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DETECTION OF EMERGENT SITUATIONS IN COMPLEX SYSTEMS BY STRUCTURAL INVARIANT (MB, M)

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Abstract: *The paper introduces complete description of the detection method that uses structural invariant Matroid and its Bases (MB, M). There are recapitulated essential concepts from the used knowledge field as "complex system, emergent situations (A, B, C)", Ramsey theorem and principal computation variables "power" and "complexity" of emergence phenomenon. The method is explained in details and the demonstration of its application is done by the detection of emergent situation – violation of Short Water Cycle in an ecosystem.*

Keywords: *Emergent situations, structural invariant, matroid, matroid bases, Ramsey theory of graph, power of emergent phenomenon, complexity of emergent phenomenon*

1 Introduction

Some properties of „Complex system" seem to be stable nowadays. Here there are:

- Many elements in mutual interactions,
- Multidimensionality,
- Quasistability in state changes,
- Nonlinear characteristics,
- Self-organizing processes,
- Emergent behavior,
- Motions in the border of chaos,
- Non stochastic future,
- Inclination to network and multiagent organizations.

Similarly the concept „Emergent situation" has a certain conceptual background [9, 10, 19]:

Emergent situations of type A – weak emergent situations.

The causes of these situations and their output forms (outputs, shapes) are known. They can be recognized and their appearance can be predicted. Examples of processes and systems that generate such situations are: the Belousov-Zhabotinski reaction; environments for initiating solitons; the oregonator; the brusselator. *They all belong to the field of Synergetics.*

Emergent Situations class B.

The causes of these situations are not known, but their output forms are known. Such situations have the following properties:

b1) The situation appears suddenly without an explicit association with situations of the previous relevant "time-space" context of the system. (The reason of it may be in insufficient evidence of possible previous situations (cognitive reason) or the system changes its structure "from inside". In most cases we assume a mixture of both the variants.)

b2) The situation appears as a discrete concept meaningful in the mind of the observer, e.g., a behavior (of a group of termites), an object (a photograph), a shape (e.g., a design of a sculpture) or a property (super conductivity).

b3) The global reason for the appearance of this type of situation is a violation of the system structure (not a violation of the system function). In other words, the situation is induced by a jump in the system structure (the author of [21] speaks about *saltatory changes*).

b4) The detailed reasons and the internal causes of the appearance of the situation are not known (and therefore is impossible to propose a complete prediction model).

(However "the shape" of the emergent situation is known - i.e., it is known how it looks like.)

b5) The appearance of a situation of this type can be detected.

Situations belonging to this class include: a change in behavior strategy in a swarm colony; the appearance of floods; the appearance of rough waves; traffic jams.

Emergent Situations of class C.
Neither the causes nor the output forms of these situations are known. Such situations have the same properties as the situations from class B), with the exception of item b4), which has the following content:
c4) No model of a situation of this kind is available before it first operates. (It is not known how the situation looks like.)
Situations that belong to this class include: potential instabilities in ecosystems; the appearance of artifacts in nano-structures; discovery situations in Problem Solving; a violation of supersymmetries in quantum mechanics.
For some cases of EMSs of type *B*), and especially of type *C),* the model of EMSs is unavailable (b4, c4). In these cases we investigate the structure of the *environment* in which an emergent situation appearance is "anticipated", and the theory of the violation of structural invariants is applied.

A few words to organization of the paper: Section 2 contains a short list of related works. In Section 3 there are introduced essential conceptual and technical background for the proposed detection method. Section 4 contains the example of application of the proposed detection method for violation of so called Short Water Cycle in an ecosystem.

2 Related works

Larger list of related works was introduced in papers [9 - 12]. Here there are introduced only some relevant works related to the "detection of novelty" [5 - 8]. All these works represent a statistical approach and do not detect emergent situations in fact. General parts about Complex systems are in [1, 2, 3].

3 Detection of Emergent situations by violation of invariant (MB, M)

3.1 Background for the detection of emergent situations

- A few words about motivation for the use matroids and their bases:
- Matroid corresponds to the image of complex systems as to a set of interacting elements.
- Its construction is based (in our case) on the testing of relation of Independence (Dependence).
- If the relation of Independence is a binary relation then is possible to use theory of graph and combinatorial geometry and especially – Ramsey theory, [15, 16, 17].
- Completing this algebraic base by a simple emergent calculus [9] we acquire a very effective computation tool.

Matroid has the following pleasant properties:

- It is possible to construct it for each set of elements (carrier of the system) when we have the relation of independence or when they are given independent sets.
- If the relation of independence exists it is easy (in most cases) to associate it with a semantic content (according to real conditions).
- Matroid is usually introduced [20] as the following structure

$$M = \langle X, IND, \{N_1,N_2, \ldots , N_n\}\rangle = \langle X, \boldsymbol{MB} \rangle, \tag{1}$$

where X is the ground set of elements (components), *IND* is a relation of independence, $N_1,N_2, \ldots , N_n$ are independent sets and ***MB*** is a set of matroid bases. Matroid bases are maximum (according to cardinality) independent sets. With advantage is used in practical cases relation Dependence (DNT).
One of definitions of Dependence (**DNT**) relation that respects a problem factor α is the following one:
Definition 3.1: Elements $x_1, x_2 \in \boldsymbol{X}$ are Dependent (**DNT**$(x_1, x_2|\alpha)$) with regard to a given problem factor α if one (or two, three or four) of the following conditions hold(s):
(i) Elements x_1, x_2 contribute to a given problem factor α in *the same way or in similar ways*, with the same or similar means and principles, taking into account elements from *X*. (Expert criterion.)
(ii) There are changes (variations) of x_1 which are *associated* with changes (variations) of x_2 (or vv.) - with regard a given problem factor α and with regard to elements from *X*.
(iii) The application of x_1 *implies* the application of x_2 (or vv.) - with regard a given problem factor α and with regard to elements from *X*.
(iv) The application of x_1 *excludes* the application of x_2) (or vv.) - with regard a given problem factor α and with regard to elements from X.
For our conditions holds simple theorem:
Theorem 1:

$$\forall\, x_1, x_2 \in X, \quad (\mathrm{Not}(\mathbf{DNT}(x_1, x_2|\alpha)))\Leftrightarrow(\mathbf{IND}(x_1, x_2|\alpha)). \tag{2}$$

The violation of this SI is considered (in this paper) *as an extension of a matroid basis* at least by one element (and it will be considered as an indicator (or a possible initiator) of emergent situation appearance).
In case that relation IND is considered as a *binary relation* and it is possible to use the following consequences:

The bases (***MB***) will be constructed as perfect sub-graphs in a perfect graph (each node is connected with all other nodes of X). Edges of this graph G_p on X represent a *common symmetric relation* (at least equivalence) defining concept "compartment".

The independent and dependent elements in the perfect graph are easy constructed by coloring the edges of this complete graph by *two* colors and the formalism of Ramsey numbers – R(#***B***, #Y)), $\boldsymbol{B} \in \boldsymbol{MB}$ is offered to be used. We introduce now a free formulation of relations on a perfect graph G_p colored by two colors as a consequence of famous Ramsey theorem [15, 17]:

Theorem 2: A perfect graph $G_p = (V, E)$ with *n* nodes where each edge belongs to class A or to class B contains a complete subgraph with *a* nodes connected by edges from class A or a complete subgraph with *b* nodes connected by edges from class B. ♦
Such a number R(a, b) = *n* is called *Ramsey number*.

In the next text we will work with a few hypotheses. Here are the first of them.
Hypothesis 1(H1): Emergence and emergent situation are induced by a sharp change of complex system structure ("jump on the structure") . ♦
Hypothesis 2(H2): In case that we accept *H1*, the eventuality of an emergent phenomenon appearance may be detected as a sharp violation of some structural characteristics of the *complex system description* (in our case the violation of so called Structural Invariants). ♦
Very important in complex system description are two factors: *level of the description* and the basic group (*compartment*) of complex system elements. There are used two descriptive sets: the first - *symptoms* represented by external observational variables (e.g., biodiversity, maximum temperature; we use here ecological variables with regard to application in Section 4).and the second - *drivers* (e.g., high velocity in transport layer, decrease of area of landscape vegetation).
The calculus for the emergent situation in a complex system (that is introduced in this paper) associates two variables for emergent situation – The *power* of emergent phenomenon and the *complexity* of emergent phenomenon. By quantified actualized symptoms is computed the power of emergent phenomenon and from the power is computed complexity of emergent phenomenon that determines the "size" of compartment. The further computations that lead to detection of a possible appearance of an emergent situation (PAES) are realized on the compartment.
Detection of emergent situations depends more than in cases of classical situations on cognitive dispositions of the observer (detector). At first we have to say what we consider as "cognitive" and "not cognitive". Simply we can say that all what is consciously registered by our mind is cognitive. It means that all what we observe and in further we process is cognitive. It means that does not exist any "objective reality". Exists only model of reality. There are many models of reality simply ordered according to "a distance" of "reality". Models that are near to "reality" explain how the processes of "reality" function. Models more distanced of reality introduce how the processes of reality can be represented, signed, computed. For the needs of this paper we will consider only two levels of models: a level very near to reality (denoted as **NAT)** and the level more distanced of "reality" (denoted here as **SYMB**). The description of process that we want to indicate in complex system compartment has in **NAT** and **SYMB** the following form:

$$\textbf{NAT:}\quad S1 \rightarrow (S1 \oplus s) \rightarrow \text{Chaotic phase} \rightarrow SOP \rightarrow EP \rightarrow S2, \tag{3}$$

S1, S2 are compartments of complex systems. S1 is extended by a sub compartment "s" and goes through a chaotic phase, phase of self organization and a phase of emergent phenomenon into S2. Symbol " ⊕" denotes an operation of extension of system S1. (Its procedural form differs according to nature of S1. E.g., for S1 as a system in molecular chemistry it differs from S1 as a hydrological network.) SOP is "Self Organizing Process" and EP symbolizes "Emergent Phenomenon".

$$\textbf{SYMB:}\quad SM1 \rightarrow (SM1 \otimes sm) \rightarrow SM2, \tag{4}$$

where SM1, SM2 are sign models representing S1 and S2, and s*m* is a sign sub model that extends SM1. Symbol ⊗ denotes an operation of extension of SM1. (Its procedural form differs according to nature of SM1. It can be operation of union for SM1 as a set or substitution in relation structure according to a rule (for SM1 as a relation structure) and others of course.)

$$\textbf{SYMB:}\ \langle X1, \boldsymbol{MB1} \rangle \rightarrow \langle X1, \boldsymbol{B1} \rangle \rightarrow \langle X1 \cup E1, \boldsymbol{B1} \cup e1 \rangle \rightarrow \langle X2, \boldsymbol{B2} \rangle \rightarrow \langle X2, \boldsymbol{MB2} \rangle, \tag{5}$$

where *X1*, *X2* are carriers of matroids (sets of matroid elements), ***MB1*** is a set of bases on *X1*, ***B1*** is a basis from *X1*, *E1* is a set of elements that extends *X1* and *e1* is an element that extends basis ***B1*** into ***B2***. Symbol ∪ denotes operation of set union.

In continuation of hypotheses *H1*, *H2* from the Introduction we introduce the following three hypotheses that associate the violation of invariant (*M, **BM***) with a *Possible Appearance of an Emergent Situation* (PAES).

NAT: *Hypothesis 3(H3)*: In order to execute emergent phenomenon the complex system increases the number of elements in *basic group* (compartment) by a minimum number of elements, according to nearest Ramsey number. ♦

SYMB: *Hypothesis 4(H4)*: One way how to represent detection of PAES by extension of a matroid basis is to anticipate the increase of number of interacting elements in basic group (compartment). ♦

SYMB: *Hypothesis 5(H5)*: A possible appearance of emergent situation (PAES) is detected as a possibility of extension (reduction) of the basis of the matroid (matroid formed on the compartment of complex system) by at least one element. ♦

These hypotheses describe from one side the assumption about the behavior of a complex system with regard to emergent situations and from the second side they contain the way of processing of information by the user of the proposed method.

Note 3.1: According to hypothesis H3 (above) the system selects as optimal those Ramsey numbers for which is needed to add the minimum elements for the extension of basis by one element.

Example 3.1. #X = 1600. (#***B*** = 11 for #X ≥ 1597) and for one element extension of Basis (#***B*** = 12 for #X ≥ 1637) is needed to add at least 40 elements. ♦

A basic rule for the detection of an emergent situation (in relation with expression (15)) is the following one:

$$\text{IF } (\#E1 \geq \min \Delta \text{ f(RN)}) \Rightarrow (\text{PAES}), \tag{6}$$

where *E1* is a set that extends matroid $\langle X1, \boldsymbol{MB1}\rangle$ (5) and contains at least one element *e1* extending basis ***B1***. The number "min Δ f(RN)" is a minimal difference between further and actual Ramsey number. PAES denotes "a possible appearance of an emergent situation".

3.2 Calculus for the detection of emergent situations

In this Section will be presented the association between the *power* H_P and the *complexity* H_{COM} of emergent phenomenon. Respecting the description of complex system by symptoms and drivers (as it was introduced in the beginning of this section) we characterize emergent phenomenon by relation between them. By quantified actualized symptoms is computed the *power* of emergent phenomenon and from the power is computed *complexity* of emergent phenomenon that determines the "size" of *compartment*. The compartment is represented by a matroid *M* with its bases ***MB*** (from (1)).

Essential relations between the power H_P and the *complexity* H_{COM} are two equations

$$H_P(\boldsymbol{B+1}) = H_P(\boldsymbol{B}) + (u/c)\ H_{COM}(\boldsymbol{B}), \tag{7}$$

$$H_{COM}(\boldsymbol{B+1}) = H_{COM}(\boldsymbol{B}) + u\, H_P(\boldsymbol{B}), \tag{8}$$

where $\boldsymbol{B} \in \boldsymbol{MB}$ is a basis of matroid and ***B+1*** is the basis ***B*** extended by one element. Variables $H_P(\boldsymbol{B})$, $H_P(\boldsymbol{B+1})$ *and* $H_{COM}(\boldsymbol{B})$, $H_{COM}(\boldsymbol{B+1})$ are power and complexity of emergent phenomenon and they are related to compartment with bases ***B*** and ***B+1***. Symbol *u* denotes the quotient of self organization and *c* is the limit of this quotient (the best self organization). Quotient $(u/c) \in \langle 0,\ 1\rangle$ represents "intelligence" of the self organizing process that will execute the emergent phenomenon. Operating with equation (7) we obtain contribution to power released by emergent phenomenon

$$\Delta H_P(\boldsymbol{B+1}) = (u/c)\ H_{COM}(\boldsymbol{B}). \tag{9}$$

The contribution to power of the emergent phenomenon $\Delta H_P(\boldsymbol{B+1})$ that has an intuitive meaning (e.g., damage of houses by floods) in some level of the description is estimated by quantities of external variables (symptoms) s_i, i = 1, …, n for emergent (s_{iem}) and for nominal (s_{inom}) situations:

$$\Delta H_P(\boldsymbol{B+1}) = \Big(\sum_{i=1,n} (\omega_i\, (s_{iem}/s_{inom}))^2\Big)^{1/2}, \text{ for } i=1,\ldots,n, \tag{10}$$

where ω_i are quotients of importance. Equation (9) is associated with equation (8) where $H_{COM}(.)$ is approximated in our case by number of elements of basis ***B***, i.e. #***B***.

$$H_{COM}(\boldsymbol{B}) = \xi\, (\Delta H_P(\boldsymbol{B+1})/\,(u/c)) = \#\boldsymbol{B}, \tag{11}$$

where ξ *(x)* is the nearest higher complete number after x (e.g., $\xi(2.86) = 3$) and *(u/c)* is the quotient iterated from Table 1 [9, 10].

Table 1

(u/c)	Classes of Complex Systems - the examples of Complex Systems
0.1	"Inanimate" natural systems – avalanches, floods, earthquake, tsunami.
0.2	Lower alive systems – bees, termites, ants.
0.3	Mixed natural and artificial systems – ecological systems, social systems, transport systems.
0.4	Complex systems coordinating billions of elements (components) – ocean, atmosphere.
0.5	Advanced organism systems – human brain, systems managing sugar in blood, chemical systems.
0.6	Systems of the synthesis of the sign (symbolic) emergent spaces.
0.7	Human problem solving systems.
0.8	Metaphorical systems – human mind, systems with sharp reduction of information.
0.9	Supervising intelligent systems not available for us since – e.g., consciousness of Universe.
1	Complex systems with super-intelligence.

4 Violation of Short Water Cycle

In paper [4] has been modeled the situation of the violation of so called Short Water Cycle in a selected ecosystem (Trebon basin in South Bohemia, Czech Republic). The Short Water Cycle (SWC) refers to the behavior of the local ecosystem (e.g., the Trebon region), in which the volume of water that comes into the ecosystem is evaporated and falls back into this system. In the Trebon ecosystem, the evaporated water rises quickly in the transport zone and does not have time to condense before it is transported outside the ecosystem to the distant mountains, where it condenses spontaneously in rising air streams. (Due to the enormous volumes of vapor that are transported, the condensation is very dynamic and sometimes leads to torrential downpours).

Approaching the computation of a searched emergent situation according to method from sub section 3.1 we use two sets of complex system variables: the first - *symptoms* represented by external observational variables (in our case biodiversity, maximum temperature, …) and the second - *drivers* (e.g., high velocity in transport layer, decrease of area of landscape vegetation, …). Both types of variables are related to the problem factor "α" - in our case "Violation of SWC" (needed lately for discovering of relation **DNT**(x_1, $x_2|\alpha$)), (**IND**(x_1, $x_2|\alpha$))).

Symptoms:
s_1 … decreased biodiversity characterized by quantity of MSA (*Mean Species Abundance*) quotient,
s_2… average and maximum temperature,
s_3… global evaporation (evaporation from the surfaces of water carriers plus evapotranspiration of plants),
s_4… trend of global evaporation.

All quantities of symptoms are related to temporary state of ecosystem in Trebon basin.
The calculus for the emergent situation in a complex system (that is introduced in the paper) associates two variables for emergent situation – The *power* of emergent phenomenon and the *complexity* of emergent phenomenon.
At first is computed the contribution to the power. We use quantified values of symptoms:

$s_{1em}/s_{1nom} = 0.7$,
$s_{2em}/s_{2nom} = 1.1$,
$s_{3em}/s_{3nom} = 0.6$,
$s_{4em}/s_{4nom} = 1.2$.

Quotients of importance are computed by Saaty method [13]:
$\omega_1 = 0.53$,
$\omega_2 = 0.32$,
$\omega_1 = 0.1$,
$\omega_1 = 0.035$.

Using expression (10):

$$\Delta H_P(\boldsymbol{B+1}) = (\sum_{i=1,4} (\omega_i (s_{iem}/s_{inom})^2)^{1/2} = (0.53*0.49 + 0.32*1.21 + 0.1*0.36 + 0.035*1.44)^{1/2} = 0.8584.$$

Now – according to expression (11) and from Table 1. for (u/c) = 0.3:

#***B***= 0.8584/0.3 = $\xi(2.86)$ = 3. It leads to matroid with #***X*** = 6 (size of compartment).

We find the following *drivers* (that probably induced violation of SWC) considered as the elements of ***X***:
x_1 … high velocity of flowing in transport level of atmosphere (200 m above the landscape surface),
x_2… high level of sun radiation,
x_3… decrease of vegetation cover of landscape,
x_4… small soakability of the soil,
x_5… decrease of volume of ground water,
x_6 … inconvenient composition of bed layer of the soil.

Table 2

	x_1	x_2	x_3	x_4	x_5	x_6
x_1	1	1	0	0	0	0
x_2		1	1	0	0	0
x_3			1	1	*	0
x_4				1	1	1
x_5					1	1
x_6						1

Analyzing relation **DNT**(x_1, $x_2|\alpha$) ("1" **DNT**(x_1, $x_2|\alpha$) holds, "0" **DNT**(x_1, $x_2|\alpha$) does not hold and "*" question about **DNT**(x_1, $x_2|\alpha$) is not reasonable) is obtained the basis of matroid.
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In Table 2 we discover one three element basis:

$$B1 = \{ x_1, x_3, x_6\}, \tag{12}$$

It means "*high velocity of flowing in transport level of atmosphere*", "*decrease of vegetation cover of landscape*" and " *inconvenient composition of bed layer of the soil*".

The last action what is necessary to realize is to find a driver that may extend this basis. We may use the expression (6) that recommend us to add to the matroid #*E1drivers* ≥ min Δ f(RN). The nearest Ramsey number is 9. So if we try to find three drivers that may contribute to violation of SWC at least one extends the basis B1. (The condition "they contribute to a violation of SWC" is very important because this is the condition unifying interaction between elements visualized as a perfect graph G_p from Theorem 2.)

Such three drivers could be:
x_7… decrease of number of water carriers (streams, lakes, ponds),
x_8… increase of anthropogenic effects in the region (e.g., industrial activities), [14].
x_9 … longtime local dry atmosphere, (arid soil).

From these three effects x_8 and probably x_7 extends B1 to B2 and induce emergent situation "violation of SWC":

$$B2 = \{ x_1, x_3, x_6, x_8\} \text{ or } B2 = \{ x_1, x_3, x_6, x_7\}. \tag{13}$$

In Fig.1 is illustrated situation in National Park Sumava in South Bohemia. Violation of SWC induced drying the trees. Then followed the invasion of wood parasites. An approximation of a final situation is an emergence of desert landscape. Such consequences of violation of SWC could have been considered as reasons and starts for violation of Long Water Cycle (LWC) and for devastation of landscapes that were originally covered by forests and meadows (Yucatan in Mexico, south-western deserts in USA, Sahara in Africa and many others). The list of drivers that induce violation of SWC brings questions as - which of these drivers are the most important and if the decrease of their intensity could bring the improvement of situation: - *high velocity of flowing in transport level of atmosphere and prevailing direction of winds* ", "*decrease of vegetation cover of landscape and small soakabiltiy of the soil*", etc. However these questions are topics for another paper.

Figure 1: Consequences of violation of SWC in national Park Sumava (South Bohemia)

As a conclusion of this section is good to note that the proposed method enables to detect not only “negative” emergent situations but also the situations that we understand as “positive” ones, e.g., coming of crayfish back to our streams and rivers.

Note 4.3: This example is introduced here as a reconstruction of the past event. PAES could have been discovered at least 10 years ago.

5 Conclusion

There was proposed the method for the detection of emergent situation using structural invariant (**MB**, **M**). The method brings a qualitative results and is convenient especially for not too easy available systems (as are, e.g., ecosystems, atmospheric systems, ocean systems, ...). In case of large industrial systems (as a system of distillation columns) the qualitative results may be completed by some quantitative method – e.g., by *modal analysis*. The method has weak places, e.g., intervals of Ramsey numbers or rather rough estimations of quotients (u/c) (it will be improved).

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