Selected Options of Vulnerability Assessment – State of the Art in Literature Review

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The paper deals with the selected aspects of vulnerability assessment of systems. Historically, the vulnerability is recognised as one of the important aspects of system properties – system quality. The wide utilization of vulnerability can be observed in the IT area. Some approaches to vulnerability assessment are based on experiences and empiricism. For some other works it is necessary to have a quantitative value used for expressing vulnerability. In this paper we have applied the methods of analytical research, information search and a synthesis. They serve to introduce selected approaches expressing system vulnerability. The attention is paid mainly to the environmental and critical infrastructure systems. The results are presented in the form of definitions, equations or graphs. All these alternatives are further usable for assessing critical infrastructure elements. The results are also suitable for deeper development of a safety research scientific discipline.

Keywords:vulnerability assessment, risk, consequences, system protection.

1. INTRODUCTION

Problem of vulnerability assessment belongs to one of the most developing aspects of dependability and safety theory and engineering. It was also the major theme of Polish Winter School on Reliability in 2013 [42].

Before developing a plan to enhance system security, a risk manager shall first gain an understanding of potential threats acting against a system, structure or building. Understanding threats is based on the carefully performed assessment of potential risks.

The paper is divided into parts dealing with the vulnerability assessment of various systems. Some specific systems are chosen while the systems are important to users in a certain way. Threats are different for:

- supply chains,
- ecosystem,
- buildings,

The assessment of supply chains vulnerability can be viewed in relation to possible natural disaster impacts and following economic consequences. As for the disasters, they can be droughts, floods, windstorms, hurricanes, etc. – see, e.g. [30, 39]. On the other hand, when dealing with supply chains vulnerability, the negative action of a human being can also be experienced, for example accidents, wars, terrorist attacks, strikes, or sabotages – they are generally on the increase – see, e.g. [10, 39]. Because of the complexity of supply chains, their present function is very weak. The return of investment in setting supply chains is measured in ROA (Return of Assets) units. Numerous supply chain initiatives were implemented in order to boost the revenue (see, e.g. [12, 36, 37], etc.). Small errors could sometimes bring stratospheric cost [26].

If we talk about ecosystems, their vulnerability is usually associated with the impact of toxic pollutants and some negative actions of a human being. Based on the original interpretation of eco-toxicological hazards and other risk (e.g. [6, 7]), the threat is viewed as the combination of the exposure to toxic, chemical, toxicological and other impacts and consequences affecting living organisms. The threat is understood as the potential resulting in certain risks. Here we assess the risks defined as the combination of harmful effect likelihood (due to a given hazard) and resulting consequences. When applying [14, 15], it is possible to work with the following definitions of various vulnerabilities related to an ecosystem (table 1):

Table 1. Definitions of vulnerabilities related to ecosystem

Vulnerability	The degree to which a system is susceptible to, and unable to cope with, injury, damage or harm.
Population vulnerability	The extent to which species experience field population effects of a stressor, as a result of their species-specific ecological traits governing potential exposure to this stressor, sensitivity, and population recovery capacity.
Community vulnerability	The extent to which structure and function of a biological community may be affected by stressor. It depends upon the vulnerability of individual populations as well as upon the interactions among the populations.
Ecosystem vulnerability	The potential of an ecosystem to modulate its response to stressors over time and space, where that potential is determined by characteristics of an ecosystem that include many levels of organisation. It is an estimate of the inability of an ecosystem to tolerate stressors over time and space. It is a combination of community vulnerability with the potential for habitat changes.
Habitat vulnerability	The possibility of habitat changes in relation to some stress factors should be accounted for. For example, hydromorphological changes may affect the habitat characteristics in a river. Changes in habitat link the community level to the ecosystem level.

Vulnerability in ecosystems is generally considered to be a function of exposure to a stressor, effect (also termed sensitivity or potential impact) and recovery potential (also termed resilience or adaptive capacity), see e.g.[1, 2, 14, 15, 33, 38]. Ecological vulnerability is a general term which can be used at several hierarchical levels (organism, population, community, ecosystem, and landscape), following e.g. [35]. Ecosystem vulnerability – as defined above – follows the work [44].

If we talk about buildings and the risks of affecting them – either by nature or a human being – it will be possible to find a large amount of results. Many of them serve to optimize risk management – see, e.g. [3, 4, 5, 11, 20, 27, 31, 32]. If we generally talk about risk assessment of building attacks, vulnerability, besides the hazards, play a fundamental role. Issues dealing with vulnerability assessment which arise from the risk analysis of landslides on buildings were presented by [3, 13, 19], for example. The impact on buildings taking into consideration their typology has been developed by [21, 39]. The effects of this impact as for the damage and destruction have been introduced in [3, 4, 8, 9, 11, 16, 43].

Specific part when assessing building vulnerability are PPS – Physical Protection Systems. These systems are designed on the basis of specified requirements, and evaluated in terms of robustness. Their standard fits the requirements of laws and orders, the nature of the facility, an identified aim and specified threat. In the case of PPS, the vulnerability assumption is applied in the range „Vulnerability is a feature or weakness that can be exploited to cause undesirable consequences". More information about assessing PPS efficiency can be found in [40].

2. POSSIBILITIES OF ASSESSING SUPPLY CHAIN VULNERABILITY

Supply chain vulnerability has been characterized a couple of times. The examples are as follows:

- "An exposure to serious disturbance" – [10];
- "The propensity of risk sources and risk drivers to outweigh risk mitigating strategies, thus causing adverse supply chain consequences" – [25];
- "Supply chain vulnerability is a function of certain supply chain characteristics and that the loss a firm incurs is a result of its supply chain vulnerability to a given supply chain disruption" – [44].

A possible example of supply chain vulnerability and disruption is shown in Figure 1.

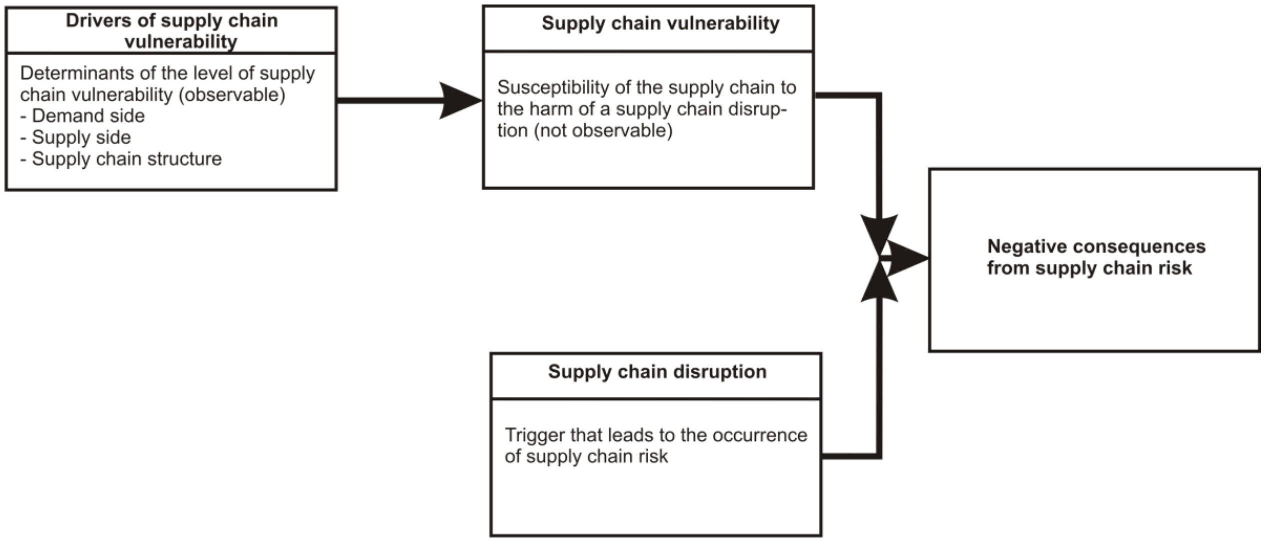

Figure 1. Supply chain vulnerability and disruption

The vulnerability assessment of supply chains might be performed aside from the standard and known methods of probability and statistics also by different methods. For complex supply chains it is suitable to use for example diagram models or to set so called supply chain vulnerability index (SCVI). Some possibilities of applying it, and the algorithm for setting SCVI might be found in ([44] - appendix A).

3. POSSIBILITIES OF ASSESSING ECOSYSTEM VULNERABILITY

When assessing ecosystem vulnerability, there are also large amounts of tools. The result of their application can be either qualitative or quantitative. Historically, besides typical ecosystems, the analysis also dealt with the vulnerability to poverty or the vulnerability to food insecurity, for example. The vulnerability of social systems represents a separate part which we are not going to tackle. In the paragraph below there is a couple of selected ways of determining vulnerability of some ecosystem elements [15, 16].

Within sea system it is:

- OVI (Oil Vulnerability Index) – this method originally developed to describe vulnerability of seabird species to oil spills;
- ESI (Environmental Sensitivity Index) – developed to map the vulnerability of shores to oil spills,
- VME (Vulnerability of Marine Ecosystems) – developed to collect expert opinions that describe which threats affect marine ecosystems, aj. např. OSPAR.

For general ecological systems:

- ReVA (Regional Vulnerability Assessment) – developed as an early warning system to identify those ecosystems most vulnerable to being lost or permanently harmed in next 25 years and to determine which stressors are likely to cause greatest risk;
- UI/VI (Utility Index/Vulnerability Index) – developed as a toll to rank terrestrial vertebrate species;
- VL (Vulnerability of Landscapes) – developed to use as a comparison for vulnerability to desertification and soil erosion;
- EVA (Ecological Vulnerability Analysis) – 19 ecological traits gathered in 144 wildlife species (aquatic and terrestrial, vertebrate and invertebrate);
- LS (Landscape Species) – developed to select the appropriate species in a landscape for conservation purposes;
- QVA (Quantitative Vulnerability Assessment of Environmental Change) – method to assess the vulnerability of

human sectors, relying on ecosystem service for future climate change;

- SES (Vulnerability of Socio-ecological Systems) – assessment that uses stakeholder value of ecosystem service, matrices to link social and ecological information about changes in ecosystem services, and information on ecosystem properties that provide ecosystem service;
- AWRVI (Arctic Water Resources Vulnerability Index) – developed as a tool for Arctic communities to assess their relative vulnerability to changes in their water resources.

Some scales and methods of utilization can be found in figure 2.

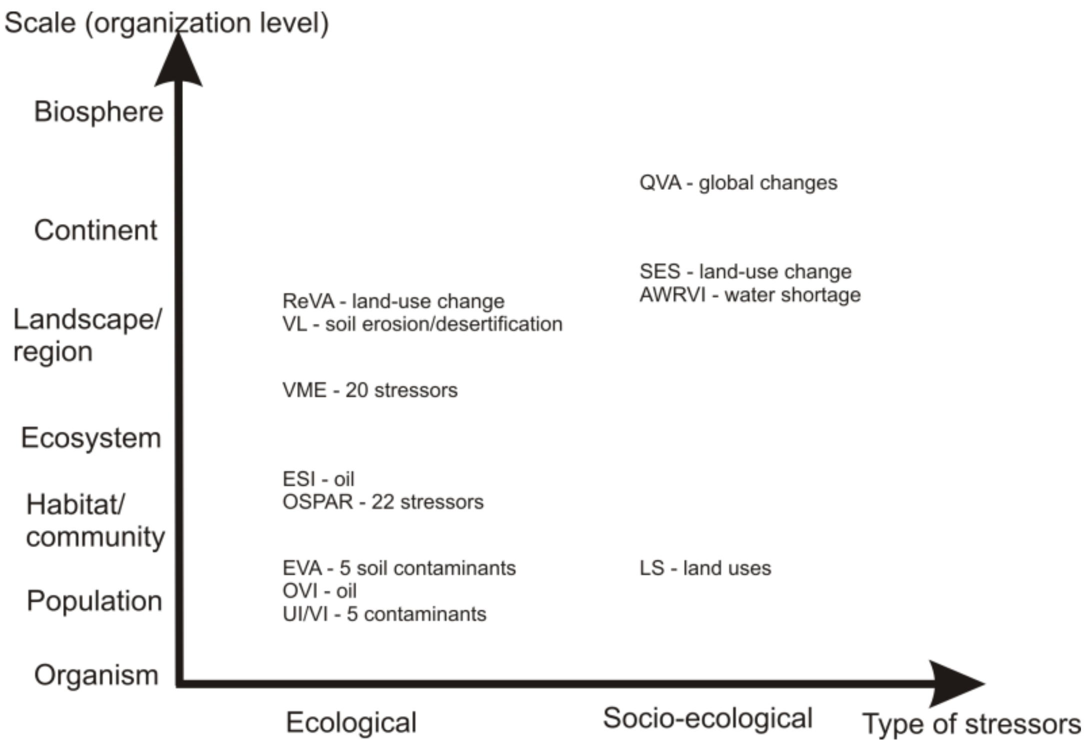

Figure 2. Scales and type of stressors of the different vulnerability methods. Methods are abbreviates as mentioned above [15, 16]

Aspects of existing methods can be described as:

- Most methods rely on expert judgement;
- Input of stakeholders is needed;
- Most methods produce qualitative ranking and mapping of vulnerability;
- Only smal percentage of methods (only one from the above mentioned) is capable to provide quantitative figures of vulnerability.

In Figure 3 there can be seen some aspects of ecological vulnerability. Bars on top indicate whether physic-chemical characteristics are the main determinant or biological characteristics or both. Environmental conditions indicated with the bar bellow have an influence on all aspects but are also influenced by the long-term impact.

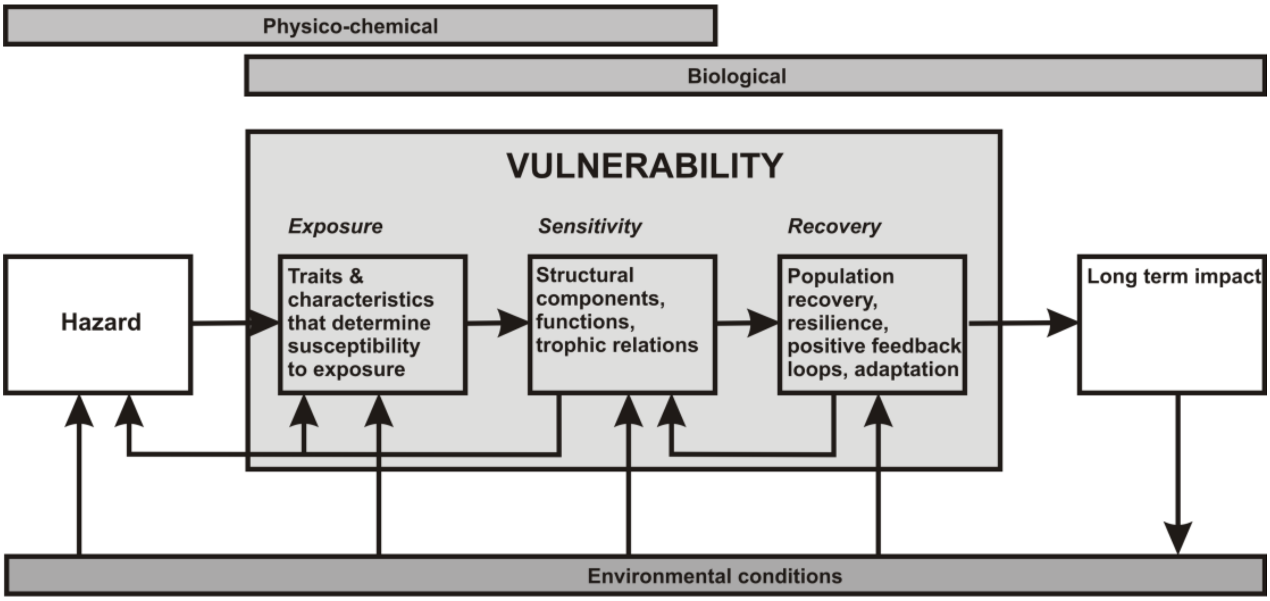

Figure 3. General framework for ecological vulnerability assessment for hazard or interaction hazards [15, 16]

When dealing with specific applications, it is possible to find the case of EVI (Environmental Vulnerability Index) enumeration for different cases [36]. In one of them [36] abut 50 indicators in the form of scales are used for setting EVI. The formula below serves as an example of EVI calculation:

$$EVI = 100 \times \sum_{l=1}^{n} \frac{Indicator\ Scale\ Value}{n} \qquad (1)$$

where: n - the total number of indicators used (1; 2;…..; 50).

4. POSSIBILITIES OF ASSESSING BUILDINGS AND PPS VULNERABILITY

When we are to assess the affection of buildings, we can also work with a few forms of setting the vulnerability. Of all known and used forms we select only some of them.

The first one is so called Damage Index (DI) – it expresses the level of structure damage for a given way of an attack, its localization and kinetic energy E_K. It is determined by the equation below (2)

$$DI = \frac{number\ of\ primary\ structural\ elements\ that\ fail}{total\ number\ of\ primary\ structural\ elements} \qquad (2)$$

Next, it is possible to set so called Building Vulnerability Index – BVI which is based on the following assumption (3) of risk existence:

$$R(P) = \sum_{i=1}^{i} \sum_{j=1}^{j} \left[P(R_i) \times P(E_j : R_i) \times P(S:T) \times V(R_{ij}) \right] \times C \qquad (3)$$

where:
$R(P)$ - expected annual loss to the property due to attack (e.g. €/yr);
$P(R_i)$ - annual probability of occurrence of attack with magnitude (volume of explosives for instance) "*i*";
$P(E_j{:}R_i)$ - probability of an attack with a kinetic energy (intensity) reaching the critical section that marks the developed area. The latter it is calculated as a function of the magnitude (volume of explosives for instance, mass of attack tool – vehicle for instance) "*i*" and the velocity "*j*";
$P(S{:}T)$ - probability of the building being on the attacker´s trajectory (calculated as the ratio of the building´s width to the critical section´s width);
$V(R_{ij})$ - vulnerability of the building for an attack with magnitude (volume of explosives for instance, mass of attack tool – vehicle for instance) "*i*" and the velocity "*j*";
C - value of the building.

The terms $P(R_i)$ and $P(E_j : R_i)$ represent the hazard, $P(S{:}\ T)$ the exposure and $V(R_{ij})$ the vulnerability. Building Vulnerability Index is than calculated as:

$$BVI(R_{ij}) = \sum_{k=1}^{k} (P_{e,k} \times RRC_k) \leq 1 \qquad (4)$$

where:
$BVI(R_{ij})$ - building vulnerability for an attack with magnitude (volume of explosives for instance, mass of attack tool – vehicle for instance) "*i*" and the velocity "*j*",
$P_{e,k}$ - encounter probability of attack with a possible structural and non-structural element of the building "*k*" that may be struck by an attack mass of magnitude "*i*",
RRC_k - relative recovery cost that corresponds to the struck of a possible structural and non-structural element of the building "*k*" by an attack with magnitude (volume of explosives for instance, mass of attack tool – vehicle for instance) "*i*" and the velocity "*j*".
$P_{e,k}$ is calculated for all the possible structural and non-structural elements that may be struck by an attack mass. For every attack magnitude a different $P_{e,k}$ is attributed to each structural element. For an attack magnitude with a given velocity and path there will be a DI and an associated RRC. Thus using equation (4) the vulnerability is calculated in function of mass and velocity of the attack respectively. The value 0 of the vulnerability expresses zero potential damage and the value 1 certain total collapse (total loss) of the building.
In the case of specific PPS we proceed from the assumption when evaluating vulnerability that efficient PPS reduces the risk resulting from the attack on a protected building at the acceptable level.
The risk is put in the following manner:

$$R = P \times C \qquad (5)$$

where:
P - the probability of consequence occurrence,
C - their severity magnitude.

In practice we are interested how successful the probability of the attack on a building will be if the attack occurs. Equation (5) might be then put the following way:

$$R = [P_A \times P_{S/A}] \times C \qquad (6)$$

where:
P_A (attack) - the probability that the attack on a building will occur,
$P_{S/A}$ - the conditional probability of a successful attack, provided it occurs.

The probability of a successful attack decreases with the growing ability of a physical protection system to withstand the attack – inherent efficiency of the PPS:

$$P_{S/A} = 1 - P_E \qquad (7)$$

where P_E is the probability that the PPS prevents from carrying out the attack successfully.

Then the formula (5) might be expressed in the following manner:

$$R = [P_A \times (1 - P_E)] \times C \qquad (8)$$

If we deal with the buildings marked as a "critical infrastructure", then it will be only a question of time when the attack really occurs. This means that the value P_A = 1 and the consequences will be serious, that is C = 1. Following the assumption introduced above, the formula (5) could be put this way:

$$R = 1 - P_E \qquad (9)$$

The lower the risk, the bigger ability to prevent from successful performing the attack by a PPS – that is the PPS is a lot more efficient to withstand the attack. The overall efficiency of a P_E system – in the form of probability means that the systems prevent carrying out the attack successfully. The probability would be expressed this way:

$$P_E = P_I \times P_N \qquad (10)$$

where:
P_I - the probability of interrupting the attack which means that a fast-deployment unit acting to stop the advance of an adversary will be in the right place at the right time,
P_N - the probability of adversary neutralization, provided a fast-deployment unit has it over the adversary.

Different analytical approaches are used for specific evaluating efficiency.

5. CONCLUSIONS

The article brings a possible view and selected ways of assessing the vulnerability of various types of systems. It is not a matter of the only possible approach but a broad spectrum of human research areas dealing with the assessment of system vulnerability. A question of vulnerability is very important here, mainly for the systems like the environment, supply chains and buildings. These give us a sense of security, supply us with energies and assure society functioning.

The possibilities of setting the level of vulnerability can range from frequently used tools of standard probability to modelling methods or soft methods such as Petri Net, Fuzzy logic, etc. The direction of research in this area is modified mainly by the use, area of application and boundary conditions. They are needed especially for fulfilling theoretically made models. If we are to limit our research to theoretical development only, then the application of diffusion processes seems to be perspective for vulnerability assessing.

Since the topic is up to date, the authors of the paper assume that the area is going to be developed also in the future.

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