment.	Hyogo Framework for Action 2005-2015 [6].	The methods for dynamic assessment of risk and its components should be developed.
Qualitative approach.	Hyogo Framework for Action 2005-2015 [6]; Sendai Framework for Disaster Risk reduction 2015-2030 [7].	The quantitative approaches to the assessment of risk and its components should be developed.
Local level (focusing on specific asset or infrastructure level).	emBRACE Resilience Framework – community resilience [8]; TRANSRISK [3] – transport infrastructure.	The methods for quantification of risk at a regional, country, and international scale should be developed.
Considering the limited set of risk components, e.g., resilience is considered restricted from the standpoint of vulnerability.	ıtrix: New Multi-HAzard and MulTi-RIsK Assessment MethodS for Europe [9]; RMIN: Critical Infrastructures Resilience as a minimum supply Concept (2016-2019) [10]; ANYWHERE: EnhANcing emergencY management and response to extreme WeatHER and climate Event (2016-2019) [11].	The approach considers all risk components reflecting characteristics of both the hazard and the object at risk.

According to Table 2, the existing risk-related projects most commonly consider independent hazards or only certain kinds of hazards. Usually, risk and its components are assessed statically and qualitatively and on a local level (focusing on specific areas, specific assets, or specific infrastructure level). In addition, much of the work on multi-hazard risk consider vulnerability instead of resilience.

Although several multi-hazard risk issues are analyzed, much remains to be done in the field of multi-hazard risk analysis. To overcome the limitations mentioned above, a comprehensive approach is needed that considers all components of multi-hazard risk in dynamics.

2. Multi-Hazard Risk Analysis

Risk originates from the interaction of hazard and some objects (infrastructures, communities, et cetera) affected by the hazard.

In this sense, risk dimensions comprise characteristics of hazard such as danger and intensity, characteristics of an object such as vulnerability and speed of recovery, as well as the proximity of object and hazard (Fig.1). Therefore, their relative position matters. For example, the risk for some objects arises when the object is situated close to disaster. Therefore, the spatial reference is of great importance here [12].

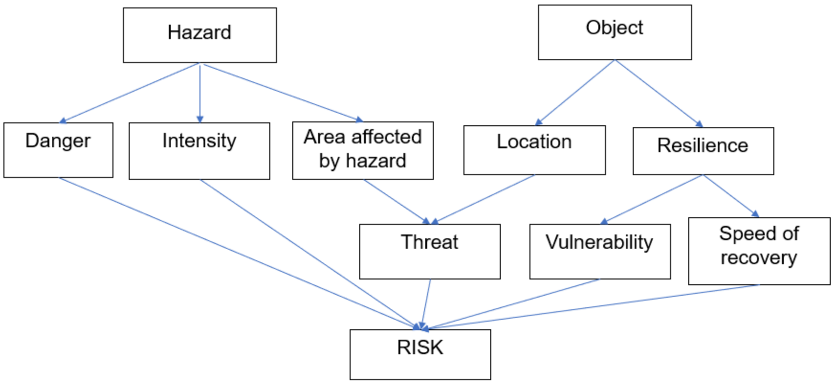

Figure 1: Risk dimensions

We need to distinguish potential hazard that has not yet occurred and active hazard that is already identified and spreading [13].

A potential hazard is characterized by danger, which is a characteristic of a certain area of territory and is assessed by a probability of hazard occurrence. Active hazard is characterized by threat, which is a spatial-temporal characteristic reflecting the proximity of hazard and vulnerable object. In simple words, a threat is measured in the time it takes for the hazard to reach the object.

Considering this, we can distinguish potential risk related to potential hazards and real-time active risk related to active hazards.

Risk in the context of this work is an assessment of the relationship between hazard scenarios – sources of risk, and vulnerable objects at risk – risk receivers.

It is proposed to consider three stages of risk (Fig.2).

The 1st stage is a potential risk; it is characterized by danger and exists until hazard occurrence when danger is materialized.

The 2nd stage is the risk of threat, which exists from the moment of hazard occurrence to the moment when hazard reaches the object and is characterized by threat. During this stage, the hazard poses a threat to the object. The threat is a spatial-temporal characteristic of proximity between hazard and vulnerable object. In simple words, a threat is measured in the time it takes for the hazard to reach the object.

The 3rd stage is the risk of destruction, which exists from the time when the hazard reaches the object when a threat is materialized. This stage is characterized by the change in the value of the object. The purpose of decision-making is to prevent this stage. This stage requires recovery actions and recovery costs [14].

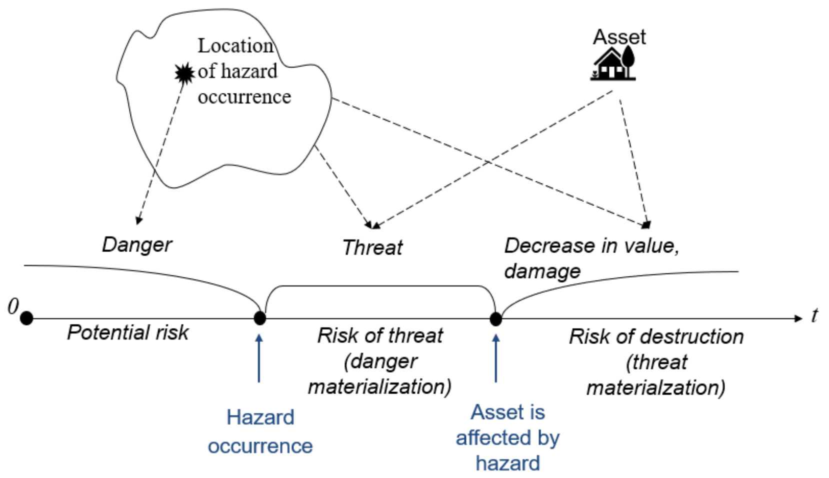

Figure 2: Risk stages

The risk from one hazard (potential or active) for a certain object is individual. In case there are several sources of risk for a particular object, a multi-risk is created. Fig. 3 shows three stages of individual risk.

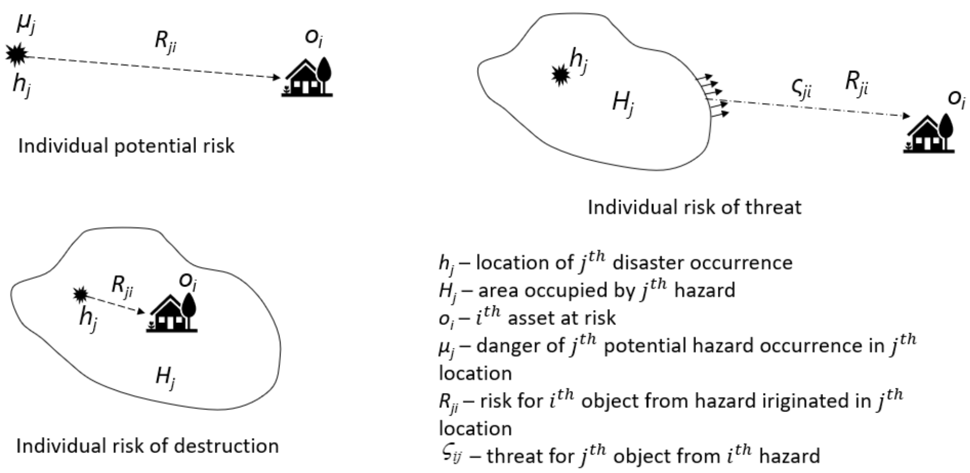

Figure 3: Risk concept

Fig. 4 shows multi-risks for two objects o_1 and o_2 from three spreading hazards (in the locations h_1, h_2, and h_3) and two potential sources of hazards (in the locations h_4 and h_5).

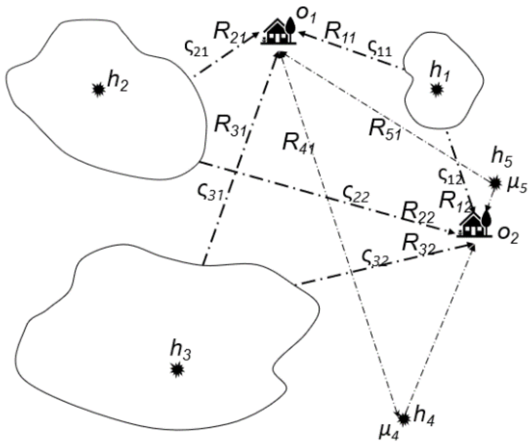

Figure 4: Multi-hazard risk

Active risk is characterized by threat. The threat model consists of a set of zones around the contour of the hazard having different degrees of threat to valuable objects. Some objects can be affected by a multi-threat from several active hazards simultaneously (Fig.5).

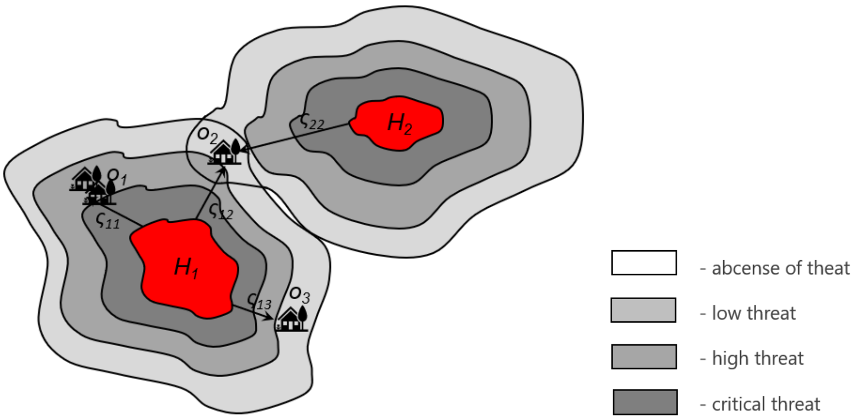

Figure 5: Multi-threat zones

Multi-threat for the object can be assessed using the operation of taking the maximum of threat assessments from individual hazards:

$$\varsigma_i = \max_{j=1}^{n} \varsigma_{ji},$$

where n is the number of hazards that simultaneously pose a threat to the i^{th} object.

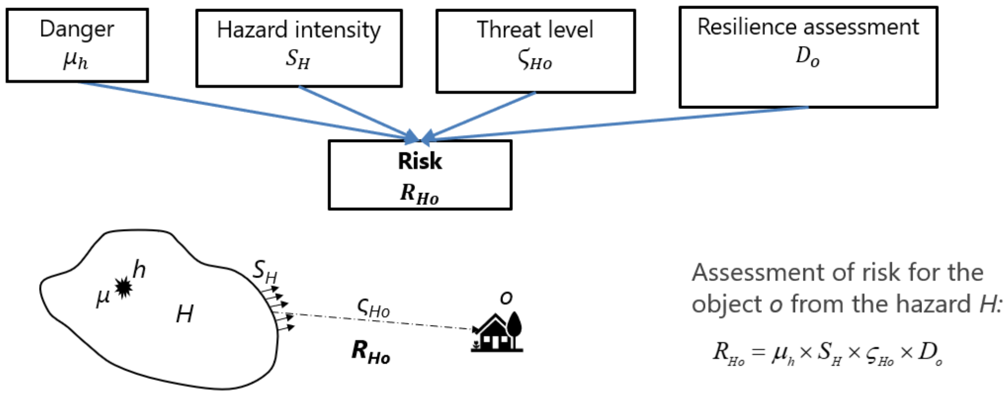

Figure 6: Risk dimensions

Therefore, risk dimensions comprise hazard characteristics (danger, intensity), object characteristics, and spatial-temporal characteristics reflecting the proximity of hazard and vulnerable object (threat) (Fig. 6). Thus, we can present risk as a point in the n-dimensional space of its parameters. However, when we combine various components into a single risk assessment, we face one problem: different risk components have different units of measurement. Therefore, to obtain risk assessment for the object *O* from the hazard *H*, we should first normalize the values of risk components so that, e.g., bring them to the range from 0 to 1, and multiply them.

In the case of several sources of hazards that simultaneously affect the vulnerable object, we obtain a multi-risk. For example, Figure 7 shows multi-risk for the object *O* from three hazards H_1, H_2, and H_3.

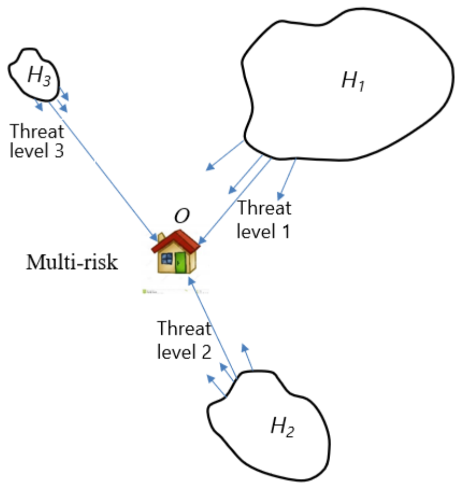

Figure 7: Risk dimensions

Each individual risk is dynamic and can be presented as a trajectory in the n-dimensional space of its parameters. For example, the graphs in Figure 8 show three trajectories of three individual risks for the object O and 3 points on their trajectories, presenting three individual risk assessments at the time moment t.

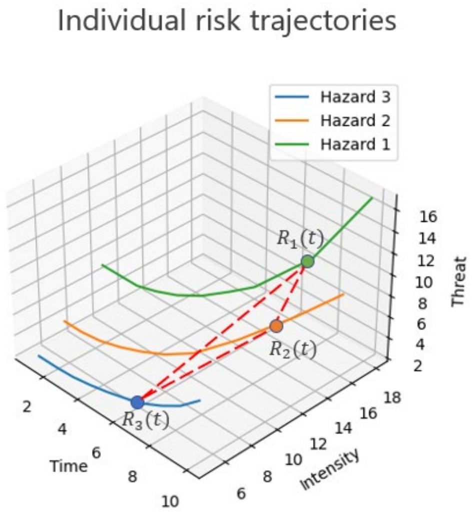

Figure 8: Risk dimensions

Suppose that at time moment t some object is simultaneously affected by k individual risks presented in the form of points in n-dimensional space of parameters p_i:

$$\begin{gathered} R_1(t)=\left(p_{11}(t),\quad p_{12}(t),\quad \ldots,\quad p_{1n}(t)\right) \\ R_2(t)=\left(p_{21}(t),\quad p_{22}(t),\quad \ldots,\quad p_{2n}(t)\right) \\ \ldots \\ R_k(t)=\left(p_{k1}(t),\quad p_{k2}(t),\quad \ldots,\quad p_{kn}(t)\right) \end{gathered}$$

Then multi-risk they create will also be presented as the point in the same space of parameters, but each coordinate will be assessed as a maximum value among the corresponding coordinates of individual risks:

$$R(t) = \left(\max_{j=1}^{k} p_{j1}(t), \max_{j=1}^{k} p_{j2}(t), \ldots, \max_{j=1}^{k} p_{jn}(t) \right)$$

In general, dynamic risk assessment can be assigned to each object and each area of the territory. Moreover, for each object, we can build a multi-risk trajectory on a time interval $[t_1, \ldots, t_n]$ as a sequence of risk values at successive points in time $[R(t_1), \ldots, R(t_n)]$.

3. Conclusions

Spatially distributed integrated assessment of multi-hazard risk can serve as a basis for diagnosing the situation and decision making throughout the entire disaster risk management cycle. Active risk assessment can serve as a basis for early warning and response actions in real-time systems. Potential risk assessment can be used for long-term adaptation strategies and resilience building [15]. Spatial distribution of risk makes it possible to identify areas or objects that require the primary attention of a decision-maker.

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