Method for identification, stability analysis and the dynamics monitoring of sociotechnical clusters

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Abstract. The problem arising in the study of sociotechnical clusters is revealed. This problem consists in the impossibility of using a standard approach for the identification and sociotechnical clusters analysis, which does not take into account the relationship of coordinated interaction between objects in such clusters, depending on their goals and objectives. The set of indicators for the identification and analysis of sociotechnical clusters is substantiated. These indicators are based on fuzzy relations of concerted interaction between objects in such clusters. The original method for identification, stability analysis and the dynamics monitoring of sociotechnical clusters is proposed. The proposed method, in contrast to the known ones, allows you to analyze: the changing of the sociotechnical clusters sizes; the sociotechnical cluster centre drift; the separation and merging of these clusters; the emergence and disappearance of sociotechnical clusters. Fuzzy cognitive approach is used for the first time: firstly, to justify and estimate a set of indicators for sociotechnical clusters; secondly, for the stability analysis of these sociotechnical clusters.

1. Introduction
Sociotechnical clusters are associations of heterogeneous interdependent social, economic, organizational and technical systems and objects connected by stable diverse relations and processes depending on the goals and objectives of their functioning and development.

The growing interest in the formation, functioning and development of sociotechnical clusters is due to the following factors:

• active innovative development and increasing the role of territorial factors at the regional level due to the sustainability of economic and other links between different systems/objects of material production and non-production sphere;
• complex nature of the sociotechnical environment, as well as the acceleration of innovative products technological cycles;
• considerable initial costs, riskiness, and uncertainty in the time profit generated from innovative products [1, 2].

The following basic approaches to the definition and presentation of sociotechnical clusters are known.
Thus, in [2] sociotechnical systems and clusters are considered from the point of view connectivity in a certain area, taking into account the effects of “synergy” and “environment”.

In [3] the main characteristic of sociotechnical clusters is the intensity of logistic flows between objects.

For sociotechnical cluster identification and analysis use the following features: the presence of common resource base; the concentration within the individual territory; technological, commercial and logistics cooperation projects; narrow professional specialization; innovative component that determines a synergistic effect and assure the competitiveness of all objects [4].

The following quantitative characteristics of enterprises associations identifying as industrial clusters are determined: the share of industrial products total value; the enterprises productivity; the share of high-performance jobs created through integration [5].

The main objectives of the sociotechnical clusters study are the identification, analysis of stability and monitoring of their change dynamics [6]. Thus, it is possible to allocate the following main problem arising at the research of sociotechnical clusters. Based on the considered interpretations, it is not possible to use a typical approach for the sociotechnical clusters identification and analysis. This is due to the object’s heterogeneity, and the diversity of relations between them.

Approaches to the analysis of complex systems based on fuzzy cognitive maps are known [7-14]. However, these approaches are not oriented on solving the problems of identification, stability analysis, and monitoring the dynamics of changes in sociotechnical clusters.

This problem is a consequence of the existing scientific and methodological contradiction between the existing sociotechnical clusters interpretations and the limitations of known fuzzy cognitive methods and the cluster analysis methods, which do not take into account the relationship of coordinated interaction between objects in such clusters, depending on their goals and objectives.

To resolve this contradiction and solve the named problem it is proposed by authors:

- the reasonable set of indicators for identification and analysis of sociotechnical clusters based on the coordinated interaction relations between objects in such clusters;
- the original method of identification, stability analysis and changes dynamics monitoring in sociotechnical clusters using this reasonable set of indicators.

Thus, fuzzy cognitive approach is used for the first time: firstly, to justify and estimate a set of indicators for sociotechnical clusters; secondly, for the stability analysis of these sociotechnical clusters.

2. Problem statement

We formulate the problem of identification, stability analysis and sociotechnical clusters dynamics monitoring as follows.

2.1. Source data

1. There are many interdependent systems or objects (hereinafter referred to as objects) associated with sustainable production and other relationships

\[ A = \{a_i | i = 1..I\} \]

2. Between these objects the stable relations of mutual influence caused by their production and other activity are established

\[ R = \{r(a_i, a_j) / (a_i, a_j) | a_i, a_j \in A\} \]

3. These relationships of mutual influence between objects determine the set of indicators

\[ P = \{p_k | k = 1..K\} \]

which allow to set the compliance status of the relevant sociotechnical objects of different clusters

\[ C = \{c_l | l = 1..L\} \].
4. At specified intervals or according to the significant events results there are assessed relations of mutual influence $R$ between objects of the plurality $A$, the values of the indicators $P$ are updated and change dynamics monitoring in sociotechnical clusters $C$.

2.2. Needs
1. To substantiate a set of indicators based on the relations of coordinated interaction between objects and allowing to identify sociotechnical clusters and to assess the degree of objects compliance to different clusters.
2. To propose a method of identification, stability analysis and changes dynamics monitoring in sociotechnical clusters, using a reasonable set of indicators.

3. Indicators to identify sociotechnical clusters based on fuzzy cognitive approach

The research carried out by the authors of this article allowed to substantiate the use of fuzzy cognitive approach to justify a set of indicators based on the relationship of coordinated interaction between objects, in order to identify sociotechnical clusters [15].

Fuzzy cognitive approach provides:
- formalized input of system-related factors as well as direct, indirect and aggregated influence of these factors on one another;
- modeling of diverse situations in order to assess and identify different factors and any relations of mutual influence and coherence that may cause the instability;
- analysis of the character and extent to which various factors of the model influence one another directly or indirectly;
- estimation of the coherence of factors in their impact on each other and on the model as a whole.

To substantiate the set of such indicators, a fuzzy cognitive model (FCM) is pre-constructed, the set of concepts of which corresponds to a set of objects $A = \{a_i | i = 1..I\}$.

Further, by experts or as a result of experimental studies determine the relationship of mutual influence between the concepts of the FCM

$$ R = \left\{ \left( r(a_i, a_j) / (a_i, a_j) \right) | r(a_i, a_j) \in [-1, 1], a_i, a_j \in A \right\}. $$

For clarity, we present the relationship in the form of an adjacency matrix $R = \left[ r_{ij} \right]_{I \times I}$, where $i, j$ – the designation of the source concept and the receiver concept, respectively; $I$ – the number of concepts of the FCM.

Due to the fact that the values of the matrix $R$ elements are presented in the range $[-1, 1]$, and operations on fuzzy relations are defined for the values from $[0, 1]$, the matrix $R$ is transformed into matrix of non-negative relationships $Q = \left[ q_{ij} \right]_{2I \times 2I}$ according to the following rules:

$$ \text{If} \ r_{ij} > 0 \ , \ \text{Then} \ q_{2i−1,2j−1} = r_{ij} \ \text{AND} \ q_{2i,2j} = r_{ij}, $$

$$ \text{If} \ r_{ij} < 0 \ , \ \text{Then} \ q_{2i−1,2j−1} = −r_{ij} \ \text{AND} \ q_{2i,2j} = −r_{ij}. $$

Then the matrix is reconciled based on its transitive closure:

$$ \bar{Q} = Q \vee Q^2 \vee Q^3 \vee \ldots, $$

where fuzzy matrix $Q, Q^2, Q^3 \ldots$ calculated on the basis of the max-prod-composition operation, and as the operation “$\vee$” is used max.

Transitive closure $\bar{Q}$ characterizes the stability of the sociotechnical clusters $C$.

If the transitive closure is not achieved, the FCM is considered unstable. Further analyses of the reasons for the model instability identifies the impacts that allow the FCM in steady state.
The transitively closed matrix $Q$ is transformed to the form of the matrix $R' = \left\{ (r'_{ij}, r'_{ji}) \right\}_{ij}$ characterizing the coordinated relations of mutual influences between objects and consisting of positive-negative pairs of elements formed by the following rules:

$$r'_{ij} = \max \left\{ q_{2i-1, 2j-1}, q_{2i, 2j} \right\}, \quad r'_{ji} = -\max \left\{ q_{2i-1, 2j}, q_{2i, 2j-1} \right\}.$$

Next, the matrix $R'$ is used to calculate indicators-oriented assessment of the object’s compliance degree with sociotechnical clusters:

- an indicator of the single object impact on sociotechnical clusters

$$p_1(a_i) = \frac{1}{I} \sum_{j=1}^{I} \left( \text{sign} \left( r'_{ij} + r'_{ji} \right) \max \left\{ \left| r'_{ij} \right|, \left| r'_{ji} \right| \right\} \right), \quad i = 1..I,$$

- an indicator of coordinated the impact of individual object on the sociotechnical clusters

$$p_2(a_i) = \frac{1}{I} \sum_{j=1}^{I} \left| \frac{r'_{ij} + r'_{ji}}{r'_{ij} + r'_{ji}} \right|, \quad i = 1..I,$$

- the measure of mutual coherence of a single object and sociotechnical cluster

$$p_3(a_i) = \max \left\{ \left( \frac{1}{I} \sum_{j=1}^{I} \left| r'_{ij} + r'_{ji} \right| \right), \left( \frac{1}{I} \sum_{j=1}^{I} \left| r'_{ij} + r'_{ji} \right| \right) \right\}, \quad i = 1..I.$$

4. Description of the method for identification, stability analysis and the dynamics monitoring of sociotechnical clusters

The proposed method consists of the following stages.

**Stage 1.** To form a set of objects to identify clusters of sociotechnical and construction of the FCM.

The procedure of a set of objects preliminary assignment for social technical clusters $C = \{c_i | i = 1..L\}$ identification is a directed or random search of subsets $A' \subset A = \{a_i | i = 1..I\}$ corresponding to the FCM concepts.

**Stage 2.** Construction of FCM to assess the sociotechnical clusters stability formed from objects from a subset $A'$, and to calculate the identification of these clusters’ indicators $Q$.

The procedure for development this FCM is described in the previous section of the paper.

**Stage 3.** Stability evaluation of selected objects subset $A'$ based on the results of matching (transitive closure) of the corresponding fuzzy matrix of positive relations $Q$.

The degree of sociotechnical clusters stability formed from subset objects $A'$ depends on the ratio of the iterations number of transitive closure procedure to the number of objects from the subset $A'$. The smaller it is, the more stable identified sociotechnical cluster is.

**Stage 4.** Calculation of indicators $p_1(a_i), \ p_2(a_i), \ p_3(a_i), \ i = 1..I$ for sociotechnical clusters identification (see previous section).

**Stage 5.** Clustering and determination of sociotechnical clusters characteristics (centers, sizes) in accordance with the values of the calculated indicators $p_1(a_i), \ p_2(a_i), \ p_3(a_i), \ i = 1..I$ (see above), based on the relationship of coordinated interaction between objects.

To solve this problem, various clustering methods can be used, for example, the $k$-means method [16-18].

**Stage 6.** Changes dynamics monitoring in sociotechnical clusters. This monitoring can be performed either at a specified periodicity, or by the results of significant events that lead to change in the interaction relationship between objects from the subset under consideration $A'$. 

According to the results of actualization of mutual influence relations, stages 2-5 of this method are iteratively repeated.

In the course of changes dynamics monitoring in sociotechnical clusters, such problems of analysis are solved: cluster size changes; drift of the cluster centers; cluster split and merge; formation of new clusters and their disappearance [19].

5. Experiment results and analysis

The results of the proposed method for the identification, stability analysis and changes dynamics monitoring of energy clusters in the Smolensk region are presented below.

As a result of the preliminary study, a subset of objects \( A' = \{ a_i | i = 1..22 \} \) was determined and the FCM was formed to analyze the relations of coordinated interaction between them and identify the energy clusters of the Smolensk region.

During the coordination procedure of the mutual influence relations of this FCM, the transitive closure of the positive relations fuzzy matrix \( Q \) converged in 4 iterations (<< \( I \)), which indicates a significant stability of the analyzed subset of objects.

On the basis of the obtained agreed influence relations matrix \( R' \), the indicators calculation for the identification of energy clusters in the Smolensk region was performed (table 1).

| Objects | \( p_1(a_i) \) | \( p_2(a_i) \) | \( p_3(a_i) \) |
|---------|-------------|-------------|-------------|
| \( a_1 \) | Desnogorsk Energy College | 0.329 | 0.678 | 0.678 |
| \( a_2 \) | Smolensk Branch of the National Research University “MPEI” | 0.448 | 0.692 | 0.692 |
| \( a_3 \) | Smolensk Nuclear Power Plant, JSC | 0.505 | 0.659 | 0.659 |
| \( a_4 \) | Smolensk Thermal Power Plant, PJSC | 0.209 | 0.512 | 0.512 |
| \( a_5 \) | Smolensk Heat and Power Plant no. 2, OJSC | 0.206 | 0.491 | 0.491 |
| \( a_6 \) | Dorogobuzh Heat and Power Plant, LLC | 0.197 | 0.48 | 0.487 |
| \( a_7 \) | Smolensk Heat Networks, Municipal Unitary Enterprise | 0.23 | 0.675 | 0.675 |
| \( a_8 \) | Dorogobuzh Heat Management, LLC | 0.145 | 0.612 | 0.612 |
| \( a_9 \) | “Gidrostroy”, LLC | 0.123 | 0.348 | 0.673 |
| \( a_{10} \) | “Firma Energo+”, CJSC | 0.137 | 0.474 | 0.474 |
| \( a_{11} \) | “Turbopar”, State Company | 0.474 | 0.67 | 0.67 |
| \( a_{12} \) | “EnergomontazhAvtomatika-EP”, LLC | 0.142 | 0.42 | 0.494 |
| \( a_{13} \) | “Analitpribor”, FSUE | 0.334 | 0.645 | 0.645 |
| \( a_{14} \) | “ABO Armatura”, LLC | 0.145 | 0.667 | 0.685 |
| \( a_{15} \) | “Stroykomplekt-Emal”, JSC | 0.122 | 0.623 | 0.629 |
| \( a_{16} \) | “Globur Service”, LLC | 0.221 | 0.376 | 0.578 |
| \( a_{17} \) | “TD Avtomatika”, LLC | 0.162 | 0.422 | 0.499 |
| \( a_{18} \) | “Dorogobuzhkoatomash”, OJSC | 0.162 | 0.643 | 0.643 |
| \( a_{19} \) | “Smolenskenergo”, OJSC | 0.351 | 0.649 | 0.649 |
| \( a_{20} \) | “SmolenskAtomEnergoSbyt”, JSC | 0.28 | 0.552 | 0.616 |
| \( a_{21} \) | “Ruselprom-SEZ”, LLC | 0.202 | 0.715 | 0.715 |
| \( a_{22} \) | “EnergoPromMarket”, LLC | 0.172 | 0.615 | 0.615 |

On figure 1 the results of stable and coordinated energy clusters in the Smolensk region identification are presented:

- \( c_1 : \{ a_4, a_5, a_6, a_9, a_{10}, a_{12}, a_{16}, a_{17} \} \).
An expert survey of specialists confirmed the results of energy clusters in the Smolensk region identification using the proposed method.

The obtained results are the basis for further research to solve the problems of monitoring the dynamics of changes in the identified energy clusters (change of the cluster sizes, drift of the cluster centers, cluster split and merge, formation of new clusters and their disappearance) of various regions of Russia.

6. Conclusion
The article describes the main approaches to the definition and sociotechnical clusters presentation. The reasons for the growing interest in their forming, functioning and development are substantiated.

The problem arising in the study of sociotechnical clusters, is the impossibility of using a standard approach for the identification and sociotechnical clusters analysis, which does not take into account the relationship of coordinated interaction between objects in such clusters, depending on their goals and objectives.

For this problem a set of indicators for identification and sociotechnical clusters analysis, based on the relationship of coordinated interaction between objects in such clusters is substantiated. Namely: an indicator of the single object impact on sociotechnical clusters; an indicator of coordinated the impact of individual object on the sociotechnical clusters; the measure of mutual coherence of a single object and sociotechnical cluster.

The original method for identification, stability analysis and the dynamics monitoring of sociotechnical clusters is proposed. The following tasks were also solved for the first time: change sociotechnical cluster sizes; the drift of the centers of these clusters; the merging and splitting of sociotechnical clusters; the formation of new clusters and their disappearance.

Fuzzy cognitive approach is used for the first time: firstly, to justify and estimate a set of indicators for sociotechnical clusters; secondly, for the stability analysis of these sociotechnical clusters.

The results of using proposed method of identification, stability analysis and changes dynamics monitoring on energy clusters in the Smolensk region are presented as the example.

The obtained results are the basis for further research to solve the problems of monitoring the dynamics of changes in the identified energy clusters (change of the cluster sizes, drift of the cluster centers, cluster split and merge, formation of new clusters and their disappearance) of various regions of Russia.
The prospective development of the proposed method is to changes dynamics monitor in sociotechnical clusters for different sets of objects, followed by a comparison of the stability conditions of the respective clusters.

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