Development of the digital model of the loading and transport enterprise infrastructure in a coal mining region

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Abstract. An argument for developing an infrastructure digital model of the loading and transport enterprise in a coal mining region is presented on the example of Kuzbass in accordance with the natural resources of the coal basin, the existing transport and logistics infrastructure and the needs of the domestic and world coal market. Optimization of traffic flows from producer to consumer is the main direction for development of facilities of transport and logistics infrastructure at a loading and transport enterprise. The scheme of the transport and logistics infrastructure of the loading and transport enterprise was digitized. A computer program for cognitive modeling was developed based on the construction of a fuzzy cognitive map and the choice of an optimal graph scheme from a set of options according to a given criterion. The strength of the system impact on the concept, the strength of the concept impact on the system, the consonances of the concepts impact on the system and the system on concepts are taken as indicators for assessing the options for developing the transport and logistics infrastructure of the loading and transport enterprise. Based on the simulation results, the main significant factors-concepts were identified, which are ranked as follows: the coal market, internal control actions, seasonal phenomena, communication and signaling.

1. Introduction
In accordance with the Order of the Government of the Russian Federation No. 1632-r dated July 28, 2017 on the approval of the program “Digital Economy of the Russian Federation” [1], an integrated digital transport and logistics platform of the transport complex is being created within the framework of federal initiatives [2]. The developed program “The digital transport and logistics as a part of the Program “Digital Economy of the Russian Federation” includes a set of solutions and key measures for managing human, material, information and financial flows based on their optimization to solve the problem of minimizing costs using modern information technologies. This direction of development of enterprises corresponds to the concept of Industry 4.0, which includes cybernetic systems consisting of various natural objects, artificial subsystems and controllers that allow representing such an entity as a single structure [3].

When implementing control actions, transport and logistics infrastructure should combine such types of logistics activities as information exchange, dispatch monitoring, corrective actions, storage, processing, loading, transportation, personnel management, resource management, etc. into a single technological process [4, 5]. The purpose of the functioning of a loading and transport enterprise is the integration and reengineering of business processes to reduce the risk of accidents and incidents, increase in the level of interaction between elements of the transport and logistics infrastructure and the quality of services provided by the transport organization to the cargo owner.
The main directions for development of mining enterprises in Russia are closely related to solving the priority tasks of companies concerning the extraction, processing, transport and sale of mineral raw materials. One of these enterprises is the Siberian Coal Energy Company (SUEK), which produces over 100 million tonnes of coal in Russia annually. The company has its own wagon fleet, the use of which covered 80% of its transportation needs in 2019. SUEK operates in 11 regions of the country, one of such regions is Kemerovo region (Kuzbass), where the company produces about 40 million tonnes of coal per year. Coal is supplied to companies in the energy and metallurgical sectors in Europe, Asia and Russia.

The current state of the infrastructure of loading and transport enterprises is characterized by the following features:

- the spatial positioning of storage points, loading and formation of transport routes depends on the geographical location of coal mining companies, connecting station of non-public tracks and the tracks of JSC “Russian Railways” (RZD), which leads to the need to minimize the costs for transportation of the mined coal to railroad storage sites of loading and transport enterprises and transportation of loaded wagons to RZD stations;
- the linking of the transport and logistics infrastructure of various loading and transport enterprises in coal mining regions to license areas, mines, open-pit mines and processing plants leads to disunity of the goals and objectives of transport and logistics infrastructure facilities.

In accordance with the stated above, the urgent task is to develop a digital model of the infrastructure of a loading and transport enterprise and scenarios for the spatial and temporal placement of infrastructure facilities for the creation and implementation of mechanisms that would manage the phased development of the enterprise infrastructure in a turbulent economy, taking into account the agreed interests of manufacturers, consumers and participants of the goods transportation.

2. Methods of research

The solution to this problem is possible with the use of modern digital technologies. Domestic and foreign experience confirms that the leaders of the transport industry in Russia, significantly ahead of other companies, have long and systematically invested in digitalization [6, 7].

The research was carried out using the methods of system analysis, cognitive modeling and matrix enumeration of scenarios for the development of complex systems.

As a basic option, loading and transport operations were used at JSC “SUEK-Kuzbass”, which are carried out by the PE “Loading and Transport Enterprise” [8, 9]. Its main transport and logistics infrastructure facilities are geographically located in Leninsky and Kiselevsky districts of Kemerovo region.

A digital model of the transport and logistics infrastructure of the loading and transport enterprise is developed on the basis of cognitive modeling, the essence of which is the construction of cognitive maps and the choice of an optimal graph scheme from a set of options according to a given criterion. The complex criterion for achieving the goal is the movement of the planned amount of coal products to the desired point along the optimal route in the required time with the lowest costs.

3. Results and discussion

To create a digital model of the transport and logistics infrastructure of a loading and transport enterprise, a cognitive map was built, which has not only a visual justification in the form of an oriented graph (figure 1), but also a mathematical description.
Figure 1. Oriented graph of the transport and logistics infrastructure at the loading and transport enterprise.

Relationships between concepts can be either positive or negative. If an increase in the value of the concept – the reasons contribute to an increase in the concept-receiver, then the influence is assumed to be positive, with a decrease in the value, the relationship is negative. The reasons for the positive connections in the cognitive map can be an increase in the demand for coal in winter, the introduction of modern technical devices, an increase in prices for coal products, etc.

The negative links include the influence of the following factors: low competence of personnel, limited coal reserves in the storage sites, a complex transport scheme for coal transportation, a decrease in the capacity of the coal market, etc.

When forming the parameters of the vertices and arcs of the directed graph, the values of the concepts at the vertices of the finite sequence \( V = \langle v_1, v_2, v_3, \ldots, v_n \rangle \) are set by the software user or a person who makes decisions based on the simulation results. The elements of the finite sequence \( W = \langle w_1, w_2, w_3, \ldots, w_n \rangle \) are determined by experts. With the same value of the element \( v_i \), several different values of the connections \( w_j \) are allowed. However, the requirement of pairwise conjunction remains, that is, for example, the following pairwise combinations are possible

\[
v_1 \wedge w_1; v_1 \wedge w_2; v_2 \wedge w_3; v_2 \wedge w_4; v_2 \wedge w_5; \ldots; v_n \wedge w_n. \tag{1}\]

In the process of cognitive modeling, the following indicators and results are determined [10-12]:

1) Direction and intensity (weight) of mutual influence between concepts

\[
P_{ij} = p(e_i, e_j), \tag{2}\]

where \( P_{ij} \) is a normalized index of mutual influence between concepts \( i \) and \( j \), the value of which varies in the range \(-1 \leq P_{ij} \leq 1\).

2) Consonance (level of maximum confidence) between concepts \( i \) and \( j \):
\[ c_{ij} = \frac{|a_{ij} + b_{ij}|}{|a_{ij}| + |b_{ij}|}, \quad (3) \]

where \( c_{ij} \) is the consonance of the influence of concept \( i \) on \( j \); \( a_{ij} \) – positive influence of concept \( i \) on \( j \); \( b_{ij} \) – negative influence of concept \( i \) on \( j \).

3) Consonance of the influence of the \( i \)-th concept on the system that includes \( n \) concepts:

\[ C_i^{\rightarrow} = \frac{1}{m} \sum_{j=1}^{m} C_{ij}. \quad (4) \]

4) Consonance of the influence of the system on the \( j \)-th concept:

\[ C_j^{\rightarrow} = \frac{1}{m} \sum_{i=1}^{m} C_{ij}. \quad (5) \]

5) The final mutual \( r_{ij} \) influence of concepts on each other:

\[ r_{ij} = (a_{ij} + b_{ij}) \cdot \max(|a_{ij}|, |b_{ij}|). \quad (6) \]

6) The impact of the \( i \)-th concept on the system:

\[ R_i^{\rightarrow} = \frac{1}{m} \sum_{j=1}^{m} R_{ij}. \quad (7) \]

7) The impact of the system on the \( j \)-th concept:

\[ R_j^{\rightarrow} = \frac{1}{m} \sum_{i=1}^{m} R_{ij}. \quad (8) \]

8) The final state of the cognitive map in impulse modeling:

\[ U = U_0 + \Delta U_0 \circ F, \quad (9) \]

where \( U \) is the final state of the cognitive map; \( U_0 \) – the initial state of the cognitive map; \( \Delta U_0 \) – the impulse applied to the input of the cognitive map; \( \circ \) – fuzzy T-composition; \( F \) – matrix of interactions.

For cognitive modeling based on dependencies (3) – (9), the authors have developed a computer program.

In cognitive modeling, three main options for the transport and logistics infrastructure of a loading and transport enterprise were considered, for average, maximum and minimum values of the concepts (table 1).

| Number and name of a concept | Average values of a concept | Max. values of a concept | Min. values of a concept |
|------------------------------|-----------------------------|--------------------------|--------------------------|
|                              | of a concept on the system  |                          |                          |
| 1 - coal market              | 0.57                        | 0.00                     | 0.00                     |
| 2 - calorific value of coal  | 0.45                        | 0.05                     | 0.03                     |
| 3 - coal reserves in         | 0.34                        | 0.05                     | 0.03                     |
|                              | 0.62                        | 0.00                     | 0.40                     |
|                              | 0.37                        | 0.07                     | 0.07                     |
warehouses
4 - external influences 0.41 0.00 0.49 0.00 0.36 0.00
5 - internal control actions 0.47 0.27 0.57 0.33 0.47 0.26
6 - coal processing 0.17 0.12 0.25 0.12 0.13 0.12
7 - condition of private tracks 0.26 0.31 0.32 0.34 0.26 0.31
8 - coal transportation and shunting operations 0.25 0.71 0.32 0.89 0.23 0.71
9 - wear of fixed assets 0.26 0.43 0.32 0.44 0.26 0.43
10 - security level 0.41 0.78 0.51 0.81 0.37 0.80
11 - seasonal phenomena 0.45 0.00 0.55 0.00 0.44 0.00
12 - staff competence 0.35 0.24 0.40 0.33 0.34 0.23
13 - communication and signaling 0.43 0.75 0.51 0.87 0.43 0.70
14 - enterprise competence 0.25 0.80 0.29 0.95 0.26 0.74
15 - profitability of production 0.24 0.79 0.30 0.97 0.19 0.73

Graphs of changes in the calculated values, indicated in formulas (3) – (9) for three variants of concept values, are shown in figure 2.
Based on the results of cognitive modeling, the following patterns were revealed:

- The maximum impact of the most significant individual concepts on the transport and logistics infrastructure of the loading and transport enterprise is distributed as follows: the coal market (0.62-0.57), internal control actions (0.57-0.47), seasonal phenomena (0.55-0.44), communication and signaling (0.43-0.51).
- The following concepts have the least influence on the transport and logistics infrastructure of a loading and transport enterprise: coal processing (0.17-0.25), the competence of the enterprise (0.25-0.29).
- The maximum impact of the entire transport and logistics infrastructure of a loading and transport enterprise on individual concepts is distributed as follows: enterprise competence (0.74-0.95), production profitability (0.73-0.97), transport and shunting operations (0.71-0.89), the level of environmental and industrial safety (0.78-0.81).
- The transport and logistics infrastructure of the loading and transport enterprise has a minimal impact on the coal market, the calorific value of coal, and coal reserves at the storage sites.

Similarly, it is possible to analyze and forecast the state of the transport and logistics infrastructure of a loading and transport enterprise based on the results of cognitive modeling using the developed computer program for any combination of concepts and their relationships, depending on the real or predicted situation.

4. Conclusion
Based on the obtained research results, it is recommended to carry out technical re-equipment and improve the methods of management at a loading and transport enterprise in the following sequence (in terms of influence): adaptation of the enterprise to the coal market, reorganization of internal control actions, elimination of the negative influence of seasonal phenomena, improvement of communication and signaling. Improvement of the efficiency of a loading and transport enterprise can lead to an increase (by levels) in: the competence of the enterprise, the production profitability, the rhythm of transport operation and shunting operations, the level of environmental and industrial safety.

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