THE ISSUE OF DEPENDENCIES WHEN ASSESSING THE CRITICALITY OF INFRASTRUCTURE ELEMENTS

Petr ROSTEK, Jiri MARKUCI, Vilem ADAMEC
petr.rostek@vsb.cz, jiri.markuci.st@vsb.cz, vilem.adamec@vsb.cz

Abstract

The paper describes frequently used terms in the field of dependencies between infrastructures and continues mentioning the issue of their potential assessment. It shows the decomposition of the linkages and outlines the approach to the evaluation of primary factors (dependencies) using time and economically dependent criteria. The identification of primary dependency serves to describe secondary impacts within the assessment of the infrastructure elements criticality.

Keywords

Critical infrastructure, influence, dependency, interdependency, criticality of critical infrastructure element, criticality.

1 Introduction

The issue of dependencies among individual infrastructure elements and sectors have recently become a highly discussed topic within security research. The key infrastructure elements and the infrastructure itself have been more and more interconnected both from technological and especially economical reasons. This mutual formation of the linkages brings, however, new challenges regarding the assessment of the element infrastructure criticality with regard to the dependency of relevant infrastructures. These linkages contribute namely both to the higher overall importance of criticality (e.g. dependency on power supplies) and to their reduction (e.g. emergency services). Nevertheless the issue of individual components of dependencies have not been addressed so far in the CR when assessing the criticality of potential elements of critical infrastructure [4],[16].

An extraordinary event attacking the infrastructure X might have, directly or indirectly, also the impact on large regions and influence both national and global economy [7]. The dependency between individual infrastructures is substantially influenced by the range of the impact on the society in a specific territory.

2 Linkages between Infrastructures

Not only in the security field but also in other branches of human activities there has been recently the effort to identify, evaluate and model the systems whose parts are interconnected, influence each other and subsequently are more or less dependent on each other. It is necessary to remark that the approach to the evaluation of systems can be called differently: the system of systems [11], a comprehensive approach, an integral approach etc. The issue of dependencies has been more and more addressed also in the field of vitally important systems, for example when assessing the dependency of critical infrastructure elements.

The growing development of knowledge in the area of the dependency and comprehensive systems causes also a quite different explication of basic terms describing relations in these systems. In the following paragraphs we present the most significant terms in

this field and their importance which can be applied in terms of the assessment of dependency or during the assessment of the infrastructure element criticality.

If we want to talk about the dependency or about the influence of individual systems, element systems, individual branches of critical infrastructure or services, there must be the **linkages.** The linkages mean the connection between elements, infrastructures or systems. From the general point of view we can divide the linkages into three basic categories:

- the influence linkages;
- the dependency linkages;
- the interdependency linkages.

If there is the dependency of the infrastructure A on the infrastructure B, the infrastructure B must have the influence on the infrastructure A by means of the linkage. Another term in the area of the dependency is then the **influence.** The influence means that the infrastructure A by means of the linkages affects either positively or negatively [3] (it has the tendency to generate „changes“ of the condition to provide the function of the infrastructure B) the infrastructure B and the infrastructure B is not (does not have to be) dependent on the infrastructure A.

The positive influence means the action which reduces the resulting level of the infrastructure element criticality (e.g. due to the backing up). The negative influence means the action which increases the level of the infrastructure criticality (e.g. the only access road for health care delivery).

The dependency means the linkages between two or more infrastructures where the condition of e.g. the infrastructure B is influenced by the condition of the infrastructure A [7]. In other words, the condition of the infrastructure B is dependent on the condition of the infrastructure A.

Rinaldi et al. in the article [7] mention the **interdependency** in case when there is the reciprocal relation between two elements. Therefore the element A is dependent on the element B and, at the same time, the element B is dependent on the element A by means of various kinds of linkages. The interdependency means a reciprocal relation (through the bilateral linkages) between two elements of infrastructure where the condition of the one influences, or is correlative, the condition of the other one and vice versa.

The interdependency responds better to real systems by which we are surrounded. Especially it responds to a comprehensible view to the issues of the infrastructures (together with critical infrastructures). We may generally conclude that the function of one infrastructure is directly or indirectly dependent on the function of the other infrastructure and if they fail, we will face the socially unacceptable impacts.

Figure 1 illustrates these linkages including the orientation and the direction of the individual kinds action.

From the above mentioned terms follows that it is possible to assess the linkages (therefore influences, dependency and interdependency) from various viewpoints. These viewpoints can be the linkages between elements, infrastructures, systems, and systems of systems. The level of the viewpoint is then dependent on the focus of the linkage analysis. For example whether we want to explore the linkages between individual elements inside the infrastructure, or whether we are interested in the view from the outside i.e. how the services/functions provided by one infrastructure can depend or influence the services or functions provided by the other infrastructure.

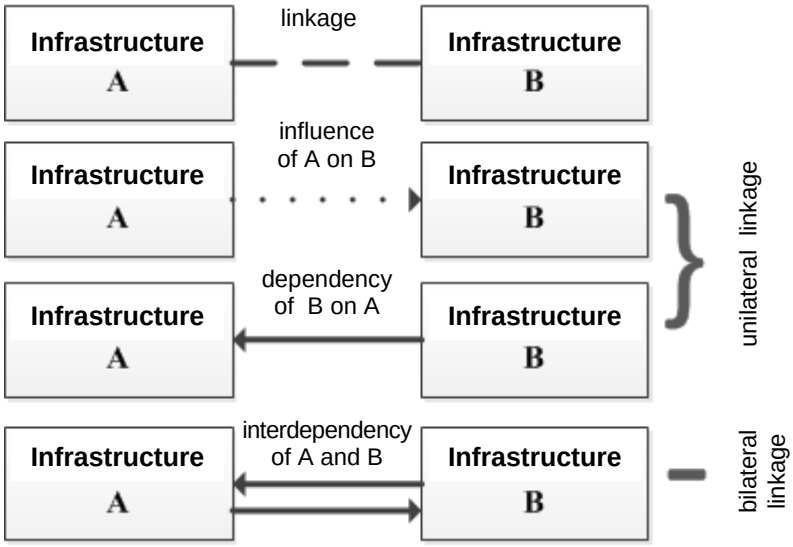


Fig. 1
Comparison of individual kinds of linkages

Rinaldi et al. distinguish four basic kinds of linkages (they are relevant to all above mentioned categories – influence linkages, dependency etc.). Mostly the linkages are physical, logical, geographical and cybernetic [7]. The **physical** linkage between two elements is when the condition of one element is physically interconnected with the material output of the other one. As long as there is the connection between the element and pieces of information transferred by information infrastructure, then it is the **cybernetic** linkage. The **geographical** linkage means that the local extraordinary event might be linked with the condition of elements in a given locality. The **logical** linkage is between two elements when the condition of one element is dependent on the condition of the other one but by means of a different mechanism than the physical, geographical or cybernetic one. [7]

Elements, infrastructures and systems can be, according to Rinaldi et al. [7] divided with regard to the dependency into two categories: supported and supporting. Supported infrastructures are all infrastructures which are dependent on the function or services of other infrastructures. The supporting infrastructures are infrastructures which influence other infrastructures.

The kind of the linkages can be understood also in a wider context, e.g. Pederson et al. in the article [6] classify the interdependency (kind of linkage) into the following five categories:

- **Physical** interdependency represents frequent technical relation between components. For example the fall of a tree on electrical wiring caused by the storm has the impact such as the loss of power supplies.
- **Information** interdependency is given by information or control requirements between components. The example is e.g. SCADA systems.
- **GeoSpace** interdependency exists between spatially bound components.
- **Politically-procedural** interdependency is represented by means of political or procedural linkages. It is connected with a condition or a change in the part of an infrastructure sector. The impact of this dependency can persist e.g. regarding the renewal of assets.

- **Social** interdependency or its influence can propagate into other areas such as public meaning, trust, fear and cultural values.

It is obvious that the description and linkages assessment in real environment of interconnected infrastructures will contribute to a detailed understanding of the linkages between individual sectors and elements of infrastructures. The objective of such assessment is the response to the following questions:

- Are there any **linkages** between infrastructures[1]?
- How fast is the propagation of the linkages, i.e. what **is the intensity of linkages** like?
- What might these linkages cause (**seriousness of the impact**)?

The assessment of primary or influence linkages will contribute to a more precise determination of criticality of the assessed elements of infrastructures.

3 Primary, Secondary, Tertiary, and n-th Linkages

In order to describe the linkages between infrastructures and their elements we have to describe the **linkages chains** which interconnect individual elements, infrastructures or systems. The key effect for modeling and understanding these chains across many sectors can induce a potentially unpredictable n-th cascade or an escalating effect [6], [7].

These chains of potentially balanced multiple types of interdependency are composed of the linkages between sets / parts of infrastructures or their elements. These linkages represent a cascade effect of consequences of events or the derived dependency of the infrastructure A on the infrastructure B. These kinds of linkages do not have to exist only during the period of the action of an extraordinary event, but they can change e.g. in time and their behavior can be accumulative. The understanding of permeating of these systems of elements and their behavior in time of their disruption is, in the modern conception, represented by comprehensive systems which are demanding both from the viewpoint of full understanding and their theoretical description. [6]

These chains can be described e.g. using scenarios and the linkages can be divided into primary, secondary and tertiary. The model of these linkages according to Rinaldi et al. [7] is demonstrated in figure 2.

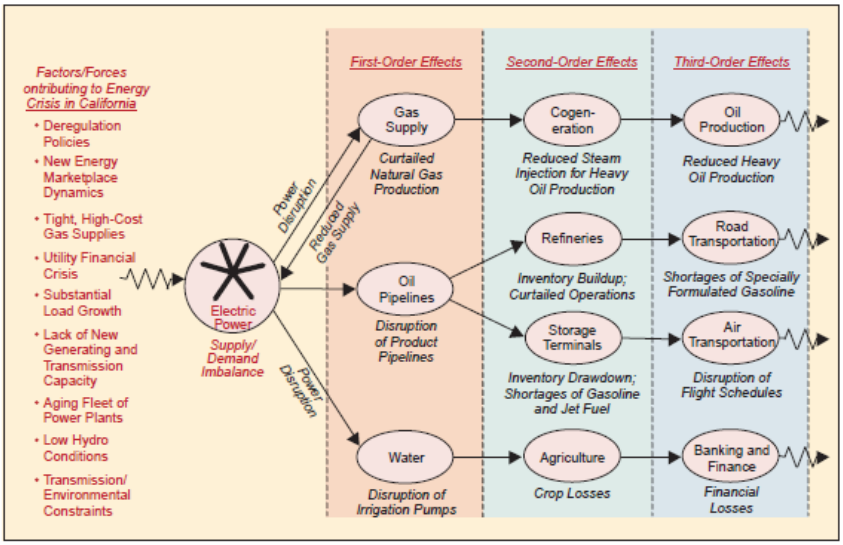


Fig. 2
Demonstration of primary, secondary and tertiary linkages, Rinaldi et al. [7]

However, this approach is for the description of a comprehensive system very complex and requires high degree of knowledge of the system and linkages between infrastructures. Last but not least, it requires a large amount of input data which are unavailable or it is very difficult to obtain them. And especially it ultimately leads to certain loops.

For the evaluation of the influence of elements, infrastructures and systems we will further deal only with the evaluation of primary linkages (influences) due to the following reasons:

- their number is finite;
- they are identifiable and it is possible to evaluate them;
- the designed model is substantially simplified.

For example in case of the elements of the road infrastructure network we can explore the physical linkages using the method of operation analysis such as the Critical Path Method (CPM), or Program Evaluation and Review Technique (PERT) [9] etc. By means of these methods we can specify the importance of the connection and subsequently determine systemically important elements of the transport infrastructure network.

However, for the specification of an overall criticality of an element it is necessary to evaluate also the influence of a systemically important element on by state protected interests, therefore: lives, health, property and the environment through the evaluation of a direct influence [10] see figure 3.

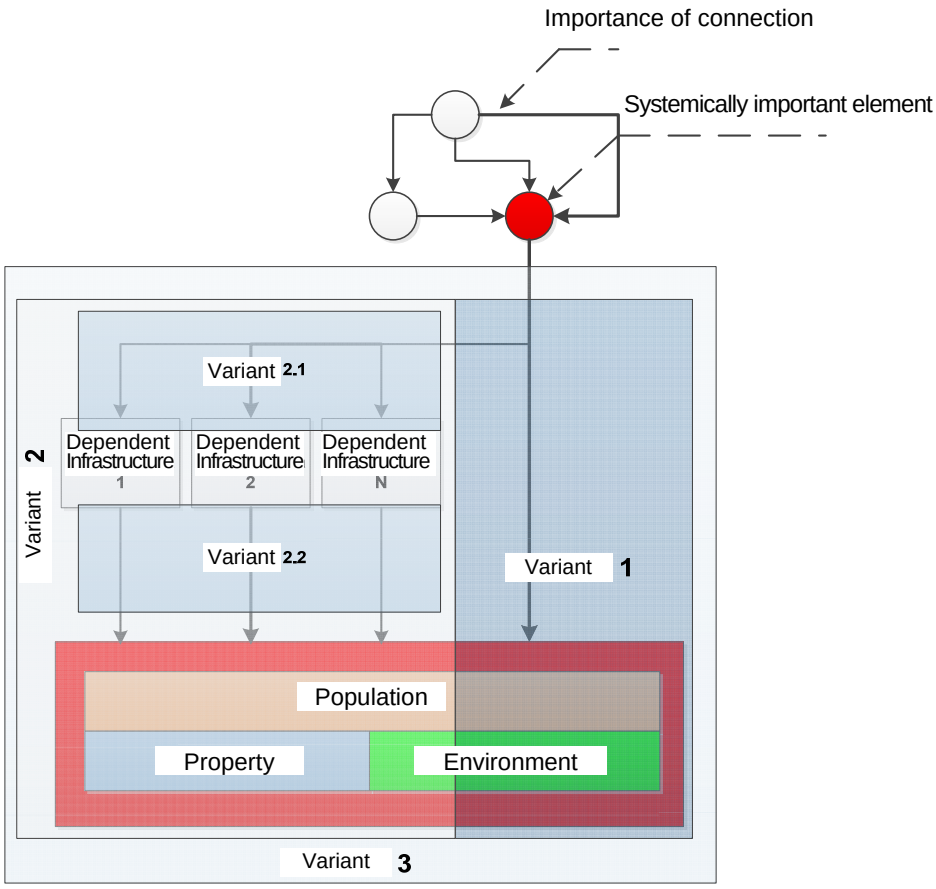


Fig. 3
Variants of the influence between infrastructures

Variant 1 in figure 3 demonstrates direct influence of a systemically important element on state-protected interests, i.e. it represents primary impacts of the failure of a systemically important infrastructure element. Variant 2 represents a mediated effect of the failure of a systemically important element by means of other infrastructures on protected interests (secondary impacts). However, for the evaluation of a secondary influence, this effect has to be divided (figure 3, variant 2.1 and variant 2.2). It means that we evaluate the influence of a systemically important element on other infrastructures – i.e. their elements (figure 3 – variant 2.1), which further affect state-protected interests (figure 3 – variant 2.2).

By synthesizing the influences of variant 1, variant 2.1 and variant 2.2 we obtain to a certain degree simplified but sufficiently comprehensive evaluation of the influence of a systemically important infrastructure element on state-protected interests in figure 3, demonstrated in variant 3.

The objective of the assessment of these effects is the specification of an overall impact of the influence of a systemically important element on state-protected interests. This way assessed influence will contribute to a more precise determination of an overall degree of the importance of a systemically important element.

4 Theoretical Analysis of Dependencies

The assessment of the influence of an infrastructure element by means of linkages is demonstrated in more details in figure 4. The basic physical layer representing e.g. road infrastructure demonstrates the set of its elements (hubs) and connections (linkages) between them and represents a road network. As already mentioned above, it is possible to determine in this layer systematically important elements.

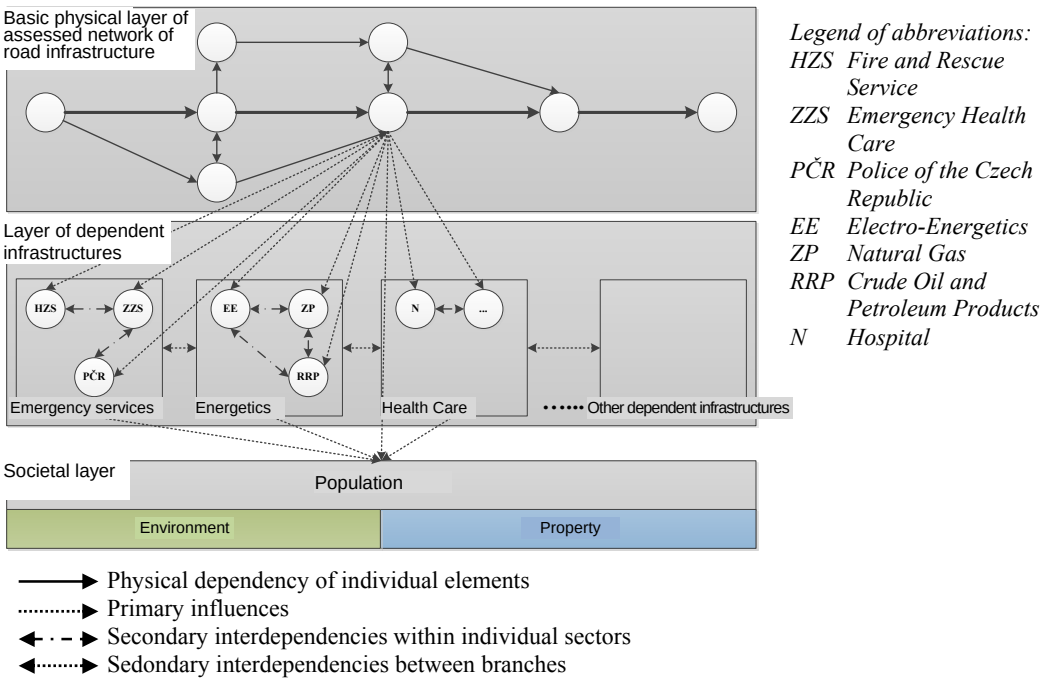


Fig. 4
Theoretical analysis of dependencies

For systematically important elements we search and evaluate linkages to elements of dependent infrastructures on which, this way determined a systematically important element has a primary influence and which have further a direct influence (impact) on protected interests.

4.1 Criteria for the Evaluation of Interdependencies

For the evaluation of linkages (interdependencies, dependencies and influences) there is a considerable number of criteria which are applied by various authors in various approaches of modeling and simulating dependencies/interdependencies see [1], [2], [5], [6], [8], [14]. Those are the methods based on: Markovov processes, Petri nets; method Monte Carlo, differential equations; tools based on aggregate supply and demand (dynamic simulation); models based on inter-mediators, physical linkages, mobility of population ; Leontief Input – Output Model and others. From the literature research and analysis we designated significant and often occurring criteria for the assessment of interdependencies. There are especially criteria which describe:

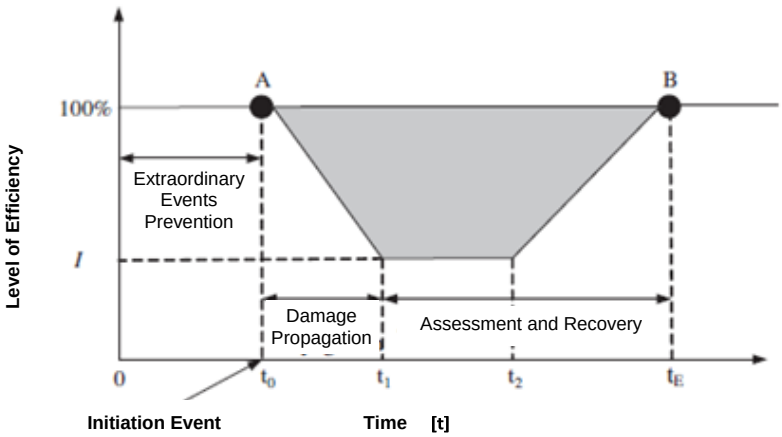
- time factors;
- geographical scale;
- cascade effect;
- socio-psychological effects;
- influence of operational procedures;
- trade policy;
- back-up and recovery procedures;
- government regulation, law, regional policy;
- interests of the owners;
- services/functions supply;
- services/functions demand;
- commodities flow, their supply, transfer, storage and consumption;
- critical time, critical quality.

Great attention is paid to time factors (so called critical time) when assessing the criticality of the infrastructure element e.g. Fekete [1]. Time factors represent e.g.: the duration of the failure, the speed of the failure onset, median time to recovery, median time to restoration of function etc. Oyung et al. in the article [5] mention also the time of propagation and time of recovery see fig. 5.

Figure 5 represents individual time moments of the failure of an infrastructure element. For example the propagation time is specified as a time interval between the moment/time of the infrastructure failure (t_1) and the moment/time of the rise of an initiating event (t_0).

Trucco et al. in the article [14] for example mention the time during which the threat occurs, the time for initiating intervention, etc. Rinaldi et al. [7] divide basic time divisions into two groups, i.e. tight and loose linkages. Time linkages, unlike the loose ones, are significantly affected by the dependence on time. To illustrate the **tight linkage**: The failure of the power supply service immediately affects the service of public lighting (immediate turn off). The **loose linkage** can be demonstrated in the following example: Coal-fired power plants have local coal reserves for three months. The malfunction in railroad coal supplies can then hardly affect the system of the electricity production from coal sources. Combination of tight and loose linkages responds to a relative degree of the dependency between services. [7]

According to Fekete, the criterion of quality at work [1] signifies the quality of provided service (e.g. water supply) dependent on time. Trucco et al. [14], expresses the quality of provided service by means of e.g. maximal and actual service, malfunction, damage, functional integrity etc.

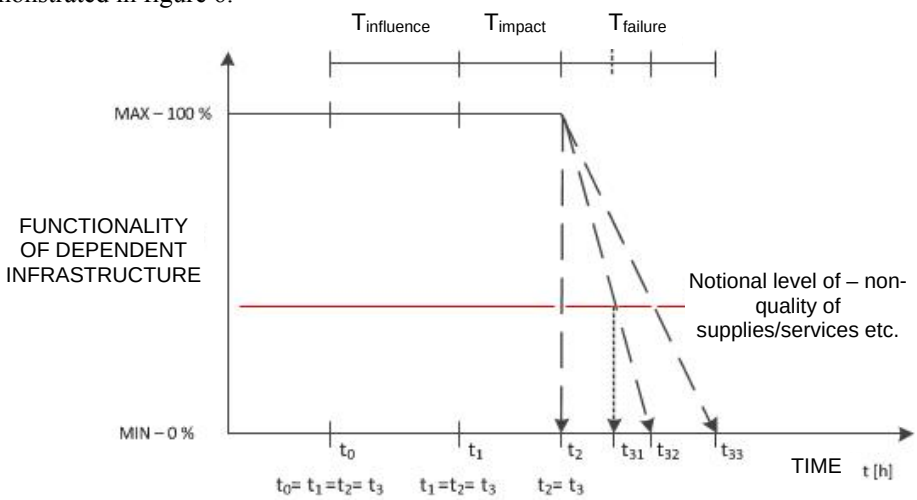


t_0 Initiating moment of the event
t_1 Duration time of infrastructure malfunction
t_2 Time of starting infrastructure recovery
t_E Termination time of infrastructure recovery

Fig. 5
Typical curve of the response of infrastructure performance due to an extraordinary event, Oyung et al. [5]

4.2 Proposal to decompose time dependencies

Basic factor which affects the degree of dependency is therefore the time course of the influence of one element, infrastructure, system on the other one and in time variable size of the impact. The significant moments of the influence of the failure of an infrastructure element are demonstrated in figure 6.



t_0 Time of infrastructure A element failure
t_1 Time of feeling the influence of the failure of infrastructure A element on inf. B
t_2 Time of feeling the impact of the failure of infrastructure A element on inf. B
t_{31}, t_{32}, t_{33} Time of infrastructure B element failure

Fig. 6
Decomposition of time dependencies

In dependence on individual moments in time we can subsequently identify time criteria which will describe the linkages between individual infrastructures.

4.2.1 Measurable time criteria describing linkages between infrastructures

The time of feeling the effect $\boldsymbol{T}_{effect}$ is defined as time interval between time/moment of feeling the effect/influence of the failure of the infrastructure element A on the infrastructure element B (t_1) and time of the failure of the infrastructure element A (t_0), see relation 1.

$$\boldsymbol{T}_{effect} = t_1 - t_0 \qquad (1)$$

In extreme cases the time of feeling the effect can be identical to the time of feeling the impact (t_2) or also to the time of the malfunction of the infrastructure element B (t_3), see figure 6. That is the worst possible variant when there is practically a giant leap in affecting the infrastructure B. Example: The failure of power supply immediately affects (turns off) the lighting in a building.

The time of feeling the impact or the time of propagation of the failure on the infrastructure B, $\boldsymbol{T}_{impact\ on\ I.}$ is defined as an interval between the time of feeling the impact of the failure of the infrastructure element A on the infrastructure element B (t_2) and time of feeling the effect of the failure of the infrastructure element A on the infrastructure element B (t_1), see relation 2. This time is dependent on the resilience or the vulnerability of the infrastructure element G – e.g. power supply reserve etc. The situation might occur when the time of the impact on the infrastructure B is identical to the time of the malfunction of the infrastructure element B (t_3).

$$\boldsymbol{T}_{impact\ on\ I.} = t_2 - t_1 \qquad (2)$$

The time of the infrastructure B failure $\boldsymbol{T}_{failure\ I.\ B.}$ is characterized as a time interval between the time of the infrastructure B (t_3) element failure and the time of feeling the effect of the failure of the infrastructure A element on the infrastructure B element (t_2), see relation 3. This time is dependent according to the type of assessed infrastructure, and also on the quality of provided services/supplies. For example the water reservoir is capable to provide drinking water even after the power supply failure. The question is, how long it will provide the water of required quality.

$$\boldsymbol{T}_{failure\ I.\ B.} = t_3 - t_2 \qquad (3)$$

In figure 6, the question of required quality of services or supplies is demonstrated by a parallel line with a vertical timeline. At a practical level it is difficult to assess this qualitative factor. The proposed process of the evaluation of the element influence by means of linkages on other elements, infrastructures or systems (the influence of the variant 1 in figure 3) is demonstrated in figure 7.

The evaluation process of the influence of the infrastructure element failure begins by the identification of an element which is subjected to the research of the influence on other infrastructures (influence of the variant 2.1, see figure 3). In the following step we determine all linkages by means of which the element can influence the infrastructure element in another branch.

In another process step we assess whether there is, by means of the linkage, the influence (e.g. using method KARS, what-if analysis etc.). In case that there is the influence, its degree is determined by means of the evaluation of determined criteria. After the assessment and evaluation of all linkages of a given element we carry out the overall evaluation of this specific element influence.

Criteria for the assessment of a primary influence of the variant 2.1, figure 3 might be then the intensity of the influence (IV) and its impact (D). The degree of the influence is then the function of its intensity and impact, see relation 4.

$$V_{21} = f(IV,D) \quad (4)$$

$$IV = f(T_{influence}, T_{impact}, T_{failure}) \quad (5)$$

$$D = f(\text{economic losses}) \quad (6)$$

The intensity of the influence is a function of time factors (relation 5) described above. The degree of the impact might be determined e.g. by economic losses per hour as a result of the linkage influence, see relation 6.

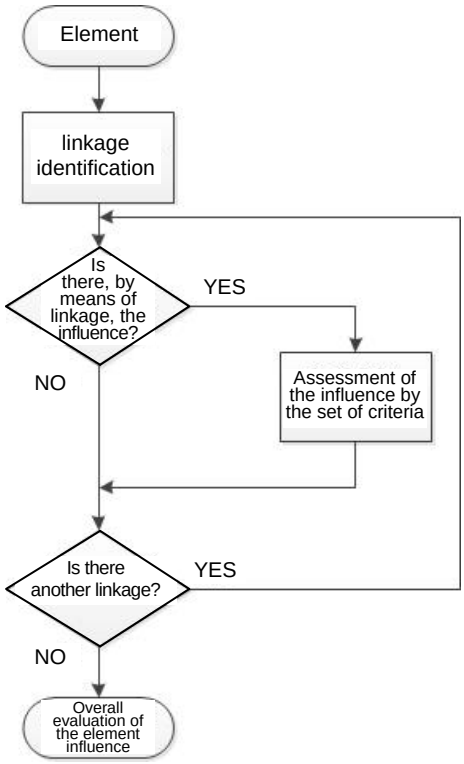


Fig. 7
Evaluation process of the element influence

5 Conclusion

The issue of the dependencies (influences) is a part of a comprehensive view of the evaluation of infrastructure elements criticality; however, the Czech Republic has not paid much attention to this issue so far.

The evaluation of dependencies (influences) of individual elements on other elements within a single infrastructure, but also beyond it, is a quite demanding task. The important aspect during the analysis of this issue is the identification of primary linkages

(influence/dependencies) or mutual linkages between infrastructures. By means of these linkages the influence (or dependency) can affect the infrastructures. During the analysis of primary and secondary sources we discovered that only professional publications mention the assessment of interdependencies, ultimately the influences or dependencies are almost always assessed since in reality it is difficult to evaluate the interdependency (different time character, direction, intensity of the action etc.).

When assessing the infrastructure element criticality it is especially important to pay attention to primary influences which are crucial for the evaluation of primary dependencies. However, it is necessary to choose appropriate criteria which will encompass both time view of the influence (time of the influence, impact, failure) ant the degree of its impact on dependent infrastructure (economic losses). Based on the evaluation of a primary influence, it is possible to precise the resulting level of criticality of the assessed infrastructure element and therefore it is important to devote a considerable attention to this field when the infrastructure element criticality is to be assessed.

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NOTES:

[1] Linkage of influences, dependencies and linkage of interdependencies.

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Information about authors

Vilem Adamec (1953)
is the head of the Department of Civil Protection at the Faculty of Safety Engineering – Technical University of Ostrava. He specializes in Population Protection, Crisis Management, Integrated Rescue System, Civil Emergency Planning and Critical Infrastructure Protection.

He graduated from the Technical University of Ostrava, Faculty of Mining and Geology; Fire Protection and Industry Security Technology section (1977). He completed his doctoral studies at the Institute of Safety Engineering with a thesis on "Management of Rescue Works – Operational and Information Centres" in 2002. He habilitated at the Faculty of Safety Engineering in 2009 with a thesis "Study of Possibilities of Establishing level of Civil Emergency Preparedness of Territorial Units".

He is an author or co-author of 16 publications, more than 30 contributions in collections of national and international conferences, 5 contributions in proceedings of international conferences abroad, more than 40 articles in national and foreign professional journals. He is also a member of several scientific councils, commissions and editorial boards of magazines.

Jiri Markuci (1988)
is a student of Master Studies at the Faculty of Safety Engineering – Technical University of Ostrava, Department of Safety Planning.

He focuses on issue of Critical Infrastructure, Population Protection, Risk Analysis and Crisis Management. Within his specialization he is a co-author of professional publications and he also participates in several projects within the field of Critical Infrastructure.

Petr Rostek (1986)
is an internal graduant of Technical University of Ostrava, Faculty of Safety Engineering, Department of Population Protection. He deals with issues of Population Protection, Crisis Management, and assessing important Territorial Infrastructure.

He graduated from the master's degree programme at Technical University Ostrava with specialization in Security Planning (2011).