Information Support of Intelligent Decision Support Systems for Managing Complex Organizational and Technical Objects Based on Markov Chains

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Abstract

Management of multilevel organizational and technical systems under the influence of environmental factors is a complex process that uses both structured and semi-structured data. For information support of management decisions in such systems, the use of probabilistic mathematical models based on Markov processes is proposed. In contrast to the traditional use of Markov chains, it is proposed to replace equal step intervals with a discrete sequence of states determined by environmental influences. This approach makes it possible to model and regulate the process of making relevant decisions when managing multi-level organizational and technical objects and increase its efficiency in difficult operating conditions.

Keywords

information support, intelligent systems, semi-structured problems, control, uncertainty, Markov chains

1. Introduction

The typology of solving complex semi-structured problems of managing multilevel control systems requires taking into account quantitative and qualitative characteristics with the dominance of uncertainty and fuzzy ideas about the influence of unpredictable environmental factors. The appearance of a hierarchical structure in intelligent semi-structured control systems is due to the presence of a large amount of information about the controlled processes in the system, the impossibility of processing this information and making decisions by one control center, as well as the decentralization of the decision-making process. One of the important problems of decision-making under conditions of uncertainty is the lack of a common methodology for constructing probabilistic models for regulating the process of making relevant decisions and information support for intelligent control systems for complex multi-level organizational and technical objects.

Decision-making information support models in the management of simple organizational and

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technical objects are used to analyze systems in which decision-making is of a one-time nature, and system components are described by static quantities. Most management models for complex organizational and technical objects are characterized by the fact that the processes they describe are dynamic in nature. Dynamic models of hierarchical control systems for complex organizational and technical objects operating under conditions of uncertainty are of particular interest due to the need to take into account controllable and uncontrollable factors.

Phenomenologically, the choice of the first step to change the current situation of managing complex organizational and technical systems is associated with a quantitative assessment and adjustment of one of the determining factors, which leads to a shift in the starting point of the management transformation process. After performing operations related to the adjustment of the subsequent factor, the starting point will again shift towards the reduction of the process. Thus, the process of changing the position of the reference point is random in nature, characterized by an arbitrary choice of a corrected factor with discrete time characteristics of the duration of the first and subsequent steps and a countable set of states. Such a process will be Markovian, since subsequent states of the starting point of the process of transformational transformations do not depend on past states.

The unresolved parts of the general problem of managing complex objects include the formalization of the accumulated knowledge and experience in managing them, taking into account the influence of uncertain destabilizing environmental factors on the cognitive component of the decision maker.

The aim of the work is to develop information support tools for intelligent decision-making systems in the management of multi-level organizational and technical objects under conditions of uncertainty.

2. Relative Works

The Markov process model applied in the construction of logical networks of the information space is presented in [1,2]. In [3], the Markov process model is used to calculate the probabilities of transitions between states of patients as a set with deviations in the anatomy of the lymphatic drainage system. The construction of the architecture of information support for the management of organizational and technical systems is presented in [4]. The use of the theory of artificial intelligence and computational linguistics to enhance the semantic connection of uncontrolled terms of knowledge representation in information systems of engineering regulations is presented in [5,6]. The procedure for information support of decision-making systems with a limited number of observations, based on interval estimates of probabilities, is presented in [7]. The information-entropy model of the basis for making managerial decisions under conditions of uncertainty is presented in [8]. The information support system for minimizing losses in the management of information systems with the analysis of the results of management decisions is presented in [9]. In [10], a description of information support for managing uncertainty by taking into account the requirements, opportunities and recommendations for the implementation of projects in corporate systems is given. Information support of mechanisms and types of control with a gradation of categories of possibilities and classes of uncertainties is presented in [11]. The use of information technologies for risk and uncertainty management in complex projects is presented in [12,13]. The influence of information systems on business efficiency is reflected in the works [14-17]. In [18], a number of new functions and influences on management activities are proposed. The adoption of preventive measures to minimize threats and risks is reflected in [19]. The work [20] is devoted to setting priorities and reducing uncertainties by digital data transformation. The use of a heterogeneous hidden Markov chain for the characteristics of wavelet coefficients is considered in [21], feature extraction based on the Markov chain for anomaly detection in time series in [22], the use of Markov chains in complex multilevel control chains in [23]. Modeling using Markov chains for a wide range of applications is presented in [24-28].

The variety of ways to study uncertainty has caused fragmentary ideas about the parameters of uncertainty and approaches to its management, inconsistency in conceptualization and measurements. The formation of a modern information support system in system research should be aimed at modernizing the tools for managing organizational and technical systems in the context of dynamic transformations.

3. Materials and Methods

The properties of information support for decision-making under conditions of uncertainty were used as research materials:

- Information security
- Protection from the influence of the external environment
- Controllability, i.e. the possibility of adjusting control actions
- Structural heterogeneity, i.e. the presence in the system of various elements with different weight contributions
- Effectiveness, i.e. the emergence of a new quality in the combination of a specific set of elements.

Probabilistic mathematical Markov processes models are used as methods of information support and decision-making modeling.

4. Methodology

The dynamics of a hierarchical control system can be described using the equations

$$\frac{\mathrm{dx}}{\mathrm{dt}} = \mathrm{f}(x, u, v_1, v_2, \dots, v_n),\ \mathrm{x}(\mathrm{t}_0)=\mathrm{x}_0 \tag{1}$$

where $x \in E_m$ – vector of phase variables, E_m – state space at a moment in time t.

The change in the state of information support of the management system occurs under the influence of the control center $u(t) \in U$ and control subsystems $v_1(t), v_2(t), \dots, v_n(t), v_i(t) \in V_i$. Assuming that the control parameter of the center u changes continuously in time, the resulting function $u(t), t \in [t_0, t]$, $u(t) \in U$, will be measured by t. Sets $U, V_1, V_2, \dots, V_n$ will be the sets of admissible controls.

Every program control $u(t), t \in [t_0, t]$ determines the trajectory of the control system $x(t), t \in [t_0, t]$. The set of ends of the trajectories of the differential equation (1) represents the reachability set starting from the initial state for all possible program controls $u(t) \in U, t \in [t_0, t]$. Each new event depends only on the previous one and does not depend on all other events. Thus, the resulting control trajectory ends with a point $x(t)$, into which the system passes at time t. This point will be the starting point of the Markov process. The original probability distribution can be represented by the equation:

$$\mathrm{P}(x_0 = \mathrm{S}) = q_0(\mathrm{S}) \forall_{S \in E} \tag{2}$$

where $\forall$ – universal quantifier,
S – discrete states,
q_0 – probability distribution at a moment in time $t_0 = 0$.
The set E represents a finite number of possible states.

$$\mathrm{E} = \{e_1, e_2, \dots, e_n\} \tag{3}$$

Range of random variable $\{x_n\}$, the values of which determine the parameters of information support of intelligent control systems, is the state space, and the value n, characterizing the movement of this parameter in the control system, – is the step number. The probabilities of transition from one state to another are represented as square matrices.

$$P_{ij}(\mathrm{n}) = \mathrm{P}(x_{n+1} = \mathrm{j} \mid x_n = \mathrm{i}) \tag{4}$$

$$P = \begin{matrix} & s_1 & s_2 & \dots & s_n \\ s_1 \\ s_2 \\ \cdot \\ s_n \end{matrix} \begin{bmatrix} p_{11} & p_{12} & \cdots & p_{1n} \\ p_{21} & p_{22} & \cdots & p_{2n} \\ \cdot & \cdot & \cdots & \cdot \\ p_{n1} & p_{n2} & \cdots & p_{nn} \end{bmatrix} \quad (5)$$

Elements, p_{ij} denote the probability of transition from the state s_i into the next.

The transition probability matrix expresses the probability that the state of the control system at time n + 1 is subsequent to other states.

$$\mathrm{P}(\mathrm{x}_{\mathrm{n+1}} = S_{\mathrm{n+1}} \,|\, \mathrm{x}_{\mathrm{n}} = S_{\mathrm{n}}) = \mathrm{P}(\mathrm{S}_{\mathrm{n},}\mathrm{S}_{\mathrm{n+1}})\forall(\mathrm{S}_{\mathrm{n+1}}, \mathrm{S}_{\mathrm{n}}) \leftarrow \mathrm{E} \times \mathrm{E} \quad (6)$$

The Markov chain will be homogeneous if the transition probability matrix does not depend on the step number.

$$\mathrm{P}_{\mathrm{ij}}(\mathrm{n}) = \mathrm{P}_{\mathrm{ij}} \quad (7)$$

According to the Kolmogorov-Chapman equation, the transition probability matrix for *n* steps in a homogeneous Markov chain is the *n-th* power of the transition probability matrix for one step.

$$P\left(x_n = S_n \,|\, x_0 = S_0\right) = P_n \quad (8)$$

Markov chain at any moment of time can be characterized by vectors by a row C_i of the matrix of transition probabilities *P*.

Transition probability or conditional probability of an event S_k^j, upon condition S_m^{j-1} is equal to

$$\mathrm{P}_{\mathrm{mk}}{}^{\mathrm{j}} \triangleq [\mathrm{S}_{\mathrm{k}}{}^{\mathrm{j}} \,|\, \mathrm{S}_{\mathrm{m}}{}^{\mathrm{j-1}}] \quad (9)$$

S_k^j – the probability that the system after *j*-steps will be in the state S_k, ≜ - mathematical equal sign by definition.

The probability distribution for identifying the state of information support of the control system does not depend on time, but only on transitions from the current state to the corresponding control iterations. By developing the proposed methodological approach, it is possible to establish a sequence of transitions from the initial current state, creating the necessary control base. The stochastic model compiled in this way is shown in Figure 1.

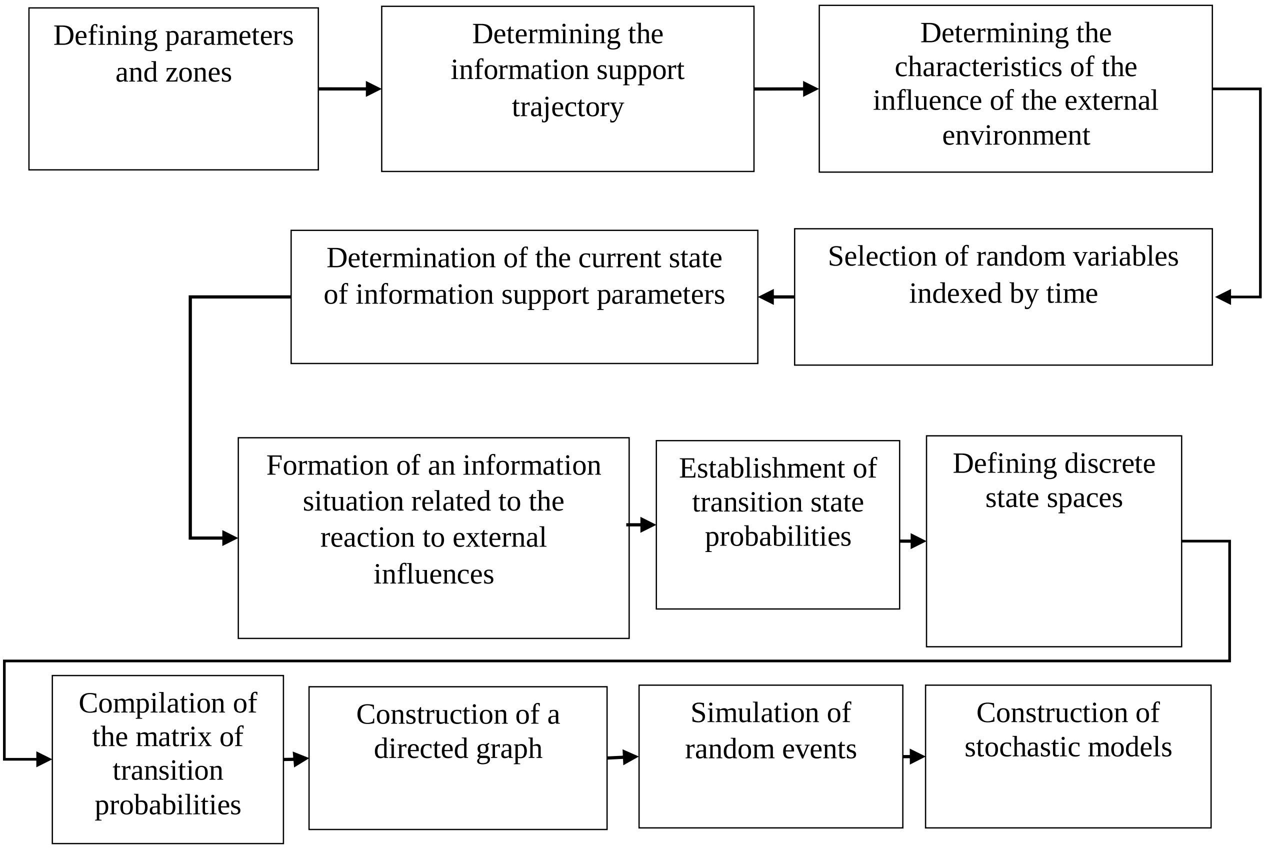

Figure 1: Stochastic model of information support for intelligent control systems for complex objects based on Markov chains

The state of the control system can be described by a random process $\xi(t)$. Random process $\xi(t)$ will be Markovian if its conditional probability distribution function at a future moment of time t_{n+1} does not depend on the values of the process in the past moments $t_1, \ldots, t_{n-1}$, and is determined only by the value $\xi(t_n)=x_n$ at the present time t_n. Conditional distribution function $P\{\xi(t_{n+1})<x_{n+1}|\xi(t_n)=x_n\}=F(x_n, t_n; x_{n+1}, t_{n+1})$ will be a Markov transition function.

5. Experiment

Below is an example of using information support for intelligent control systems for complex organizational and technical objects based on Markov chains, compiled on the basis of an expert assessment of the management activities of a real production facility (Table 1).

Table 1
Probability distribution of the current state of the parameters of information support of the control system

Information support parameters	Information provision	Protection from the external environment	Controllability	Structural heterogeneity	Efficiency
efficiency	v_1	v_2	v_3	v_4	v_5
weight contribution,%	27	19	17	12	25

Each combination of information support parameters of intelligent control systems is assigned a certain probability, which is written as a line of the state matrix. In this case, the sum of the probabilities in the rows of the matrix is always equal to one.

$$\sum_{k=0}^{n} P[S_k^j] = \sum_{k=0}^{n} p_k(j) = 1, \quad j \geq 0 \qquad (10)$$

The values of conditional probabilities of information support parameters at different stages of management are presented in Table 2.

Table 2

Conditional probabilities of information support parameters of intelligent control systems

Subsequent state / Current state	Information provision	Protection from the external environment	Controllability	Structural heterogeneity	Efficiency
information provision	0,11	0,29	0,14	0,2	0,26
protection from the external environment	0,12	0,19	0,17	0,25	0,19
controllability	0,19	0,25	0,17	0,12	0,27
structural heterogeneity	0,17	0,27	0,19	0,12	0,25
efficiency	0,12	0,17	0,27	0,19	0,25

The initial state vector, according to Table. 1 will be written in the form:

$$p(0)=(0.27, 0.19, 0.17, 0.12, 0.25) \qquad (11)$$

The transition probability matrix is the following:

$$A=\begin{vmatrix} 0.11 & 0.29 & 0.14 & 0.2 & 0.26 \\ 0.12 & 0.19 & 0.17 & 0.25 & 0.19 \\ 0.19 & 0.25 & 0.17 & 0.12 & 0.27 \\ 0.17 & 0.27 & 0.19 & 0.12 & 0.25 \\ 0.12 & 0.17 & 0.27 & 0.19 & 0.25 \end{vmatrix} \qquad (12)$$

Each row in the presented matrix has its own probability distribution. It is necessary to determine what is the probability of the influence of the information support parameters of intelligent control systems at various stages of their use.

State S_0 characterized by the fact that the working conditions are stable and do not depend on the influences of the external environment. Information support at the initial stage will be determined by the parameters v_i, presented in table 1.

The state of information support at the first stage of management S_1 will be determined by the first row vector of the matrix *A*. The probability of the influence of this parameter *p(1)*, characterizing the information security of the management process v_i according to the methodology for calculating Markov chains will be equal to:

$$p(1)=(0.27, 0.19, 0.17, 0.12, 0.25) x \begin{vmatrix} 0.11 & 0.29 & 0.14 & 0.2 & 0.26 \\ 0.12 & 0.19 & 0.17 & 0.25 & 0.19 \\ 0.19 & 0.25 & 0.17 & 0.12 & 0.27 \\ 0.17 & 0.27 & 0.19 & 0.12 & 0.25 \\ 0.12 & 0.17 & 0.27 & 0.19 & 0.25 \end{vmatrix} =$$

$$= (0.1393, 0.2318, 0.1893, 0.1838, 0.2447) \quad (13)$$

The probability that, being in a state S_1, information support of the control system will go into the state S_2, characterized by unstable, albeit predictable, changes in the environment is *p(2)*. Information support at this stage of management will be determined by the parameter v_2. The probability of the influence of this parameter characterizing the security of the control system v_2 and its information support from fluctuations in the external environment is equal to:

$$p(2)= (0.1393, 0.2318, 0.1893, 0.1838, 0.2447) x \begin{vmatrix} 0.11 & 0.29 & 0.14 & 0.2 & 0.26 \\ 0.12 & 0.19 & 0.17 & 0.25 & 0.19 \\ 0.19 & 0.25 & 0.17 & 0.12 & 0.27 \\ 0.17 & 0.27 & 0.19 & 0.12 & 0.25 \\ 0.12 & 0.17 & 0.27 & 0.19 & 0.25 \end{vmatrix} =$$

$$= (0.1392, 0.2218, 0.1915, 0.1763, 0.2374) \quad (14)$$

Comparison of probability parameter values represented by a row vector *p(0)*, with the corresponding probability distributions of the information support of the control system at the first stage of control *p(1)* ed to the formation of a number of practical recommendations. A comparison of identical values of the parameters presented in (11) and (13) showed their increase at the first stage of management information support, which can be considered satisfactory, except for the last parameter "effectiveness" v_5, which has decreased. This forces us to move to the next stage of control information support with the probability *p(2)*.

In conditions of instability of functioning due to unpredictable pressures of the external environment, the probability of transition of information support of the control system from the state S_2 and S_3 is equal to *p(3)*. Information support at this stage of management will be determined by the parameter v_3. The probability of the influence of this control information support parameter characterizing controllability v_3, that is, the possibility of adjusting control actions is equal to:

$$p(3)=(0.1392, 0.2218, 0.1915, 0.1763, 0.2374) x \begin{vmatrix} 0.11 & 0.29 & 0.14 & 0.2 & 0.26 \\ 0.12 & 0.19 & 0.17 & 0.25 & 0.19 \\ 0.19 & 0.25 & 0.17 & 0.12 & 0.27 \\ 0.17 & 0.27 & 0.19 & 0.12 & 0.25 \\ 0.12 & 0.17 & 0.27 & 0.19 & 0.25 \end{vmatrix} =$$

$$= (0.1368, 0.2184, 0.1874, 0.1725, 0.2335) \quad (15)$$

Comparison of identical parameters presented in (14) and (15) showed an increase for the parameters v_1 and v_3. All other parameters have been reduced. This was the basis for the transition to the next stage of management information support. It should be noted that the state p(0) characterizes only the initial state of the system without control. The first control step starts with *p(1)*. In this case, the probability of the influence of information support parameters at each control step should decrease.

The probability of transition of information support of the control system from the state S_3 into a state S_4 is equal to *p(4)*. Information support at this stage of management will be determined by the parameter v_4. It is determined by cyclic multiplication (12) by the corresponding row of the transition matrix *A*.

$$p(4)=(0.1368, 0.2185, 0.1874, 0.1725, 0.2335) x \begin{vmatrix} 0.11 & 0.29 & 0.14 & 0.2 & 0.26 \\ 0.12 & 0.19 & 0.17 & 0.25 & 0.19 \\ 0.19 & 0.25 & 0.17 & 0.12 & 0.27 \\ 0.17 & 0.27 & 0.19 & 0.12 & 0.25 \\ 0.12 & 0.17 & 0.27 & 0.19 & 0.25 \end{vmatrix} =$$

$$=(0.1342,\ 0.2143,\ 0.1839,\ 0.1695,\ 0.2291) \quad (16)$$

Comparison of identical parameters of information support of the control system, presented in (15) and (16), showed a decrease in all parameters except v_3. This served as the basis for the transition to the next stage of management. The probability of transition of information support of the control system from the state S_4 into a state S_5 is equal to *p(5)*.

$$p(5)=(0.1342,\ 0.2143,\ 0.1839,\ 0.1695,\ 0.2291)\text{x}\begin{vmatrix} 0.11 & 0.29 & 0.14 & 0.2 & 0.26 \\ 0.12 & 0.19 & 0.17 & 0.25 & 0.19 \\ 0.19 & 0.25 & 0.17 & 0.12 & 0.27 \\ 0.17 & 0.27 & 0.19 & 0.12 & 0.25 \\ 0.12 & 0.17 & 0.27 & 0.19 & 0.25 \end{vmatrix}=$$

$$= (0.1318,\ 0.2103,\ 0.1804,\ 0.1664,\ 0.2249) \quad (17)$$

Comparison of identical parameters of management information support, presented in (16) and (17), showed their decrease in all parameters. This indicates the quality of information support of the management system.

Oriented graph of Markov chains for the considered example of information support of intelligent control systems for complex organizational and technical objects presents on Figure 1.

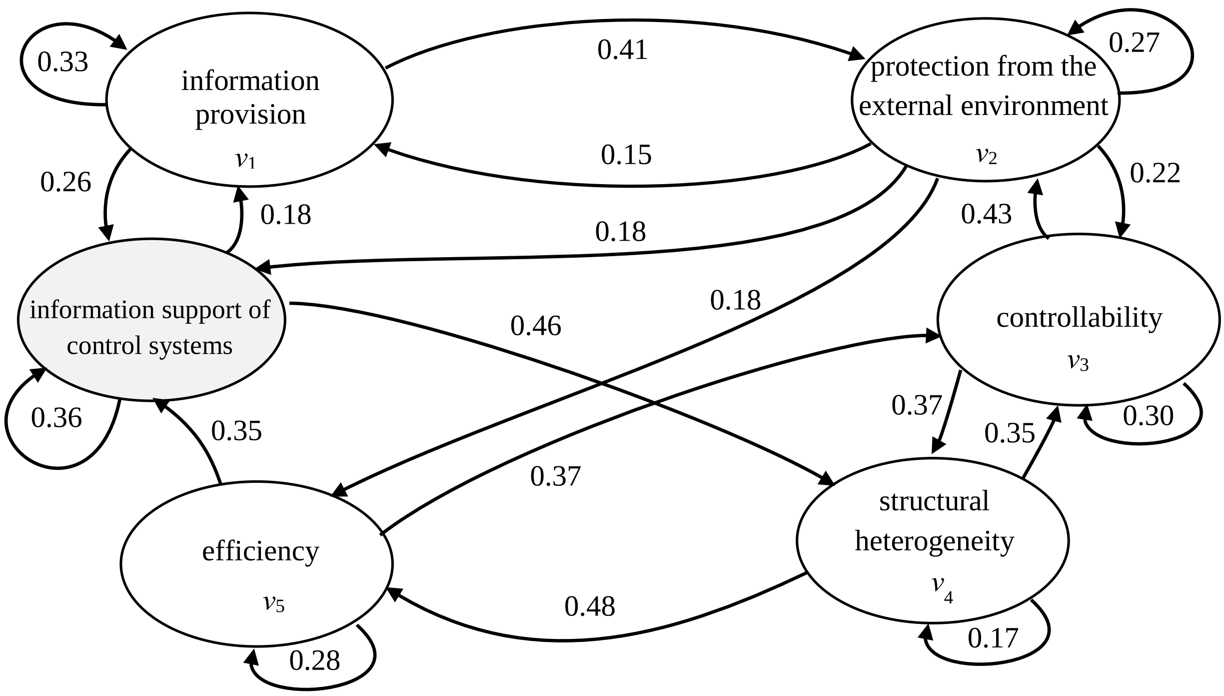

Figure 2: Oriented graph for building Markov chains for evaluating the information support of intelligent control systems for complex organizational and technical objects

Since in the presented directed graph the sum of the outgoing probabilities for each parameter of the information support of the control system is equal to 1, the presented scheme can be considered adequate to the calculations performed.

Since in the presented directed graph the sum of the outgoing probabilities for each parameter of the information support of the control system is equal to 1, the presented scheme can be considered adequate to the calculations performed.

6. Results and Discussion

Markov processes are a convenient mathematical model for various technical applications. When managing complex multi-level organizational and technical objects, depending on the values of a random process $\xi(t)$ and sets of observation moments Markov processes can be divided into moments with discrete and continuous time. The transition from one state of the system to another occurs at regular intervals, which are steps.

Problem situations arising in the process of managing complex multi-level organizational and technical objects, caused by the influence of the external environment, can be methodologically reduced to separate associative homogeneous classes of management decisions, i.e. to some set of strategic alternatives. If the analyzed problem situation is not associated with the existing classes of control alternatives, the next hierarchy level procedure for the formation of control information support is formed, which allows other properties of control information support to be involved in solving the problem.

At the initial moment of time, focusing on the initial conditions, the optimal control of the organizational and technical system is chosen in the time interval $[t_0, t]$. After some time, the state of the system changes, additional information appears, and there is a transition to the next level of the hierarchy of information support for the management process. All possible states of information support process parameters are enumerated. These iterations are carried out for various states of the intelligent control system with their own parameters and probabilities. Since the processes of transformational transformations in the control system do not have a continuous time stamp, a sequence of states can be used as time.

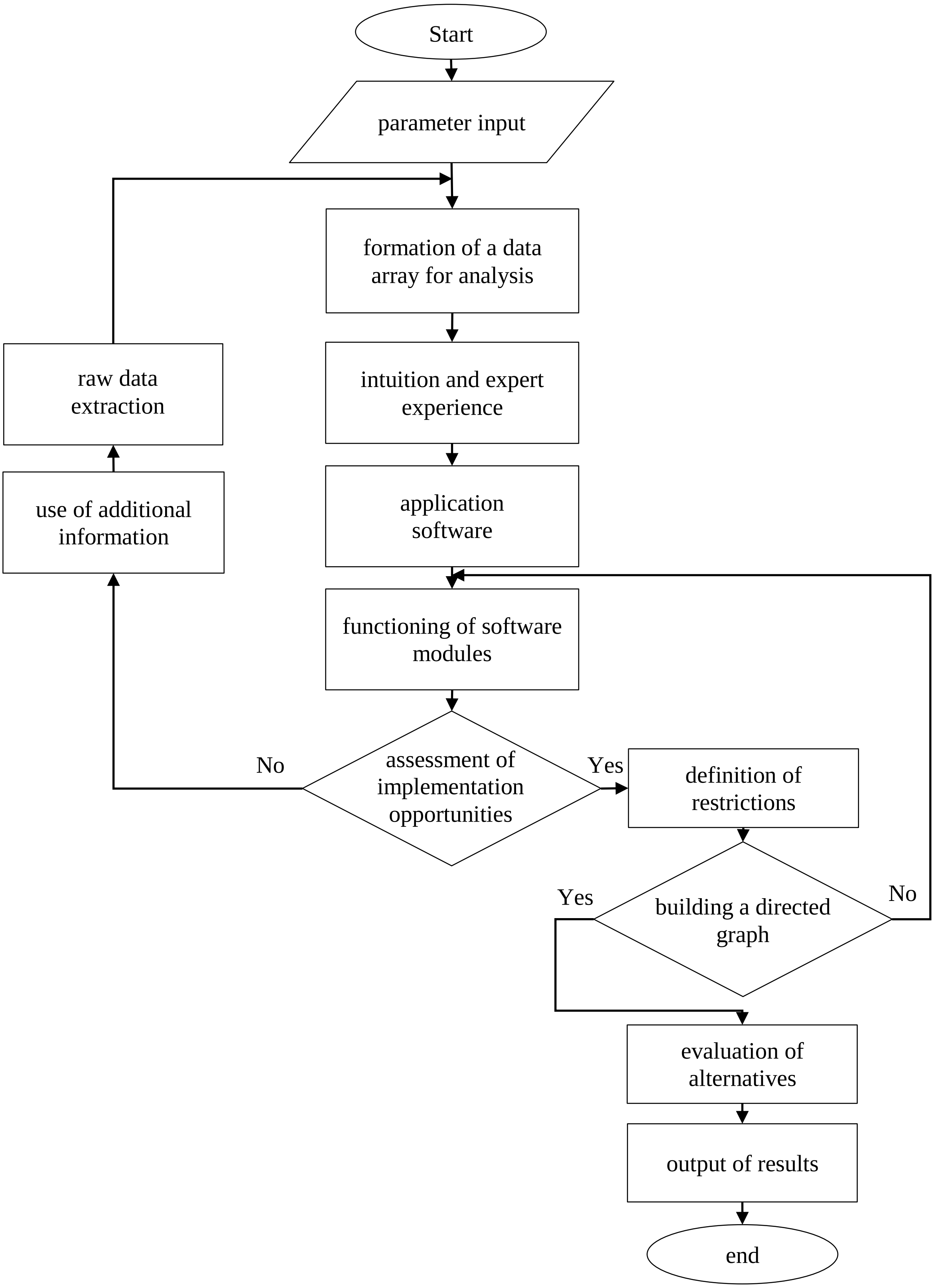

Figure 3: Structuring the information space for interactive support of management decisions under conditions of uncertainty

The proposed modernization of the use of Markov chains consists in replacing equal step intervals with a discrete sequence of states, which is determined by unpredictable external environmental influences. Such modernization of Markov chains is a novelty of use in decision-making information support in the management of multi-level organizational and technical objects.

The processes of developing and improving the management of organizational and technical systems operating under conditions of unpredictable influence of the external environment are determined by the information space.

The processes of developing and improving the management of organizational and technical systems operating under conditions of unpredictable influence of the external environment are determined by the information space, the structuring of which is shown in Figure 3.

The performed structuring of the information space for interactive support under conditions of uncertainty makes it possible to assess the scope of information support for intelligent control systems for complex multi-level organizational and technical objects, which is based on software and tools, expert systems, intelligent components, systematization of organizational processes. It is based on information retrieval, data mining, knowledge search in databases, reasoning based on precedents, simulation modeling, neural networks, cognitive modeling.

7. Conclusions

1. For information support of decision making in the management of multilevel organizational and technical objects under conditions of uncertainty, it is proposed to use probabilistic mathematical models based on Markov processes. This makes it possible to simulate and regulate the process of making relevant decisions in real time under conditions of uncertainty.
2. In contrast to the traditional use of Markov chains, information support for decision-making in the management of multi-level organizational and technical objects under the uncertainty of the influence of environmental factors provides for the replacement of equal step intervals by a discrete sequence of states determined by unpredictable external environmental influences in the study of control operations. This will contribute to solving the urgent problem of increasing the efficiency of managing organizational and technical facilities in difficult operating conditions.

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