Formalized description of motorway construction, reconstruction and repair control system

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Abstract. The paper provides information on the technical and organizational condition of the Novosibirsk Region's construction complex, volumes of under-repairs, problems of improving and creating an intelligent transport system, the first stage of which can serve as a control center for the construction and maintenance of roads. Therein is given an approach to building a control system from an advanced position. The importance of economic and mathematical models of building production and their insufficient justification in the road industry is noted.

A formalized description of the control system is given with a multi-echelon graph model developed by the authors. The paper proposed the structure of a complex of formalized descriptions, consisting of groups of system structure models and indicators that describe a system behavior, production processes, information processes, decision-making procedures. It is proposed to describe the multi-echelon structure of an organization as a graph model, wherein each echelon as local graph models representing economic, organizational and technological connections. The main purpose of this model, with the complete independence of private business, is the designing and operation of a center for construction and maintenance of infrastructure facilities of the road network. This circumstance is reflected in model formulating. Modelling of information flows at the lower levels of the control systems needs a fairly detailed description of processes. Modelling at the highest levels of management requires aggregated indicators. Therefore, models of complex systems should be oriented to indicators that operate on information of different levels of aggregation. The main advantages of the formalized description of the structure of road complex control systems are noted.

1. Introduction
The total length of the road network in the Novosibirsk Region is 28.151 km. At the same time, the length of federal motorways is 796 km, the length of regional and intermunicipal motorways is 12.730 km, the length of local roads is 14.625 km.

At the end of 2017, the start of the national project “Safe and High-Quality Roads”, the share of regional and intermunicipal roads, the technical condition of which meets regulatory requirements, was 36.7% or 4.675 km out of 12.732.9 km, and the share of roads complying with regulatory requirements and taken into account within the Novosibirsk agglomeration was 42.6% or 450.6 km out of 1058.8 km. This condition was assessed as a global under-repair of the road network of the Novosibirsk Region, the elimination of which required the simultaneous allocating funds in the amount of at least 71 billion rubles.

As of the end of 2019, the share of roads of regional and inter-municipal significance, the technical
condition of which meets regulatory requirements, amounted to 30.0% or 4,837 km of 12,730 km, and the share of roads that meet regulatory requirements and are considered within the Novosibirsk agglomeration was 64.4% or 149.6 km out of 232.4 km (for all roads, respectively, 56.6% or 599.4 km out of 1,060.0 km).

In the region there are a sufficient number of quarries of inert materials necessary for building production (9 stone careers and 3 sand pits). The total annual output of such quarries is about 11 million m$^3$. Taking into account the program of work planned under the national project, the total demand for inert materials is going to be about 2 million m$^3$.

There is also a cement production plant, a road bitumen production plant, as well as enterprises for the manufacture of road traffic organization equipment. The capacity of manufacturers allows to increase the volume of road construction.

Thus, in order to implement the road activity program of the national project "Safe and high-quality roads," the road construction complex of the Novosibirsk region has all the necessary production and raw materials capacities and currently does not allow disruption of the national project.

The road complex has more than 20 road organizations performing construction and installation works on the construction, reconstruction and repair of roads and road facilities on them. In each district of Novosibirsk region there are road organizations performing road works and possessing asphalt concrete plants and the necessary fleet of road construction equipment.

Any road organization, LLC, OAO, grassroots division or section, administrative structures of the Ministry of Transport are a complex hierarchically organized system, the activities of which are aimed at the implementation of investment projects (IP), solving the tasks of the road complex, development of the road network, their construction, repair and operation. The management system is designed for efficient and cost-effective management. Management is effective when objectives are achieved within a set time frame. Management is cost-effective if objectives are achieved with minimal resource consumption. The problem of establishing such a system, improving existing ones aimed at minimizing costs, ensuring the quality and safety of roads, is urgent. One of the approaches to its solution is the creation of intelligent transport systems (ITS), the first stage of which can be the Dispatching Center for the Management of Construction, Road Maintenance (DCMCRM). The works of Russian and foreign scientists are devoted to the study of ITS and related organizational, technological and construction processes [1-16].

2. Research methods

2.1. System analysis of organizations

System analysis of organizations and enterprises of any form of ownership is an effective tool for system research. The diagram shown in Figure 1 [17] is used as a generalized representation of the control system.

At the input $X$, the material and technical $X_1$, financial $X_2$, energy $X_3$ and information $X_4$ resources, as well as the impacts of outer environment, are received in the organization (object and subject of control). Impacts of outer environment, in turn, can be material, energy, financial. These resources and impacts enter the organization in real form, and the control subject receives information about them. It
circulates through channels $K_1$, $K_2$, $K_3$, $K_4$, which connect the object and subjects of control to each other and to the outer environment.

Main parameters of output in any organization: products (material, energy, financial, information); environmental impacts (material, energy). The organization (in terms of cybernetics - processor) is characterized by the following parameters: vector of goals; vector of benchmarks used by a management team in managing the organization; vector of management errors; power; human resources (number, professional staff, level of qualification); possessed machines, mechanisms, tools; production processes and technologies; financial flows; information flows; status vector.

Vector of the organization's goals has direct connection with investment projects (IP). It reflects the organization's participation in the implementation of IP (composition and scope of works, duration, costs and profits, quality, etc.). The vector of goals is formed by the control subject. Its local goals are designed to ensure effective management. They are distributed to the echelons and elements of the control system.

The efficiency of management is determined by the vector of management errors, which should contain information on deviations of actual indicators from the projected, directive and planned ones. If managed effectively, they must match or be close. At the same time, it should be noted that the approach to analysis of data on the vector of management errors taking into account the complex interaction of state and business structures in the implementation of road projects does not contribute to the achievement of the general results on the construction of safe and high-quality roads [18, 19].

In today's conditions, large-scale construction management is associated with a number of factors that have led to the application of economic and mathematical models (EMMs) of building production, which allow to adequately reflect the real construction process [20, 21]. However, new approaches to project lifecycle management, including in the road industry, nowadays are not sufficiently substantiated from the point of science and not fully reflected in known models.

### 2.2. Formalized description of control system by multi-echelon graph model

The authors find it relevant and effective for the construction of organizational, technological and information models to develop a set of formalized descriptions (CFDs), the creation and use of which can be based on some principles inherent in the system of organizations of the road complex, namely:

- Elements of a hierarchically organized system are targeted, implementing the main goal or group of goals, in the course of their activities;
- System as a whole, and any element thereof, operates under limited resources and internal constraints;
- Information processes, formed on the basis of initial information from the control object and environment, form the information base of organizational and management decisions;
- Management systems, including project management, have a hierarchical structure.
- An enlarged SFD can be represented as consisting of the following groups of models:
  - Models of system structure and indicators describing its behavior;
  - Production process models in the system elements;
  - Models of information processes;
  - Models of decision-making procedures.

The model of the road complex management system by analogy with [22] can be represented by a multi-echelon structure. In particular, the model of a large joint-stock company is appropriate to describe the three-echelon structure: the first tier is OJSC, the second tier is road repair and construction department, third tier is construction sections, each tier of which is represented by local graph models, and together with a system of graphs representing the model of vertically integrated structure of the road complex of production profile [11]. The main purpose of such a model, with full independence of private business, is to design and operate a management center for the construction and maintenance of infrastructure facilities of the motorway network.
2.3. Results of Control System Study with Multi-Model Graph

Each graph is represented by elements corresponding to links of organizational structures of organizations and connected by arcs. The graph contains a root vertex, hanging and intermediate vertices. Unidirectional arcs indicated by arrow are oriented, bidirectional are called undirected [23]. Oriented arcs connect vertices of graph of elements of echelons sequentially, besides, from root vertex of arc only come, arc of element of K-th echelon enters only one element (K-1) - th echelon except root one.

Each K-th level contains M_k elements described by a certain vector number l_k. It can be defined as follows:

1) for echelon with root vertex of graph K = 0 vector number l_k=l_0=0;
2) K=1 l_k=l_1=1,2,…, M_{l_0} – scalar element number of the first echelon, varying from 1 to M_{l_0};

The set of values of a first level vector set \{l_1\}={1,2…M_{l_0}} will be denoted by L_{l_0};
3) for l_{K-1} – vector number (K-1) - th echelon,

\[ l_{K-1} = \left( l_{K-1}^{(1)}, l_{K-1}^{(2)}, \ldots, l_{K-1}^{(K-1)} \right) , \]

by analogy, vector numbers at other echelons:

\[ l_{K1} = \left( l_{K-1}^{(1)}, 1 \right) , \]
\[ l_{K2} = \left( l_{K-1}^{(2)}, 1 \right) , \]
\[ \ldots \]
\[ l_{KM_{l_{K-1}}} = \left( l_{K-1}^{(1)}, M_{l_{K-1}} \right) , \] (1)

The set \{l_k\}={l_K; r=1,2…M_{l_{K-1}}}, again, is similarly denoted by L_{l_{K-1}}.

Let us denote through L_K(l_{K'}) the set of all l_{K'}- elements of K-echelon, included in element l_{K'} (K'<K).

Then:

\[ L_K(l_{K'}) = l_{K'} \]
\[ L_{K+1}(l_{K'}) = l_{K'} \] (2)

\[ L_K(l_{K'}) = U \ldots U \]

Each echelon is represented by a graph of economic, organizational and technological relations of structural elements of K-echelon. In the following, we will use the term “graph model of K-echelon object” and represent as G_K(L_0, Q_k). The sets of structural elements K and (K+1) of echelons are represented as sets L_K(l_0) \cup L_{K+1}(l_0), Q_k and Q_{K+1} of graph model. Mappings of graph G_{K+1} in G_K of corresponding echelons will be described as \( \varphi_{K+1} \). This mapping will take the following form:

\[ \varphi_{K+1} : G_{K+1} \rightarrow G_K \quad K=0,N \] (3)

Figure 2 shows a schematic diagram of a multi-echelon graph model.
3. Research results of information processes occurring in system structural elements

It is obvious that the main reserve for productivity improvement lies in the improvement of management. In construction, the management methodology based on the development and implementation of IP has almost everywhere. The production structure of construction organizations and the organizational structure of their management are developed as part of the IP. IP functions always in a certain environment, including internal and external components, through which the influence of natural, economic, technological, technical and other factors is manifested. In structural elements of the system there are information flows in the form of control actions of higher levels, feedback, from lower elements to higher ones, containing reporting information about the process, organizational, technological and economic in interaction with adjacent elements and external environment. Meanwhile, the interaction of each element both vertically and horizontally is performed in opposite directions described by input parameters $x_j = (x_j^{(1)}, x_j^{(2)}, \ldots, x_j^{(m_j)})$, wherein the set $\{1, 2, \ldots, m_j\}$, and output parameters $y_j = (y_j^{(1)}, y_j^{(2)}, \ldots, y_j^{(n_j)})$ reflecting either informational or material relationships. $x_j \in X_j$; $y_j \in Y_j$. The space of input and output indicators of an individual structural element of the system is represented in the form of a classification table 1.

Table 1. Space of input and output indicators of system structural element.

| Relation to j- element | Indicators of system elements interaction |  
|------------------------|------------------------------------------|
|                        | with outer environment | with higher rank element | with adjacent element | with lower rank element |
| Input parameters space $X_j$ | $X_{j_1}$ | $X_{j_2}$ | $X_{j_3}$ | $X_{j_4}$ |
| Output parameters space $Y_j$ | $Y_{j_1}$ | $Y_{j_2}$ | $Y_{j_3}$ | $Y_{j_4}$ |

A graphical representation of information links of the $j$ structural element $j \in L_K(I_0), K=\overline{0, N}$ is shown in Figure 3.
In each j-element of the system, the input data expressed by certain indicators are converted to output. The law of this transformation $T_j$, is represented by the map:

$$T_j : X_j \rightarrow Y_j$$

$$j \in L_K(I_0); K=0, N$$  (4)

In the hierarchical system of road complex control, the level of aggregation of indicators, which significantly affects the quality of decisions made, is of great importance. This circumstance is reflected in model formulating. The modelling of information flows at the lower echelons of the control systems needs a fairly detailed description of the processes. Modelling at the highest levels of management requires aggregated indicators. Therefore, models of complex systems should be oriented to indicators that operate on information of different levels of aggregation. We will denote through $\alpha$ levels of aggregation of input parameters; through $\beta$ levels of output indicators. The procedure for aggregation and disaggregation of key figures is represented by the following mappings.

1. Aggregation of input indicators:

$$P_j^{\alpha-1} : X_j^\alpha \rightarrow X_j^{\alpha-1}$$

.................................

$$P_j^{10} : X_j^{01} \rightarrow X_j^0$$  (5)

2. Aggregation of output indicators:

$$Q_j^{\beta-1} : Y_j^\beta \rightarrow Y_j^{\beta-1}$$

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$$Q_j^{10} : Y_j^{01} \rightarrow Y_j^0$$  (6)

3. Disaggregation of input indicators:

$$P_j^{01} : X_j^0 \rightarrow X_j^1$$

$$P_j^{12} : X_j \rightarrow X_j^2$$

.................................

$$P_j^{(\alpha-1)\alpha} : X_j^{(\alpha-1)} \rightarrow X_j^\alpha$$  (7)
4. Disaggregation of output indicators:

\[ Q_i^{10} : Y_i^0 \rightarrow Y_i^1 \]
\[ Q_i^{12} : Y \rightarrow Y_i^2 \]

\[ Q_i^{(β-1)0} : Y_j^β \rightarrow Y_j^1, j \in L_k(I_k); \beta = 0, N \]  \hspace{1cm} (8)

Schematic diagram of mappings of the spaces of input and output actions is given in Figure 4.

Consider the algorithm for transforming some indicator into a "graph-indicator" of the tree type. Let us allocate a certain vector \( x_j^r \) (\( x_j^r \in X_j^r \) \( r < α \)) Let \( J_j^r \) is a set of its components, and \(|J_j^r|\) is their number. Obviously, the dimension of space is \(|J_j^r|\). Let us select from the vector \( x_j^r \) some arbitrary component \( x_{sj}^r \), wherein \( 1 \leq S \leq |J_j^r| \).

Let us now consider the vector \( y_j^{r+1} \), which is obtained as a result of applying the transformation \( P_{j}^{(r+1)} \) to the vector \( x_j^r \). Let us select from this vector all the components involved in the formation of the indicator \( y_{sj}^{r+1} \), mark them, and connect them with arcs to \( x_{sj}^r \).

Now we apply the transformation \( P_{j}^{(r+1)(r+2)} \) to the vector \( x_{sj}^{r+1} \), that is, we again disaggregate the indicators. From the vector of the obtained indicators, we select previously formed from the previous ones and connect them with the arcs to the previous ones. We perform this procedure to the level \( α \). In the end, we form a graph-indicator for \( x_{sj}^{r+1} \).

Let us describe the mappings that occur during the formation of the "graph indicators" of structural elements of the \( K \)-echelon system from the graph-indicators of structural elements of the \( (K+1) \)-echelon.

\[ Q_i^{01} : Y_i^0 \rightarrow Y_i^1 \]
\[ Q_i^{12} : Y \rightarrow Y_i^2 \]

\[ Q_i^{(β-1)0} : Y_j^β \rightarrow Y_j^1, j \in L_k(I_k); \beta = 0, N \]

**Figure 4.** Schematic diagram of transforming spaces of input and output actions.

Let us denote as \( J_{K+1}^α \) and \( J_{K+1}^β \), respectively, the sets of indices of the input and output indicators of \( l_{K+1} \), the structural element of the \( α \)-level aggregation of the \( (K+1) \)-echelon (i.e., \( l_{K+1} \in L_{k_{K+1}} \)).

Then the transformation of the input and output "graph-indicators" of \( (K+1) \)-echelon into the corresponding "graph-indicators" of the \( l_{K} \)-element of the \( K \)-echelon can be described by the mappings:

\[ E_{k}^{(α+1)K} : \{x_{ik}^α \} \in J_{K+1}^α \Rightarrow \{x_{ik}^α \} \in J_k^μ \]
Similarly, the conversion of higher-level information to lower level information is described.

\[
F_{l_{k}}^{h(K+1)K}: \{y_{i_{lk}}^{h}\} \in E_{l_{k}}^{h} \Rightarrow \{y_{i_{lk}}^{h}\} \in E_{l_{k}}^{h}
\]

Meaning of the mapping \(E_{l_{k}}^{h(K+1)}\) is to describe the algorithms that recalculate the "graph-indicator" of the underlying (overlying) echelon into the "graph-indicator" of the upper (lower) echelon. This is also true for maps \(F_{l_{k}}^{h(K+1)K}\) and \(E_{l_{k}}^{h(K+1)K}\).

Now the production process, which takes place in an arbitrary \(l_{k}\)-element of the \(K\)-echelon, can be described taking into account the level of detail of the input and output indicators.

\[
T_{l_{k}}^{h}\left( X_{l_{k}}^{h}\right) \rightarrow \{y_{i_{lk}}^{h}\} \in E_{l_{k}}^{h}; K=0, N
\]

where

\[
X_{l_{k}}^{h} = \{x_{i_{lk}}^{h}\} \in E_{l_{k}}^{h}; \quad \{y_{i_{lk}}^{h}\} \in E_{l_{k}}^{h}
\]

The functioning of the construction organization occurs in time. Therefore, in the mapping (11) describing the production process, the corresponding input and output vectors \(x_{i_{lk}}^{h}\) and \(y_{i_{lk}}^{h}\) \((x_{i_{lk}}^{h} \in X_{l_{k}}^{h}; y_{i_{lk}}^{h} \in Y_{l_{k}}^{h})\), \(j \in L_{l_{k}}(l_{k}), K=0, N\), in essence, should be tied to fixed timepoints and reflect its state for certain periods.

4. Discussion of results of a research

Formalized description of road complex control system structure has the following main advantages:

- Invariance to change the goals of the integrated road system and the goals of its structural units;
- Possibility of describing system links with different types of models;
- Possibility of developing the road complex system by introducing new echelons, units and links between them;
- Structure of the model does not depend on the level and period of relevance (long-term) of management decisions;
- Model is invariant to organizational and technological processes implemented by a set of elements of organization structures.

When building organizational management structures, managers at each level are given local goals consistent with the organization’s global objective. Managers are given certain powers that contribute to the achievement of their goals. It follows that their need for information will differ in its qualitative and quantitative composition and degree of aggregation. In practice, most of the current management apparatus is engaged in converting information from one time period to another. At the same time, the conversion of information of traditional, usually planning periods, into operational ones, reflecting the actual state of production, and vice versa, is the most labor-intensive process.

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