Chapter

Multiset-Based Assessment of Resilience of Sociotechnological Systems to Natural Hazards

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Abstract

The chapter describes multiset-based approach to the assessment of resilience/vulnerability of the distributed sociotechnological systems (DSTS) to natural hazards (NH). DSTS contain highly interconnected and intersected consuming and producing segments, and also resource base (RB), providing their existence and operation. NH impacts may destroy some local elements of these segments, as well as some parts of RB, thus initiating multiple chain effects, leading to negative consequences far away from the NH local strikes. To assess DSTS resilience to such impacts, multigrammatical representation of DSTS is used. A criterion of DSTS sustainability to NH, being generalization of similar criterion, known for industrial (producing) systems, is proposed. Application of this criterion to critical infrastructures is considered, as well as solution of the reverse problem, concerning subsystems of DSTS, which may stay functional after NH impact.

Keywords: resilience and vulnerability, natural hazards, sociotechnological systems, critical infrastructures, multisets, multiset grammars, unitary multiset grammars

1. Introduction

Modern large-scale distributed sociotechnological systems (DSTS) include anthropogenic and technogenic components, i.e., humans and various technical devices, respectively, operating in common in order to provide sufficient quality of life to humans, and this sufficiency may be defined by some threshold amounts of resources, consumed by them during some fixed period of life. These resources, in turn, must be produced and relocated from places of their production to places of their consumption by application of the aforementioned devices and their aggregates. The last also uses specific resources, necessary for their operation.

By this, every DSTS may be represented as composition of two segments—consuming and producing (both containing humans and devices)—and resource base, which provides their existence and operation. These segments are highly interconnected and intersect, because a large number of humans and devices are consumers and creators of resources simultaneously.

Natural hazard impacts (NHI) may destroy some local elements of the aforementioned segments and resource base, and this destruction initiates multiple chain (or cascading) effects, caused by the absence or lack of resources, necessary for normal operation of some devices and/or humans; such effects may lead to the destructive consequences far away from places (areas) where natural hazard (NH) occurred.

By growth of complexity of DSTS and degree of their internal interconnectivity, it becomes more and more difficult to assess such consequences and, as a whole, resilience (or, reversely, vulnerability) of DSTS to various NH. Here, we shall understand DSTS *resilience* to NH as its property not to reduce humans' quality of life lower than some predefined level (as was said higher, it may be determined by the amounts of resources, consumed by anthropogenic part of DSTS).

Well-known approaches to formal description and solution of DSTS resilience/vulnerability problems, integrally considered in [1], are not applicable to most practical cases by the reason of only partial adequacy of representation of the main structural and functional features of DSTS, as well as by the reason of sharply increasing computational complexity of detecting algorithms on real dimensions.

As it was shown in [1, 2], multiset-based approach to such assessment is one of the most suitable perspectives from both descriptional and computational points of view. The core of this approach is representation of technological base of the industrial systems (IS), producing necessary resources, by special multiset grammar (MG), and its resource base (RB)—by multiset (MS).

The simplest formal definition of resilience of IS, completing some order, is based on the presumption, that if RB, reduced by NHI, is, nevertheless, sufficient for this order completion by at least one possible way, then such IS is *resilient to this impact*.

However, this definition and all formalizing it relations concern only industrial systems (producing segments of DSTS) and single orders, so until now criterion of DSTS resilience in multiset-based form is unknown. The main reason for this is that there is no technique for the assessment of the whole set of orders, which may generate consuming segment of DSTS. So, this chapter is dedicated to consideration of such general case. The basic presumption for all lower discourse is that DSTS after NHI has no any opportunity to contact with external systems in order to compensate loss of resources, being the result of NHI, i.e., DSTS is a "closed system" in terms of [3, 4]. Also, NHI is considered as single instant strike, which touches some finite set of places (areas), destroying all material objects located there.

Section 2 contains brief consideration of the previous results on IS resilience. Section 3 is dedicated to generalization of the known criterion of IS resilience on the case, when resource base of IS contains not only primary (terminal) resources but also resources, produced by IS since the start of its operation upon the initial state of RB until the moment of NHI. Section 4 is dedicated to the multigrammatical representation of local sociotechnological systems (STS) and formulation of criterion of their resilience, while Section 5—to the general case of DSTS. The current global reality makes extremely important development of a toolkit for the assessment of resilience of multiple interconnected DSTS, producing and delivering to the consumers specific types of resources (electrical energy, fuel, water, etc.). Such DSTS are addressed usually as critical infrastructures (CI), following their critically important mission for whole countries and world regions [5–11]. The basic approach of the proposed criteria application to CI is considered in Section 6. After NHI, some subsystems of vulnerable DSTS may stay in the active state ready for operation. So, the reverse problem, concerning such subsystems detection, is studied in Section 7. Possible directions of development of the proposed approach is announced in the conclusion.

2. Assessment of resilience of industrial systems

Let us remind that *multiset* is a set of multiobjects (MO) that is written as

$$v = \{n_1 \cdot a_1, \ldots, n_m \cdot a_m\}, \tag{1}$$

where v is the name of multiset and $n_1 \cdot a_1, \ldots, n_m \cdot a_m$ are the multiobjects, entering this MS; the integer number n_i, $i = 1, \ldots, m$ is called multiplicity of object a_i, which means, that v contains n_1 identical objects $a_1, \ldots, n_m$ identical objects a_m, and for $i \neq j$ $a_i \neq a_j$. Set

$$\beta(v) = \{a_1, \ldots, a_m\} \tag{2}$$

is called *basis of multiset* v. Both object a and multiobject $n \cdot a$ are said to be entering v that is written without ambiguity as $a \in v$ and $n \cdot a \in v$. From the substantial point of view, object a and multiobject $1 \cdot a$ are equivalent. In general case, multiplicities may be not only positive integers but also positive rational numbers [12, 13]. Empty set and empty multiset are denoted $\{\varnothing\}$. Further in this chapter objects will be denoted also by symbol b with indices, as well as by strings of italic symbols.

The main multiset-based tool, which would be used below, is *unitary multiset grammars* (UMG) (we shall use also "multigrammar" as synonym of "multiset grammar") [12, 13].

UMG is a couple $S = \langle a_0, R \rangle$, where a_0 is called *title object* and R is called *scheme*, being the set of *unitary rules* (UR), having the form

$$a \to n_1 \cdot a_1, \ldots, n_m \cdot a_m, \tag{3}$$

where object a is called *head* and list $n_1 \cdot a_1, \ldots, n_m \cdot a_m$—*body* of this UR. List is interpreted as multiset, i.e., $\{n_1 \cdot a_1, \ldots, n_m \cdot a_m\}$.

The so-called structural and technological interpretations of unitary rules are used in the IS resilience assessment [2].

According to *structural interpretation*, (3) means that some material (physical) object (unit of resource) a consists of n_1 objects $a_1, \ldots, n_m$ objects a_m (to distinguish mathematical notion "object" from the physical one, we shall use below notion "object/resource," abbreviated OR).

Technological interpretation is an extension of the structural one, so that the body of UR

$$a \to n_1 \cdot a_1, \ldots, n_m \cdot a_m, n'_1 \cdot a'_1, \ldots, n'_k \cdot a'_k \tag{4}$$

contains structural components (usually spare parts of the produced device), which are MO $n_1 \cdot a_1, \ldots, n_m \cdot a_m$, as well as resources, which are necessary for assembling (manufacturing) a from these components and are represented by MO $n'_1 \cdot a'_1, \ldots, n'_k \cdot a'_k$.

Example 1. Let $S = \langle aircraft, R \rangle$, where R contains the following two unitary rules:

$$aircraft \to 1 \cdot fuselage, 2 \cdot wing,$$
$$wing \to 1 \cdot frame, 1 \cdot engine, 4 \cdot wheel.$$

According to structural interpretation, this means that aircraft consists of fuselage and two wings. Any of the wings consists, in turn, of frame and engine, as well as four wheels, all connected to the wing frame. Let now $S' = \langle aircraft, R' \rangle$, where R' contains the following two URs:

$$aircraft \to 1 \cdot fuselage, 2 \cdot wing, 10 \cdot kW, 160 \cdot mbt\text{-}asm\text{-}aircraft, 150000 \cdot USD$$

$$wing \to 1 \cdot frame, 1 \cdot engine, 4 \cdot wheel, 12 \cdot kW, 240 \cdot mnt - asm - wing, 400000 \cdot usd.$$

According to the technological interpretation of UR, this means that assembling aircraft from a fuselage and two wings requires 160 min of operation of the aircraft's assembling line, 10 kW of electrical energy, as well as 150,000 dollars being the total cost of this work. Similarly, assembling one wing from the frame, engine, and four wheels requires 12 kW, 240 min of operation of the wing's assembling line, and 400,000 dollars. ∎

As seen, UMG provide easy and natural decomposition of complicated technological systems (devices) until elementary (non-decomposed) objects and resources, used in the manufacturing process.

A set of objects, having placed in the UMG S, is denoted A_S, while a set of so-called *terminal* objects, having placed only in bodies of UR, is denoted $\overline{A}_S$. Evidently, $\overline{A}_S \subset A_S$. Objects, entering set $A_S - \overline{A}_S$, are called *non-terminal*. Similarly, corresponding OR also may be terminal and non-terminal.

Mathematical semantics of unitary multiset grammars is defined in such a way that UMG $S = \langle a_0, R \rangle$ is applied for generation of the set of multisets (SMS) V_S according to the following relations:

$$V_{(0)} = \{\{1 \cdot a_0\}\}, \tag{5}$$

$$V_{(i+1)} = V_{(i)} \cup \left(\bigcup_{v \in V_{(i)}} \bigcup_{r \in R} \{\pi(v, r)_0\} \right), \tag{6}$$

$$\pi(v, \langle a \to n_1 \cdot a_1, \dots, n_m \cdot a_m \rangle) = \begin{cases} v - \{n \cdot a\} + n * \{n_1 \cdot a_1, \dots, n_m \cdot a_m\}, \\ \qquad\qquad\qquad\qquad if\ n \cdot a \in v \\ \{\varnothing\}\ otherwise \end{cases} \tag{7}$$

$$V_S = V_{(\infty)}, \tag{8}$$

where UR $a \to n_1 \cdot a_1, \dots, n_m \cdot a_m$ for unambiguity is represented in the angle brackets, and $+$, $-$, $*$ are symbols of operations on multisets (addition, subtraction of multisets, and multiplication of constant on multiset, respectively) [1, 2, 12, 13].

As seen from (5) to (8), new multisets are generated by applying all unitary rules $r \in R$ to SMS $V_{(i)}$, created on previous i steps. Every such UR $a \to n_1 \cdot a_1, \dots, n_m \cdot a_m$ is applied to MS $v \in V_{(i)}$ by a special function π. If v contains MO $n \cdot a$, it is replaced by MS $n * \{n_1 \cdot a_1, \dots, n_m \cdot a_m\}$ and by semantics of MS addition, and after that multiplicities of the identical objects are summarized; otherwise, the result of π application is an empty set.

Described generation process is in general case infinite, and SMS V_S, defined by UMG S, is its fixed point $V_{(\infty)}$.

Terminal multiset (TMS) $v \in V_S$ contains only terminal objects, i.e.,

$$\beta(v) \subseteq \overline{A}_S, \tag{9}$$

and the set of terminal multisets (STMS) is denoted $\overline{V}_S$.

Further in this chapter if it will not be said the contrary, we shall consider only *finitary* UMG, which define finite STMS. UMG S is finitary, if these exists i such, that $V_{(i)} = V_{(i+1)}$, and if so, $V_{(i)} = V_S$. The problem of recognition of UMG finitarity is algorithmically decidable [12, 13].

Example 2. As may be seen, UMG S and S' from the previous example are finitary, and, according to (5)–(8),

$$\overline{V}_S = \{\{1 \cdot fuselage, 2 \cdot frame, 2 \cdot engine, 8 \cdot wheel\}\},$$
$$\overline{V}_{S'} = \{\{1 \cdot fuselage, 2 \cdot frame, 2 \cdot engine, 8 \cdot wheel, 34 \cdot KW, 160 \cdot mnt - asm - aircraft, 480 \cdot mnt - asm - wing, 950000 \cdot usd\}\}. \blacksquare$$

Returning to the considered application of UMG, i.e., description and assessment of industrial systems, we may represent *technological base* (TB) of IS (set of its producing devices) as scheme R of UMG:

$$S = < tb, R >, \tag{10}$$

where tb is the title object and R is the set of unitary rules in the technological interpretation.

Order, completed by IS with TB S, may be represented by MS

$$q = \{n_1 \cdot b_1, ..., n_l \cdot b_l\}, \tag{11}$$

which means goal of this order is to obtain n_1 OR b_1, ..., n_l OR b_l. The set of possible variants of resource amounts, necessary for order q completion, is nothing, but set of TMS, generated by UMG:

$$S_q = < tbq, R \cup \{ < tbq \to n_1 \cdot b_1, ..., n_l \cdot b_l > \} >, \tag{12}$$

i.e., STMS $\overline{V}_{S_q}$ (for short we shall use $\overline{V}_q$ instead of it).

In general case $|\overline{V}_q| > 1$ because of the possibility of multiple ways of order completion, which usually is a consequence of some redundancy of TB (however, such redundancy is the background of IS resilience, as it will be shown below).

Resource base of IS may be represented by MS $v = \{n_1 \cdot a_1, ..., n_k \cdot a_k\}$ in such a way that n_1 OR a_1, ..., n_k OR a_k are available to technological base R while orders completion.

Described representation of TB and RB makes it quite simple to formulate *criterion of possibility of order completion*.

Statement 1. Order q to IS with technological base R and resource base v may be completed, if

$$(\exists \overline{v} \in \overline{V}_q) \overline{v} \subseteq v. \blacksquare \tag{13}$$

Such RB v is called *sufficient* for order q completion by IS.

For further consideration of resilience/vulnerability issues, it is useful to unify TB and RB by including to the bodies of UR_S in the technological interpretation of one additional multiobject $1 \cdot r$, where r is the name of the device, which provides manufacturing (assembling) OR, defined by the head of UR. By this, the presence of multiobject $n \cdot r$ in the resource base is equivalent to the possibility of n manufacturing cycles, executed by device r while current order completion.

Described techniques integrate TB and RB in the integral resource base, which does not contradict to the reality, because multiobjects like $n \cdot r$ represent, in fact, technological (active) resources of IS, along with passive resources, consumed by devices.

Note that there may be one and the same object r in different UR bodies that reflects the capability of device r to produce one and the same OR by various ways or even to produce various OR. Moreover, in general case, there may be not only multiobjects like $1 \cdot r$ in the UR bodies but also $l \cdot r$, where $l > 1$, that, in fact, allows to represent the duration of manufacturing cycle, providing creation of one unit of OR a, represented by the head of the UR. This technique is simply implemented by the use of so-called composite objects, or *composites*, like t-r, where "-" is the divider, r is the unique identifier of manufacturing device, and t is the time unit (second, minute, etc.), so $l{\cdot}t$-r means that there are sufficient l time units of work of device r to produce one unit of OR a, represented by the head of the UR. Both r and t are strings in some basic alphabet, and t does not contain divider "-".

If resource base of IS contains multiobjects like $L{\cdot}t$-r, that means there are L units of time of work of device r available while current order completion.

Speaking about the use of time in UR, we must take into account that time is not fully an additive resource; it is additive regarding only separate device. If to consider the whole IS, then due to parallel operation of various devices, time, spent for order completion, may be less than in the case of their sequential application. Precise modeling of IS operation is possible on the basis of the so-called temporal multiset grammars, introduced in [2], which will be considered thoroughly in the separate publications.

Example 3. Let $S' = <aircraft, R>$ be as in Example 1, order $q = \{r \cdot aircraft\}$, and IS resource base is

$$v = \{6 \cdot fuselage, 10 \cdot frame, 12 \cdot engine, 40 \cdot wheel, 250 \cdot kW,$$
$$800 \cdot mnt - asm - aircraft, 2600 \cdot mnt - asm - wing,$$
$$1000000 \cdot usd\}\}.$$

As seen, order q may be completed with technological base R' and resource base v, which is sufficient for this order completion.

However, if

$$v = \{6 \cdot fuselage, 10 \cdot frame, 3 \cdot engine, 12 \cdot wheel, 250 \cdot kW,$$
$$800 \cdot mnt - asm - aircraft, 2600 \cdot mnt - asm - wing,$$
$$1000000 \cdot usd\}\},$$

then order q cannot be completed, and RB v is not sufficient, because there is lack of five engines for manufacturing four aircrafts. ∎

Let us consider now IS, affected by natural hazard *impact*, which may be represented by multiset Δv, defining amounts of resources, eliminated by NHI from IS resource base, so the last becomes $v - \Delta v$.

Concerning passive resources, such representation is quite evident: if NHI destroys n' OR a from n, which had placed in RB before the impact, then the remained amount of these OR will be $n - n'$ (if $n < n'$ or $n = n'$, all such OR will be eliminated from RB), so respective multiobject, entering $v - \Delta v$, will be $(n - n') \cdot a$. In the case of active resources, $n' \cdot t$-$r \in \Delta v$ means that n' time units of operation of ith devise r would be lost, so this device may not execute all work, which it would do while order completion, and this obstacle may be the reason for IS vulnerability. So, similar to passive resources, the result of NHI regarding active resource would be $(n - n') \cdot t$-r. If $n' = \infty$, the result of NHI would be elimination of MO $n \cdot t$-r from R; when implemented, ∞ may be replaced by some very large number $\boldsymbol{N}$, which is greater than any possible multiplicity, ever used in TB and RB representations.

Let IS has TB R and RB v, which is sufficient for order q completion.

Statement 2. IS, completing order q, is resilient to NHI Δv, if reduced RB $v - \Delta v$ is sufficient for this order completion. Otherwise, this IS is vulnerable to this NHI.∎

This criterion is basic for *distributed industrial systems* (DIS), in which facilities are located at different places (areas) and some of them may be affected by NHI. Every such impact may destroy some of the aforementioned facilities, eliminating some local parts of TB and RB, thus reducing its capabilities for order completion.

To represent DIS, OR, having placed in unitary rules and multisets, are extended by geospatial information in such a way that a/z, where "/" is the divider, means that OR a is located at place z. Both a and z are the strings in some basic alphabet, excepting "/", and z is the name of location.

We use names of locations instead of their usual coordinate representations (CR), supposing that there is a separate key-addressed database, containing couples $<z, X>$, where key z is the name of place and X is its CR in any possible form (points of perimeter, center of the circle along with its radius, etc.), most convenient for concrete location. This database provides the simplest implementation of intersection of two locations, which is the basic operation in the algorithmics of assessment of resilience of any distributed systems.

Since the described extension, all UR have the form

$$a/z \rightarrow n_1 \cdot a_1/z_1, \dots, n_m \cdot a_m/z_m, \tag{14}$$

that means OR a may be produced at location z, if there are n_1 OR a_1 at location $z_1, \dots, n_m$ OR a_m at location z_m. As seen, $a/z, a_1/z_1, \dots, a_m/z_m$ are also composites.

Representation of time resource is just the same: if MO $n \cdot t\text{-}r/z$ enters UR body, that means follows: to produce OR a, located at place z, device r, located at place z, would operate for n time units.

Similarly, resource base would be

$$v = \{n_1 \cdot a_1/z_1, \dots, n_k \cdot a_k/z_k\}, \tag{15}$$

as well as order

$$q = \{n_1 \cdot b_1/z_1, \dots, n_l \cdot b_l/z_l\}. \tag{16}$$

The new moment is the representation of NHI by set z of affected by it locations (in general case, areas):

$$Z = \{z_1, \dots, z_p\}. \tag{17}$$

For simplicity we shall limit a variety of locations having placed in (14)–(17) by points, while in (17) every z_i may be an area of any form. Also, we shall use denotation $\overline{Z}$ for the set of points entering Z (it is join of sets $z_1, \dots, z_p$).

To formulate the criterion of resilience of DIS, we shall use relation $z \in \overline{Z}$ that means point z enters set $\overline{Z}$.

Let us define

$$\Delta v(Z) = \{n \cdot a/z \mid n \cdot a/z \in v \,\&\, z \in \overline{Z}\}, \tag{18}$$

i.e., multiset of OR, affected by NHI z, because they are located at the affected points. Thus, all these OR must be eliminated from the resource base, being destroyed by the impact.

Let DIS has TB R and RB v, which is sufficient for order q completion.

Statement 3. DIS, completing order q, is resilient to NHI z, if reduced by it RB, $v - \Delta v(Z)$ is sufficient for this order completion. Otherwise, this DIS is vulnerable to this NHI. ∎

Concerning affected active resources, it is reasonable to underline that NHI may destroy them up to unrecoverable state (this may be represented by inclusion to Δv MO $\boldsymbol{N} \cdot t\text{-}r/z$) or, in the better case, transfer them to the unoperational, but reparable, state, that may be represented by inclusion to Δv MO $n' \cdot t\text{-}r/z$, where n' is less than multiplicity n of OR $t\text{-}r/z \in v$.

By this we finish a short survey of known results on resilience of industrial systems. Before we move to sociotechnological systems, let us generalize the introduced criteria.

3. Generalized criterion of resilience of industrial systems

As seen, both introduced criteria of IS resilience operate only terminal resources, which are used by IS for production of amounts of OR, being the goal of order. By this, they trivially repeat criterion of order completeness (12) with the only replacement of the IS initial resource base by RB, reduced by NHI.

However, if to take into account that there may be some non-terminal OR, already manufactured by IS during time interval between the start of order completion and moment of NHI, it would be sensible to consider these OR during recognition of IS resilience, or, in the other words, to generalize notion of resource base, including to RB not only terminal, but also non-terminal OR.

But, evidently, this generalization makes the introduced criteria non-applicable. Let us propose correct criterion for the case of RB, containing not only terminal but also non-terminal OR.

For this purpose we propose here so-called unitary multiset grammars with reduced generation (UMG RG).

UMG RG is triple $S(v_0) = < a_0, R, v_0 >$, where a_0 and R are, as higher, the title object and scheme, respectively, and v_0 is the multiset, which may contain non-terminal multiobjects, used for elimination of the number of generation steps. So, this version of UMG has specific semantics, which fully corresponds to the sense of order completion by the use of aforementioned RB.

The main difference of UMG RG from UMG is that they generate not multisets, but pairs $< v, v' >$, where v is the MS, created while previous generations steps, and v' is the rest of RB, which may be used at the next such step.

If there is a non-terminal multiobject $n \cdot a$ in multiset v, and at the same times MS v' includes MO $n' \cdot a$, then following action depends on the relation between n and n'. If $n > n'$, then there are already n' OR a in the resource base, and there is no any need to manufacture them—it is sufficient to manufacture $n - n'$ OR a and eliminate n' OR a from v' to represent that they are already used while order completion. If $n' \leq n$, then all necessary OR a are already in the RB, and there is no need in generation here at all; it is sufficient to subtract $\{n \cdot a\}$, so there would be MO $(n - n') \cdot a$ in the RB after this action, because n OR a are spent (if $n' = n$, there would be no OR a in the RB).

Formal definition of semantics of UMG RG $S(v_0) = < a_0, R, v_0 >$, i.e., a set of relations, describing generation of a set $\overline{V}_{S(v_0)}$ of pairs $< v, v' >$, is as follows:

$$\overline{V}_{(0)} = \{ < \{1 \cdot a_0\}, v_0 > \}, \tag{19}$$

$$V_{(i+1)} = V_{(i)} \cup \left(\bigcup_{<v, v'> \in V_{(i)}} \bigcup_{r \in R} \{\varphi(v, v', r)\} \right), \tag{20}$$

$$\varphi(v, v', <a \to n_1 \cdot a_1, ..., n_m \cdot a_m>) = \\ = \begin{cases} <v - \{n \cdot a\}, v' - \{n \cdot a\}>, \textit{if } n \cdot a \in v \,\&\, n' \cdot a \in v' \,\&\, n' \geq n \\ <v - \{n \cdot a\} + (n - n') * \{n_1 \cdot a_1, ..., n_m \cdot a_m\}, v' - \{n' \cdot a\}>, \\ \qquad \textit{if } n \cdot a \in v \,\&\, n' \cdot a \in v' \,\&\, n' \neq 0 \,\&\, n' < n \vee \\ \qquad n \cdot a \in v \,\&\, n' = 0 \\ \{\varnothing\} \textit{ otherwise,} \end{cases} \tag{21}$$

$$\overline{V}_{S(v_0)} = V_{(\infty)}. \tag{22}$$

This definition fully corresponds to the previous verbal description and is similar to (5)–(8). The mission of function φ, defined by (21), is the same as the mission of function π, defined by (7). Some comments would be done to its second alternative, namely, the case where multiset v' does not contain OR a at all (or, just the same, multiplicity n' of multiobject $n' \cdot a$, entering v', is zero); this is equivalent to a more general case, when $n' \cdot a \in v'$ and non-zero multiplicity n' is less than n. As seen, the result of subtraction of the empty multiset $\{n' \cdot a\}$, where $n' = 0$, from multiset v', is unchanged v', and this branch of (21) is just the same, as the first alternative of (7).

The introduced UMG RG provide formulation of the generalized criterion of IS resilience.

Let $q = \{n_1 \cdot b_1, ..., n_l \cdot b_l\}$ be order, R—technological base of the industrial system, and v—its resource base, such that

$$\beta(v) \subseteq A_s. \tag{23}$$

(That is, it contains not only terminal but also non-terminal OR). Consider UMG RG $S_q(v) = <tbq, R_q, v>$, where

$$R_q = R \cup \{<tbq \to n_1 \cdot b_1, ..., n_l \cdot b_l>\}. \tag{24}$$

(Here, UR is written in the angle brackets for unambiguity.)

Statement 4. Order q to IS with technological base R and resource base v may be completed, if

$$\left(\exists <\overline{v}, \overline{v}'> \in \overline{V}_{S_q(v)} \right) \overline{v} \subseteq \overline{v}'. \blacksquare \tag{25}$$

As seen, if RB does not contain non-terminal OR, (25) and (13) are equivalent. As higher, RB, relevant to criterion 4, is called sufficient for order q completion by IS. Evidently, $\overline{v}' - \overline{v}$ is RB, remained after completion of order q.

Example 4. Let $S' = <aircraft, R'>$ be as in Example 1, order $q = \{4 \cdot aircraft\}$, and resource base of the industrial system is $v = \{6 \cdot fuselage, 12 \cdot wing, 300 \cdot kW, 800 \cdot mnt - asm - aircraft, 1100000 \cdot usd\}$.

As seen,

$$S_q(v) = <tbq, R_q, v>,$$

where

$$R_q = R' \cup \{<tbq \to 4 \cdot aircraft>\},$$

and resource base v contains non-terminal multiobject $12 \cdot wing$, which means 12 wings are already manufactured and ready to be mounted to fuselages in order to make aircrafts.

According to (19)–(21), $\overline{V}_{S_q}(v) = \{<\overline{v}, \overline{v}'>\}$, where

$$\overline{v} = \{4 \cdot fuselage, 40 \cdot kW, 640 \cdot mnt - asm - aircraft, 600000 \cdot usd\},$$
$$\overline{v}' = \{6 \cdot fuselage, 4 \cdot wing, 300 \cdot kW, 800 \cdot mnt - asm - aircraft, 1100000 \cdot usd\}.$$

Because $\overline{v} \subset \overline{v}'$, order q may be completed by IS due to the number of already manufactured wings, which is greater than the required for manufacturing of four aircrafts. ∎

Let resource base v be sufficient for order q completion by IS with technological base R, and Δv is NHI on this system.

Statement 5. IS, completing order q, is resilient to NHI Δv, if

$$\left(\exists <\overline{v}, \overline{v}'> \in \overline{V}_{S_q(v-\Delta v)}\right) \overline{v} \subseteq \overline{v}'. \tag{26}$$

Otherwise, this IS is vulnerable to this NHI. ∎

This criterion may be generalized on distributed IS in the same manner, as it was done in [2] and described in the previous section.

Let RB v be sufficient for order q completion by DIS with TB R, and Z is NHI on this system.

Statement 6. DIS, completing order q, is resilient to NHI Z, if

$$\left(\exists <\overline{v}, \overline{v}'> \in \overline{V}_{S_q(v-\Delta v(Z))}\right) \overline{v} \subseteq \overline{v}'. \tag{27}$$

Otherwise, this DIS is vulnerable to this NHI. ∎

It is clear that DIS RB contains both terminal and non-terminal objects, located at various places.

Example 5. Let DIS be represented by UMG $S = <aircraft/z_1, R>$, where R contains the following unitary rules:

$$aircraft/z_1 \to 1 \cdot fuselage/z_1, 2 \cdot wing/z_1, 10 \cdot kW/z_1,$$

$$wing/z_2 \to 1 \cdot frame/z_2, 1 \cdot engine/z_2, 4 \cdot wheel/z_2, 12 \cdot kW/z_2,$$

$$wing/z_1 \to 1 \cdot wing/z_2, 1000 \cdot l - petrol/z_2, 1 \cdot vel/z_2,$$

$$l - petrol/z_2 \to 1 \cdot l - petrol/z_3, 1 \cdot link/z_3, 1 \cdot pump/z_3, 0.001 \cdot kW/z_3.$$

Here, the first two UR are slightly modified versions of technological base, described by UMG S; the only difference is that all OR are composites, including names of locations. As seen, aircrafts are assembled at place z_1, while wings—at place z_2. The third UR defines that to remove one wing to z_1 from z_2, some transportation vehicle *vel* must be used, and also 1000 liters of petrol for its refueling, necessary for wing removal to z_1 and return to z_2. At last, the fourth UR defines that to transport petrol from place z_3, where it is stored, there is used pipeline fragment, consisting of link and pump, the latter consuming 0.001 kW of electrical energy to remove 1 liter of petrol from z_3 to z_2. Assembling one aircraft and one wing is also an energy-consuming operation that is represented by multiobjects $10 \cdot kW/z_1$ and $12 \cdot kW/z_2$, having placed in the bodies of the first and the second UR, respectively.

Let order $q = \{2 \cdot aircraft/z_1\}$, and resource base of DIS is

$$v = \{3 \cdot fuselage/z_1, 2 \cdot wing/z_1, 4 \cdot frame/z_2, 5 \cdot engine/z_2, 8 \cdot wheel/z_2,\\ 500 \cdot l - petrol/z_2, 1 \cdot wing/z_2, 100 \cdot vel/z_2, 10000 \cdot l - petrol/z_3,\\ 100000 \cdot link/z_3, 100000 \cdot pump/z_3, 50 \cdot kW/z_1, 150 \cdot kW/z_2, 200 \cdot kW/z_3\}.$$

This means that at location z_1 there are three fuselages, ready to be mounted with wings, but there are only two wings at this location, so two more wings, necessary for the production of two aircrafts, must be removed to z_1 from z_2. However, there are two ready wings at z_2; there is only one such wing, as well as four frames, five engines, and eight wheels, which may be used for manufacturing of some additional number of wings. Moreover, there is transportation vehicle *vel* at z_2, which may remove ready wings from z_2 to z_1, and also 500 liters of petrol for refueling this vehicle. But, as seen, this amount of petrol is not sufficient for the relocation of two wings from z_2 to z_1. So, the required amount of petrol, i.e., 500 liters, must be removed by the pipeline to z_2 from z_3, where petrol storage is located, containing at the current moment 10,000 liters of this fuel. Multiobjects $100000 \cdot link/z_3$ and $100000 \cdot pump/z_3$ represent the technical state of petrol pipeline link and pump, which is sufficient for execution of 100,000 working cycles, each providing removal of 1 liter of petrol from z_3 to z_2. Similarly, MO $100 \cdot vel/z_2$ represents the technical state of the vehicle, which is able to make 100 transportation cycles from z_2 to z_1 and back without repair.

This verbal description makes it evident, how in fact order completion may be planned by UMG RG application. Let us consider how it is really done according to (19)–(21):

$$\begin{aligned}\overline{V}_{S_q(v)} &= \{<\{2 \cdot aircraft/z_1\}, v>\}\\ &= \{<\{2 \cdot fuselage/z_1, 4 \cdot wing/z_1, 20 \cdot kW/z_1\}, v>\}\\ &= \{<\{2 \cdot fuselage/z_1, 1 \cdot wing/z_1, 20 \cdot kW/z_1\}, v - \{3 \cdot wing/z_1\}>\}\\ &= \{<\{2 \cdot fuselage/z_1, 1 \cdot wing/z_2, 1000 \cdot l - petrol/z_2, 1 \cdot vel/z_2\},\\ &\quad v - \{3 \cdot wing/z_1\}>\}\\ &= \{<\{2 \cdot fuselage/z_1, 20 \cdot kW/z_1, 1 \cdot frame/z_2, 1 \cdot engine/z_2,\\ &\quad 4 \cdot wheel/z_2, 12 \cdot kW/z_2, 1000 \cdot l - petrol/z_2, 1 \cdot vel/z_2\},\\ &\quad v - \{3 \cdot wing/z_1\}>\}\\ &= \{<\{2 \cdot fuselage/z_1, 20 \cdot kW/z_1, 1 \cdot frame/z_2, 1 \cdot engine/z_2,\\ &\quad 4 \cdot wheel/z_2, 12 \cdot kW/z_2, 500 \cdot l - petrol/z_3, 500 \cdot link/z_3,\\ &\quad 500 \cdot pump/z_3, 1 \cdot kW/z_3\}, v - \{3 \cdot wing/z_1, 500 \cdot l/petrol/z_2\}>\}.\end{aligned}$$

Because

$$\{2 \cdot fuselage/z_1, 20 \cdot kW/z_1, 1 \cdot frame/z_2, 1 \cdot engine/z_2, 4 \cdot wheel/z_2, 12 \cdot kW/z_2,\\ 500 \cdot l - petrol/z_3, 500 \cdot link/z_3, 500 \cdot pump/z_3, 1 \cdot kW/z_3\}\\ \subset \{3 \cdot fuselage/z_1, 50 \cdot kW/z_1, 4 \cdot frame/z_2, 5 \cdot engine/z_2, 8 \cdot wheel/z_2, 150 \cdot kW/z_2,\\ 9500 \cdot l - petrol/z_3, 100000 \cdot link/z_3, 100000 \cdot pump/z_3, 200 \cdot kW/z_3\},$$

order q is completed by DIS with technological base R and resource base v; the latter is sufficient for this order completion.

If this DIS is affected by NHI $Z = \{z_3\}$, then

$$v - \Delta v(Z)$$
$$= \{3 \cdot fuselage/z_1, 50 \cdot kW/z_1, 4 \cdot frame/z_2, 5 \cdot engine/z_2, 8 \cdot wheel/z_2, 150 \cdot kW/z_2\},$$

and, as may be seen without generation, DIS is vulnerable to this NHI while order q completion. This means that destruction of petrol storage, necessary for refueling of transportation vehicle, which, in turn, is necessary for assembled wing removal to the place of the final assembling of aircraft, makes impossible completion of the order, i.e., manufacturing of two aircrafts. ∎

This example is a primary illustration of multigrammatical representation and modeling of chain effects, occurring in distributed industrial systems as a result of NHI.

Now, we have the widest criterion of resilience of distributed industrial system, completing single order, to natural hazard impact. The thing is that in general case there is a flow of such orders, generated by human segment of distributed sociotechnological system.

It is evident that DSTS would be considered resilient to NHI, if the aforementioned flow would be completed by the producing (industrial) segment of this system with resource base, reduced by this NHI.

Before we move to further discourse, let us clarify interconnections between basic notions, which will be used below.

As it was said in Section 1, any sociotechnological system includes anthropogenic and technogenic parts—humans and used by them technical devices (systems). We call them human and technological segments (STS HS and STS TS, respectively). From the order side, STS include producing (industrial) and consuming segments (STS IS and STS CS, respectively), both consisting of humans and devices. So, there are humans and devices that participate in the manufacturing process and produce resources, which, in turn, are necessary for their own existence and operation, as well as for all other humans and devices, not participating in the manufacturing process and thus entering only consuming segment.

The described decomposition of STS will be exclusively important while studying issues, concerning consequences of total robotization of the industry, logistics, and various services that lead to massive unemployment, and the main problem to solve this will be to assess, whether global technosphere and natural resource base would be able to provide sufficient quality of life of unemployed people, as well as other groups of population, being out of the producing segment.

However, here we shall use the described decomposition of STS for continuation of development of criterial base of their resilience. To consider distributed STS at all, we shall begin from the simplest case of local STS.

4. Multigrammatical representation of local sociotechnological systems and criterion of their resilience

Let us consider first the local case, where all humans live and work at a single place. If so, decomposition of the human socium, having placed at this location, may begin from the unitary rule

$$socium \to 1 \cdot structures, 1 \cdot persons, \tag{28}$$

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where non-terminal object *structures* is a start point for all business and state structures, while non-terminal object *persons* is similarly a start point for individuals, not entering any of the aforementioned structures.

Object *structures* is the head of the single unitary rule

$$structures \to m_1 \cdot str_1, \dots, m_k \cdot str_k, \tag{29}$$

that means there are m_1 structures (of type) $str_1, \dots, m_k$ structures (of type) str_k; if any $str\ i$ of $str_1, \dots, str_k$ is unique, then $m_i = 1$.

Any structure may be decomposed to substructures, individual positions, and multiple access technological systems (MATS), used by personnel of this structure and its substructures. Relevant unitary rules would have the following form:

$$str \to n_1 \cdot pstn_1, n_p \cdot pstn_p, m_1 \cdot str_1, \dots, m_s \cdot str_s, \\ l_1 \cdot tech_1, \dots, l_t \cdot tech_t, \tag{30}$$

which means there are $n_1, \dots, n_p$ positions $pstn_1, \dots, pstn_p$ and $m_1, \dots, m_s$ substructures $str_1, \dots, str_s$, as well as $l_1, \dots, l_t$ MATS $tech_1, \dots, tech_t$ (all, respectively). Every substructure is decomposed in the same way recursively until substructures, which multigrammatical representation is like

$$str \to n_1 \cdot pstn_1, \dots, n_p \cdot pstn_p, l_1 \cdot tech_1, \dots, l_t \cdot tech_t \tag{31}$$

or

$$str \to n_1 \cdot pstn_1, \dots, n_p \cdot pstn_p, \tag{32}$$

i.e., they have no any substructures, but in general case may have MATS, providing their operation.

MATS, in turn, operate due to some attached (affiliated) personnel, which mission is to maintain technological system in the active state and apply it according to its destination. Also, MATS may consist of some subsystems, each with its own personnel, and its multigrammatical representation in general case may be as follows:

$$tech \to n_1 \cdot pstn_1, \dots, n_p \cdot pstn_p, l_1 \cdot tech_1, \dots, l_s \cdot tech_s, \tag{33}$$

$$tech \to l_1 \cdot tech_1, \dots, l_s \cdot tech_s, \tag{34}$$

the latter case corresponding to the fully robotized (unmanned) system. Every $tech_i$, in turn, may be decomposed recursively until terminal objects, which names have been placed only in the bodies of unitary rules.

Concerning the second multiobject from the body of UR (28), it may be approved that all set of individuals of the considered STS may be divided to subsets (classes), each joining person with the similar sets of personal technical devices and consumed resources. This may be represented by unitary rule

$$person \to n_1 \cdot person_1, \dots, n_l \cdot person_l, \tag{35}$$

and

$$person_i \to k_1^i \cdot res_1^i, \dots, k_{r_i}^i \cdot res_{r_i}^i, m_1^i \cdot dev_1^i, \dots, m_{l_i}^i \cdot dev_{l_i}^i, \tag{36}$$

that means each person, belonging to the ith class, during the predefined period of time consumes $k_1^i, \ldots, k_r^i$ units of resources $res_1^i, \ldots, res_{r_i}^i$ and is using $m_1^i, \ldots, m_{l_i}^i$ devices $dev_1^i, \ldots, dev_{l_i}^i$, respectively.

From here, it is evident that the same assignment of the consumed resources and used devices must be done regarding all positions, having placed in structures, described by UR (30)–(32). Relevant unitary rules are similar to (36):

$$pstn \to k_1 \cdot res_1, \ldots, k_r \cdot res_r, m_1 \cdot dev_1, \ldots, m_l \cdot dev_l, \tag{37}$$

or

$$pstn \to k_1 \cdot res_1, \ldots, k_r \cdot res_r \tag{38}$$

(the latter retains possibility of "deviceless" positions). All devices, represented by multiobjects, having placed in the body of UR (37), are in private use of a person; holding this position, for all time this person is assigned to this position (i.e., these devices are not of multiple access and are not the property of the person).

Let us take into account that every MATS, as well as every device, used by the person also consumes resources, necessary for its operation. To represent this obstacle, it is sufficient to use URs like

$$tech \to k_1 \cdot res_1, \ldots, k_t \cdot res_t, \tag{39}$$

regarding "terminal" MATS and subsystems of "non-terminal" MATS, which are not decomposed during STS description. Similar URs define resources, consumed by devices:

$$dev \to k_1 \cdot res_1, \ldots, k_d \cdot res_d. \tag{40}$$

Let us denote S_H unitary multiset grammar, which title object is *socium*, and scheme R_H contains all unitary rules, representing considered human segment of STS. By this it is evident that total amount of resources, consumed by this segment during predefined time interval, is $\overline{V}_{S_H}$ and, namely, this amount must be produced by the STS industrial segment for STS operation. Since then it is obvious that interconnection and intersection between human and technological segments are formed by URs, defining STS IS:

$$res \to k_1 \cdot res_1, \ldots, k_m \cdot res_m, \tag{41}$$

which means STS IS manufactures one unit of resource res_i, consuming during production cycle $k_1, \ldots, k_m$ units of resources $res_1, \ldots, res_m$, respectively.

As may be seen, industrial segments of considered STS do not produce nothing but OR, necessary for the existence of humans of this STS, and structures, having placed in (29)–(32), are also producing nothing. By this reason any such STS is closed not only in the sense it has no contact with external systems, which may supply it by resources, but also in the sense that it does not produce any OR for mentioned external systems, i.e., does not complete any orders of such systems.

However, it is not difficult to represent STS, which do complete orders of external systems: it is sufficient to join to the body of UR (28) multiobject $1 \cdot order$ and to include to the set R_H of unitary rules, representing human segment of STS, UR

$$order \to n_1' \cdot or_1, \ldots, n_m' \cdot or_m, \tag{42}$$

where MS $q = \{n'_1 \cdot or_1, ..., n'_m \cdot or_m\}$ is total external order (TEO), which would be completed by STS during the considered time period. Of course, set R would contain unitary rules, representing STS IS capabilities to complete TEO.

Before we shall formulate following statements, let us clarify one important issue, concerning representation of resources, consumed by producing MATS and devices, entering industrial segment of STS. Namely, if MATS/device enter STS IS, it seems that its resource consumption is accounted twice—in R_H as well as in R_I.

However, there is no any duplication.

R_H contains representation of resources, contained by producing MATS/device *during all considered time period independently of amounts of produced by OR*. Most often it may be electrical power, consumed for MATS/device maintenance in the state, ready for operation, which is represented by MO $n \cdot kW$ (number of consumed kW). In general case, this resource is "readiness" of MATS/device to work, represented by MO 1·*ready-tech* or 1·*ready-dev*. Of course, the same MO must present in the resource base of STS. NHI may eliminate such OR from RB that reflects transfer of MATS/device out of operation, so RB becomes insufficient for STS.

At the same time, URs, representing MATS/device productive capabilities and having placed in the set R_I, describe resources, *consumed while STS produces OR and necessary, namely, for this operation cycle*. Obviously, amounts of resources, consumed while OR production, depend on amounts of produced OR.

As seen from the said, there is no any double count, and both parts of consumed collections of OR are summarized, when their total amounts are obtained.

To unify and to distinguish representation of producing MATS/devices, we shall include the body of any such unitary rule with head x multiobject 1·*ready-x*. Thus, all other MATS/devices, entering set R_H and represented by UR without such MO in their bodies, do not enter STS IS.

Now, we may formulate a primary criterion of sufficiency of the resource base of STS during the considered time period. Let TMS v be the resource base of STS at the beginning of this period, while unitary multigrammars $S_H = <socium, R_H>$ and $S_I = <tb, R_I>$ represent human and industrial segments of this STS.

Statement 7. Resource base v is sufficient to STS, if

$$\left(\exists \overline{v} \in \overline{V}_S\right) \overline{v} \subseteq v, \tag{43}$$

where $S = <socium, R_H \cup R_I>$.∎

If v contains not only terminal but also non-terminal (produced) OR, then sufficiency of this RB may be recognized according to (25), if to suppose $q = \{1 \cdot socium\}$. Not more difficult is generalized criterion of STS sustainability to NHI Δv.

Statement 8. STS, represented by UMG $S = <socium, R_H \cup R_I>$, with resource base v is resilient to NHI Δv, if

$$\left(\exists \langle \overline{v}, \overline{v}' \rangle \in \overline{V}_{S_q(v-\Delta v)}\right) \overline{v} \subseteq \overline{v}', \tag{44}$$

where $q = \{1\, socium\}$. Otherwise, this STS is vulnerable to this NHI. ∎

Example 6. Let sociotechnical system contain human segment, represented by the following set of unitary rules R_H:

$$socium \rightarrow 1 \cdot structures, 1 \cdot persons,$$

$$structures \rightarrow 1 \cdot office, 1 \cdot food\text{–}factory, 1 \cdot generation\text{–}facility,$$

$$
\begin{gathered}
office \to 1 \cdot top\text{–}manager, 1 \cdot department, 1 \cdot server - unit, \\
department \to 1 \cdot head\text{–}dpt, 3 \cdot manager, \\
persons \to 50 \cdot person, \\
top\text{–}manager \to 1 \cdot mob\text{–}phone, 1 \cdot desktop, 1 \cdot lunch, \\
head\text{–}dpt \to 1 \cdot mob\text{–}phone, 1 \cdot desktop, 1 \cdot lunch, \\
manager \to 1 \cdot mob\text{–}phone, 1 \cdot desktop, 1 \cdot lunch, \\
person \to 1 \cdot lunch, \\
server - unit \to 1 \cdot hardware, 1 \cdot engineer, \\
engineer \to 1 \cdot mob\text{–}phone, 1 \cdot desktop, 1 \cdot lunch, \\
food\text{–}factory \to 1 \cdot factory\text{–}director, 1 \cdot food\text{–}line, \\
food\text{–}line \to 1 \cdot food\text{–}complex, 3 \cdot food\text{–}maker, \\
factory\text{–}director \to 1 \cdot mob\text{–}phone, 1 \cdot desktop, 1 \cdot lunch, \\
food\text{–}ma\text{ker} \to 1 \cdot mob\text{–}phone, 1 \cdot lunch, \\
generation\text{–}facility \to 1 \cdot generator, 1 \cdot engineer, \\
engineer \to 1 \cdot mob - phone, 1 \cdot desktop, 1 \cdot lunch, \\
generator \to 1 \cdot ready - generator, \\
mob - phone \to 0.001 \cdot kW, \\
desktop \to 0.1 \cdot kW, \\
hardware \to 1 \cdot kW, \\
food - complex \to 1 \cdot ready - food - complex, 5 \cdot kW.
\end{gathered}
$$

As seen, STS HS contains three structures—office, power generation facility, and food factory—as well as 50 persons out of these structures. Office includes one top manager, three departments, and one MATS—server, providing office operation. Each department, in turn, consists of the head of the department and three managers. The server unit is composed of hardware and an engineer, providing its operation. Every listed position is provided with a mobile phone and desktop, and the person, holding this position, consumes lunch daily. Other structures, entering this socium, are MATS food factory, consisting of a factory director, and food line, producing food, necessary for all humans of the considered socium.

Food line, in turn, is broken down into food complex and three food makers. The factory director is provided with a mobile phone and desktop, while every food maker—with a mobile phone. Every person from the food factory also consumes one lunch. All devices consume electrical energy, in which amounts are multiplicities of OR kW in the bodies of the last four URs. The amount of electrical power, consumed by food complex (5 kW), does not depend on the number of lunches it does produce and is constant for all considered time interval. The third structure is MATS power generation facility, containing a power generator and maintained by an engineer. Generator consumption is described by UR, entering set R and containing MO 1·*ready-generator*, reflecting readiness of a generator to operation.

Let us consider industrial segment of STS, represented by the following set of unitary rules R_I:

$$tb \to 1 \cdot lunch,$$

$$tb \to 1 \cdot kW.$$

This means that technological base of STS IS produces two types of OR—lunches and electrical energy. The first contains "something to eat" and "something to drink". To produce 1 kW, it is necessary to deliver to the generator 0.01 cubic meter of gas:

$$lunch \to 1 \cdot lunch\text{–}eat, 1 \cdot lunch\text{–}drink,$$

$$kW \to 0.01 \cdot m3\text{–}gas,$$

$$lunch\text{–}eat \to 1 \cdot chease\text{–}cake,$$

$$lunch\text{–}eat \to 1 \cdot sandwich,$$

$$lunch\text{–}drink \to 1 \cdot coffee,$$

$$lunch\text{–}drink \to 1 \cdot tea,$$

$$lunch\text{–}drink \to 1 \cdot juice,$$

$$chease\text{–}cake \to 100 \cdot g\text{–}bread, 5 \cdot g\text{–}sugar, 10 \cdot g\text{–}chease,$$

$$sandwich \to 100 \cdot g\text{–}bread, 10 \cdot g\text{–}butter, 50 \cdot g\text{–}meat,$$

$$tea \to 200 \cdot g\text{–}water, 5 \cdot g\text{–}sugar, 1 \cdot tea\text{–}cube,$$

$$coffee \to 200 \cdot g\text{–}water, 5 \cdot g\text{–}sugar, 1 \cdot coffee\text{–}cube,$$

$$juice \to 200 \cdot g\text{–}fresh\text{–}juice.$$

As may be seen, the total order is

$$\overline{V}_{S_H} = \{\{1 \cdot ready - generator, 1 \cdot ready - food - complex,$$
$$0.07619 \cdot m3\text{–}gas, 69 \cdot lunch\}\},$$

while

$$\overline{V}_S = \{\{1 \cdot ready - generator, 1 \cdot ready - food - complex, 0.07619 \cdot m3\text{–}gas,$$
$$6900 \cdot g\text{–}bread, 690 \cdot g\text{–}sugar, 690 \cdot g\text{–}chease,$$
$$13800 \cdot g\text{–}water, 69 \cdot tea\text{–}cube\},$$
$$\{1 \cdot ready - generator, 1 \cdot ready - food - complex,$$
$$0.07619 \cdot m3\text{–}gas, 6900 \cdot g\text{–}bread, 345 \cdot g\text{–}sugar, 690 \cdot g\text{–}chease,$$
$$13800 \cdot g\text{–}fresh\text{–}juice\},$$
$$\{1 \cdot ready - generator, 1 \cdot ready - food - complex,$$
$$0.07619 \cdot m3\text{–}gas, 6900 \cdot g\text{–}bread, 690 \cdot g\text{–}sugar, 13800 \cdot g\text{–}chease,$$
$$13800 \cdot g\text{–}water, 69 \cdot coffee\text{–}cube\},$$
$$\{1 \cdot ready - generator, 1 \cdot ready - food - complex,$$
$$0.07619 \cdot m3\text{–}gas, 6900 \cdot g\text{–}bread, 690 \cdot g\text{–}butter, 3450 \cdot g\text{–}meat,$$
$$13800 \cdot g\text{–}water, 345 \cdot g\text{–}sugar, 69 \cdot tea\text{–}cube\},$$
$$\{1 \cdot ready - generator, 1 \cdot ready - food - complex,$$
$$0.07619 \cdot m3\text{–}gas, 6900 \cdot g\text{–}bread, 690 \cdot g\text{–}butter, 3450 \cdot g\text{–}meat,$$
$$13800 \cdot g\text{–}fresh\text{–}juice\},$$
$$\{1 \cdot ready - generator, 1 \cdot ready - food - complex,$$
$$0.07619 \cdot m3\text{–}gas, 6900 \cdot g\text{–}bread, 690 \cdot g\text{–}butter, 3450 \cdot g\text{–}meat,$$
$$13800 \cdot g\text{–}water, 345 \cdot g\text{–}sugar, 69 \cdot coffee\text{–}cube\}\}.$$

So if $v = \{1 \cdot ready - generator, 1 \cdot ready - food - complex,$
$1 \cdot m3\text{–}gas, 10000 \cdot g\text{–}bread, 1000 \cdot g\text{–}sugar, 1000 \cdot g\text{–}chease,$
$20000 \cdot g\text{–}water, 100 \cdot tea\text{–}cube, 15000 \cdot g\text{–}fresh\text{–}juice,$
$100 \cdot coffee\text{–}cube, 100 \cdot tea\text{–}cube, 5000 \cdot g\text{–}meat, 1000 \cdot g\text{–}butter\},$

this resource base is sufficient for this STS.

If $\Delta v = \{0.91 \cdot m3\text{–}gas\}$, then the considered STS is resilient to this impact, while in the case $\Delta v = \{0.91 \cdot m3\text{–}gas, 15000 \cdot g\text{–}water\}$, this STS is vulnerable to the impact. The same result would be, if $\Delta v = \{1 \cdot ready - food - complex\}$, that means food complex is destructed by the impact.■

Let us consider now a general case of distributed sociotechnological systems.

5. Resilience of distributed sociotechnological systems

We shall describe distributed STS by application of techniques, considered in Section 2 regarding distributed IS, to local STS, considered in the previous Section 4.

However, we shall minimize the number of multiobjects, extended by geospatial information, by doing this only to those MO, which represent resources. This techniques not only essentially reduces the amount of work, necessary for knowledge base creation, but also excludes the necessity of consideration of rather complicated issues, concerning MATS/device division to producing and nonproducing, as well as implanting associated information to unitary rules, entering set R_I and representing producing capabilities of the industrial segment of STS.

If so, all multiobjects like $n \cdot res$ in URs, entering both R_H and R_I, would be replaced by $n \cdot res/z$, where z, as higher, is the name of place (area) where n units of resource *res* are (would be) located.

Let us now define the so-called total order (TO), being multiset representation of the aforementioned flow of orders, generated by human segment of DSTS. This total order must be completed by STS IS to provide STS HS after NHI by necessary resources. After that we may apply Statement 8 to TO and UMG RG, which scheme represents technological base of STS IS, reduced by elimination of unitary rules, representing elements of STS IS, which are destroyed by NHI, and to resource base, which, similarly, is reduced by elimination of MO, representing OR, located at places, destroyed by NHI.

We shall introduce the following definition of the aforementioned total order $Q(Z)$:

$$Q(Z) = \{n \cdot a/z \mid n \cdot a/z \in \overline{v} \;\&\; \overline{v} \in \overline{V}_H \;\&\; \neg(z \in \overline{Z})\}, \tag{45}$$

because it is necessary to produce only those resources, which are consumed at locations, not destroyed by NHI. Here, $\overline{V}_H = \{\overline{v}\}$ is one-element set of TMS, generated by UMG $S_H = <socium, R_H>$ (let us remember that all locations of OR are points).

On the other hand, TO would be completed by technological base, also affected (partly destroyed) by the same NHI. The result of this impact may be adequately represented by elimination from the set R_I those unitary rules, in which heads contain affected locations: it is clear that if point of origination of OR is destroyed, no OR is created.

So, TB of STS IS after NHI may be defined as follows:

$$\begin{aligned} R(Z) = \{ & \langle a/z \to n_1 \cdot a_1/z_1, \ldots, n_m \cdot a_m/z_m \rangle \mid \\ & \langle a/z \to n_1 \cdot a_1/z_1, \ldots, n_m \cdot a_m/z_m \rangle \in R \& \neg(z \in \overline{Z})\}. \end{aligned} \tag{46}$$

Similarly, STS IS resource base after NHI is

$$v(Z) = \{n \cdot a/z \mid n \cdot a/z \in v \& \neg(z \in \overline{Z})\}. \tag{47}$$

By this it is easy to formulate criterion of sustainability of distributed sociotechnological system; generalization of (43) is evident.

Statement 9. DSTS, represented by UMG $S = <socium, R_H \cup R_I>$, with resource base v is resilient to NHI Z, if

$$\left(\exists <\overline{v}, \overline{v}'> \in \overline{V}_{S'_{Q(Z)}(v(Z))}\right) \overline{v} \subseteq \overline{v}', \tag{48}$$

where

$$Q(Z) = <n_1 \cdot a_1/z_1, \ldots, n_m \cdot a_m/z_m>, \tag{49}$$

$$S'_{Q(Z)} = <q, R(Z) \cup \{<q \to n_1 \cdot a_1/z_1, \ldots, n_m \cdot a_m/z_m>\}>. \tag{50}$$

Otherwise, this DSTS is vulnerable to this NHI. ∎

As seen, (45)–(50) fully correspond to verbal description of this criterion.

Now, it would be reasonable to consider in more details multigrammatical representation of the most significant elements of DSTS IS, usually named critical infrastructures.

6. Multigrammatical representation of critical infrastructures and their interconnections

We shall consider the most important critical infrastructures, which operation is absolutely necessary to provide human segment of DSTS by all required resources and services. Until it is said otherwise, we assume that all elements of these CI are stationary.

Let us begin with *electricity infrastructure* (EI), containing generation facilities (power plants), transforming/distributing substations (TDS), and terminal units (TU), providing delivery of electrical energy to the consumers. All listed elements are connected by links and joined by transmission networks together into electrical grids, which all together form EI [14–16].

We shall analyze EI, beginning from terminal units. Any TU in order to deliver one unit of power to the consumer, switched to this TU, must get it from the closest TDS, connected with it by link. So, unitary rule, representing this fragment of EI, would be as follows:

$$kW/z \to n \cdot kW/z', 1 \cdot link/z'', \tag{51}$$

where z, z', and z'' are, respectively, locations of TU, supplying it TDS, and connecting them link. Here, z and z' may be, as usual, the points, while z'' is the line, represented by coordinates of its basic points (if it is straight, two such points—start and final—are sufficient, and they are, evidently, z' and z). Value $n > 1$ depends, finally, on losses of power while its transfer by the link; n is a rational number (as higher in Section 4, we use multiobjects with rational multiplicities, which do not change any of definitions, introduced higher for integer case [12, 13]).

If TDS, located at point z', is connected to terminal units, located at points $z_1, ..., z_m$, this fragment of EI is represented by m unitary rules:

$$\begin{gathered} kW/z_1 \to n_1 \cdot kW/z', 1 \cdot link/z_1'', \\ .... \\ kW/z_m \to n_m \cdot kW/z', 1 \cdot link/z_m''. \end{gathered} \tag{52}$$

where $z_1'', ..., z_m''$ are the lines, beginning at z' and ending at $z_1, ..., z_m$, respectively.

Similarly, fragments of EI, consisting of connected TDS, may be described. In this case z' would be the location of delivering substation, while $z_1, ..., z_m$—the locations of substations, consuming power from it.

Thus, treelike fragment of EI is described, until z' is the location of power plant, generating electrical energy.

Power plant, in turn, may be represented by UR:

$$kW/z \to n_1 \cdot res_1/z_1, ..., n_k \cdot res_k/z_k, \tag{53}$$

where $n_1, ..., n_k$ are the amounts of resources $res_1, ..., res_k$, which must be delivered to locations $z_1, ..., z_k$, respectively, in order to generate 1 kW of electrical energy at location z, from which it may be delivered by links to the closest TDS. By this, evidently, $z_1, ..., z_k$ are locations of terminal units of other CI, which, in turn, deliver aforementioned resources (energy carriers, EC)—most frequently, natural gas and oil products—transferred to power plants by pipelines, forming *fuel infrastructure* [6–9, 17].

Terminal units of the pipeline, which deliver resources to consumers, are represented as heads of unitary rules of the form

$$res/z \to n \cdot kW/z', 1 \cdot link/z', 1 \cdot res/z', \tag{54}$$

where multiobject $n \cdot kW/z'$ represents the TU of electricity infrastructure, providing delivery of one unit of resource *res* from location z' to location z. This amount of energy is consumed by pump, executing resource transfer. If there are some losses during such transfer, then MO $n' \cdot res/z'$, where $n' > 1$, would be used in (54) instead of $1 \cdot res/z'$.

Distributing facilities of pipelines may be represented similarly to (52):

$$\begin{array}{c} res/z_1 \to n_1 \cdot kW/z', 1 \cdot link/z_1', n_1 \cdot res/z_1', \\ .... \\ res/z_m \to n_m \cdot kW/z', 1 \cdot link/z_m', n_k \cdot res/z_m', \end{array} \tag{55}$$

which means delivered energy carrier, entering this facility, is distributed to m pipes by application of the corresponding amounts of electrical power. As higher, $z_1', ..., z_m'$ are the lines, beginning at z' and ending at $z_1, ..., z_m$, respectively.

As it is clear, described techniques may be applied in the case of place of origination of EC, i.e., facility, producing various oil derivatives and pipeline gas, used as fuel by power plants. This facility is described as follows:

$$res/z \to n_1 \cdot res_1/z_1, ..., n_k \cdot res_k/z_k, \tag{56}$$

where all multiobjects are interpreted as higher.

The same techniques may be easily applied to *water supply* [18–20], *heating networks* [21–23], as well as *sewage networks* [24]. The latter differ from all previous by direction—“generation” of sewage waters is performed by terminal points, and “delivery” is performed to the root of the network, being the outflow point.

As may be seen from this short description, different critical infrastructures contain stationary facilities, producing various resources, as well as intermediate nodes and links, delivering necessary amounts of these resources to terminal units, contacting with objects of another CI, which operation depends on the mentioned amounts.

Let us note that operation of any DSTS is based not only on stationary objects of CI but also on its logistical capabilities—first of all, on mobile component of DSTS, providing relocation of material objects. Thus, sustainability of DSTS in a great degree depends on capabilities of transportation vehicles, which remained in the active state after NHI, as well as of stationary objects of *transportation infrastructure*, providing motion of these vehicles, as well as of the required resources (first of all, fuels and electrical energy). Such capabilities are necessary for relocation of mentioned objects from places of their creation or storage to places of their consumption.

To represent transportation capabilities of DSTS, we shall use the following techniques. Unitary rule

$$res/z \to m \cdot way - z' - z, 1 \cdot res/z' \tag{57}$$

means that one unit of resource *res* may be removed from the place of its storage z' to the place of its consumption z by any of ways, which are available by mobile component of technological segment of DSTS. It is important that multiplicity m is the mass of one unit of resource *res*, measured in some fixed for DSTS units (e.g., kg). According to the techniques of multigrammatical representation of similar problems, proposed in [12, 13], OR $way - z' - z$ is detailed by unitary rules like

$$way - z' - z \to 1 \cdot z_1, l_1 \cdot e/z', \tag{58}$$

$$z_1 \to 1 \cdot z_2, l_2 \cdot e/z', \tag{59}$$

$$\ldots$$

$$z_{k-1} \to 1 \cdot z_k, l_k \cdot e/z', \tag{60}$$

$$z_k \to 1 \cdot z', l_{k+1} \cdot e/z', \tag{61}$$

which describe path from z' to z, passing through points $z_1, \ldots, z_k$, such that distance from z' to z_k is l_{k+1} km; from z_k to z_{k-1} — l_k km, ...; from z_2 to z_1 — l_2 km; and from z_1 to z — l_1 km. As becomes evident, application of unitary rules (57)–(61) provides generation of multiset:

$$\{1 \cdot res/z', m \cdot z', K \cdot e/z'\}, \tag{62}$$

where

$$K = m \cdot \sum_{i=1}^{k+1} l_k \tag{63}$$

is the number of kg-km, which must be removed from point z' to point z by the aforementioned mobile segment of DSTS in order to relocate one unit of resource *res* from z' to z. If the total order contains multiobject $M \cdot res/z$, then it is necessary to remove from z' to z $M \cdot K$ kg km. So if the resource base of DSTS, no matter, before NHI or after it, contains such or more amount of kg-km, this operation is possible; otherwise, it is not.

As seen, the presence of multiobjects like $K \cdot e/z'$ in the RB describes the capability of mobile segment of DSTS to relocate resources between its points, no matter what kind of transport is used (trains, trucks, aircrafts, helicopters, ships, etc.). NHI may eliminate some part of such resource, thus reducing transportation capabilities of DSTS. Also, if NHI strikes some points, entering path from z' to z, corresponding URs will be extracted from scheme R. So, NHI may destroy transportation segment of DSTS both in topological and resource dimensions.

Of course, there may be different ways of one and the same resource relocation. Representation of any of them begins from UR like (58), which the head is $way - z' - z$.

One more issue to be considered here is interconnection of the transportation infrastructure with other CI (first of all, electricity and fuel). This one may be done by including to scheme R unitary rules like

$$e/z' \to 1 \cdot vel/z', k \cdot res - mov - vel/z', \tag{64}$$

which means relocation of one kg km from place z' may be done by vehicle *vel* and this operation requires k units of resource, used by this vehicle for motion. If electricity-moved ground transport is used, then (64) becomes

$$e/z' \rightarrow 1 \cdot vel/z', k \cdot kW/z', \tag{65}$$

and electricity infrastructure is connected by terminal unit, having placed at z'. If petrol-moved ground transport is used, then (65) becomes

$$e/z' \rightarrow 1 \cdot vel/z', k \cdot l - petrol/z', \tag{66}$$

where multiobject $k \cdot l - petrol/z'$ represents the amount of liters of petrol, required for relocation of one kg-km by vehicle *vel*. Thus, connection of fuel infrastructure to transportation infrastructure is represented.

The same description may be used for aircrafts, helicopters, ships, etc., and such detailing may be done for every concrete vehicle, not only a class of vehicles.

Possibility of non-terminal multiobjects in the resource base of DSTS provides opportunity of representation of such ways of resource relocation, which use different vehicles, moving over one and the same path, and even different vehicles, moving over sequential fragments of the path. Such techniques will be considered in the separate publication, as well as issues, concerning recovery of the vulnerable DSTS.

Some primary results on the assessment of capabilities of vulnerable DSTS are presented in the next section; these results are based on the approach, applied to industrial systems in [2].

7. Assessment of maximal acting subsystem of vulnerable DSTS

Problem, which is considered in this section, is reverse to the previous one and may be formulated as follows.

Let DSTS be vulnerable in the sense of criterion, formulated by Statement 9, i.e., its producing segment and resource base, affected by NHI, are not sufficient for completion of total order, generated by human segment of DSTS.

Question is that what maximal part (subsystem) of DSTS may stay active, being supplied by sufficient amounts of resources, produced by the remained manufacturing facilities and resources. Similar question was for the first time posed in [2], where its objective was to get part of the order, which may be completed by the affected industrial system and its resource base.

Solution of this problem, proposed in [2], is based on application of the so-called dual multiset grammars for generation of orders, which may be completed given the remained resource base.

Let us consider at first local case, which in the simplest form may be described by UMG $S = < socium, R_H \cup R_I >$, resource base v, and NHI Δv, which in aggregate do not satisfy generalized criterion, represented by Statement 8.

We shall use MG $S^{-1} = < v - \Delta v, R^{-1} >$, where $R = R_H \cup R_I$, which is called *dual to UMG S*.

As may be seen, every terminal multiset $v \in \overline{V}_{S^{-1}}$ in general case may be a join of the following multisets:

1. $\{n_1 \cdot str_1, ..., n_l \cdot str_l\}$, representing integral structures, which may be active after NHI, because they have sufficient amounts of resources for operation

2. $\{n_1 \cdot pstn_1, ..., n_k \cdot pstn_k\}$, representing separate positions, entering some structures, which as a whole do not enter the previous set by the reason some of their positions cannot be supplied by all necessary resources

3. $\left\{n_1 \cdot person_1, \ldots, n_p \cdot person_p\right\}$, representing amounts of different types of persons, which may stay alive after NHI, because they would be supplied by necessary resources

4. $\{n_1 \cdot tech_1, \ldots, n_s \cdot tech_s\}$, representing amounts of the types of technical systems, which may operate after NHI, because resource base of STS contains all necessary resources for their operation

5. $\{n_1 \cdot dev_1, \ldots, n_q \cdot dev_q\}$, representing amounts of the types of separate devices, which do not enter any technical system from the previous set, but may operate separately because they may be supplied by necessary resources

6. $\{n_1 \cdot res_1, \ldots, n_t \cdot res_t\}$, representing amounts of resources, which would remain in the resource base of STS after all the rest RB would be attached to all previous elements of STS

In general case

$$\left|\overline{V}_{S^{-1}}\right| \geq 1, \tag{67}$$

so the only TMS, representing the final variant of distribution of the resources, remained in the RB after NHI, would be selected by application of some additional conditions. This task may be easily done by the use of filtering multigrammars (FMG); each FMG $S = <v_0, R, F>$ along with kernel v_0 and scheme R contains filter F, joining conditions, which provide selection of terminal multisets, generated by application of rules from scheme R [12, 13].

General case of the distributed STS is not more complicated and may be easily solved by application of the introduced techniques.

8. Conclusion

Proposed multiset-based framework for the assessment of resilience of distributed sociotechnical systems to natural hazards provides flexible and sufficiently easy representation of knowledge about DSTS operation, understood as resource production, relocation, and consumption. Criterial base, introduced in this paper, may be effectively applicable in a posteriori as well as in a priori mode, i.e., for detection of "weak places" in DSTS and their strengthening, not waiting, when NH will occur.

As it was said higher, analytical capabilities of the described framework may be extended by implanting universal time scale into the basic knowledge representation, i.e., into multiset grammars and their various modifications. Such extension would provide full description of dynamics of manufacturing processes, implemented by DSTS in normal state as well as by DSTS, partly destroyed by NHI, and estimation of time periods, necessary for production of various amounts of resources in both cases. This approach makes possible also precise solution of different problems, concerning DSTS recovery [25, 26], on the unified background of resource-based techniques. The main tool for such work is the aforementioned temporal multiset grammars, which will be described in the following publications.

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