Synthesis of a Composite Imitation Model of the Cognitive Structure of the Ergatic System Operator on the Basis of Conceptual Pattern Technology

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Abstract. To create effective training programs for operators of ergatic systems, it is necessary to investigate their cognitive structures. A powerful tool for the study of the dynamics of complex systems is simulation. Cognitive structures are considered as compositions of professionally important qualities. The technology of synthesis of a composite simulation model of the cognitive structure of the operator from patterns that implement individual professional-important qualities is proposed.

Keywords: Ergatic system, Human-operator, Cognitive structure, Information technology, Synthesis, Conceptual patterns.

1 Introduction

The effectiveness of a person's professional activity depends on his psycho-physiological state and the possibilities of mastering certain types of activity. Therefore, the actual problem is the training of an individual in certain types of professional activity, taking into account the individual characteristics of sensory, cognitive and motor responses [1]. This problem is most acute in the field of professional activity related to human-machine interaction. At present, an integrated approach is being born in the development of human-machine interaction from the standpoint of research and the formation of human cognitive structures.

We will consider the tasks of professional training of a human operator in man-machine systems. Analysis of the literature indicates that the modern concept of providing man-machine "cooperation" is based on the theory of ergatic systems. An ergatic system is a complex control system, of which the human operator is a component, and the main task is the optimal distribution of functions between the operator and the technical device and their mutual addition [2].

On the other hand, a system in which a human operator or group of operators interacts with a technical device in the process of production of material assets, management and information processing is called a human-machine system [3].

The concepts of “ergatic system” and “man-machine system” are identified in a number of works on ergonomics and engineering psychology. For example, we can find this point of view in the works of V. Mukhin [4], A. M. Bozhok and B. Kh. Draganova [5], V. A. Morozova et al. [6] etc. Other authors have a different meaning in these concepts. Among them are A. A. Piskoppel and L. P. Shchedrovitsky [7], A. P. Pyatibratov and M. Kh. Abdel-wahed [8].

In both cases, one of the objects of the system is a human operator, the need for the presence of which is determined by the following well-known factors:

- the person sets the goal of functioning, both the control object and the operation support system, and manages them to achieve this goal;

- for many reasons, an ergatic system cannot be absolutely reliable, therefore, operator intervention is required to monitor, diagnose and troubleshoot;

- due to the incompleteness and imperfection of our knowledge of all processes in the ergatic system in the external environment, situations may arise that are called algorithmically unsolvable.

According to the research of P. G. Belov [9] more than 60 % of the largest incidents of the last century were registered at the last quarter of 20-th century, and 33% of them were in 80th years. At the same time, the damage from accidents, injuries and occupational diseases in the workplace reached 7-10% of the gross national product of industrialized countries.

Analysis of the accident rate at hazardous production facilities shows that the causes of about 70% of accidents are caused by the human factor [10, 11].

The human factor is an even more significant cause of accidents in the event of adverse events (for example, natural disasters) [12].

The above literature review indicates that the modern concept of ensuring the reliability of technogenic objects is based on the theory of ergatic systems.

One of the main goals of this concept is to reduce the likelihood of critical situations and risk zones, providing a mode of sustainable functioning of ergatic systems, which is possible only using a systematic approach to its design in an interdisciplinary research format.

The need to abandon the concept of the analysis of individual operator actions in favor of a model of joint human and machine performance is shown by E. Hollangel [13]. The author emphasizes the need for a comprehensive study of man-machine "cooperation", and not "interaction", as is customary now. The use of a systematic approach was proposed as a methodological basis instead of traditional methods of analysis and reliability assessment [13].

The main procedure for a systematic approach is a decomposition of the operator’s professional qualification to the level of professionally important qualities in this context. For effective implementation of professional activity, the operator must have a certain set of professionally important qualities (PIQ) characterizing the physical, anatomical and physiological, mental and personal characteristics of a person, useful or necessary for the rapid and accurate development and solution of his professional tasks.

From the point of view of a systematic approach this set should be corresponded to the goal of the operator activity.

At present, the issues of the relationship between individual PIQs and the success of operator activities in general are not sufficiently studied, questions of developing tools for the intellectual support of managerial decisions on the degree of correspondence of the operator to the position deserve to be asked, there is an incomplete solution to the problem of professional selection and training of operational personnel based on the achievements of modern intelligent technologies.

Therefore, an important task is to study the cognitive structures of the operator in the form of compositions of PIQ, the possibilities of the development of PIQ, taking into account their mutual influence.

2 Research Methods

Modeling of the operator’s cognitive structures is used to solve the task with the necessary completeness and versatility to achieve practical results. The features of cognitive structures, primarily their dynamic complexity, complicate the creation of models significantly.

Simulation in such cases allows for the most effective use of the experience and intuition of specialists in the study of complex systems. The development of computing technology led to the appearance in the 1960s of a specialized method of simulation modeling - system dynamics [14]. The method of system dynamics allows for exploring the behavior of complex systems, based on the possibilities of computer simulation. In contrast to the "traditional" methods of computer modeling, system dynamics gives the researcher the tools for modeling in the form of computer-implemented analytic descriptions of system elements and the connections between them.

Initially, the method was known as “industrial dynamics” and was used exclusively to study management problems in production [14]. After some time, this name ceased to correspond to the content, since the application of the method turned out to be much wider. It turned out to be effective for solving other problems, for example, related to urban dynamics, resource management, and the spread of diseases etc. Due to the fact that this method can be used for modeling and studying practically any complex systems, it was called system dynamics [15, 16, 17].

System dynamics is aimed at studying not the systems themselves, but the tasks associated with these systems. The main features of such systems is that they are dynamic, contain feedback loops, and their structure is characterized by delays, non-linearity and variability of the causes of complex behavior.

System dynamic models are not able to form their own solution in the form in which it takes place in analytical models, but can only serve as a means to analyze the behavior of the system under conditions that are determined by the experimenter [18].

An important component of system dynamics is the dialogue between the researcher, developer, designer in the modeling process with a complex that implements the model, which allows the most use of the experience and intuition of specialists in the study of real complex systems [19]. This is necessary to control the current results and the ability to adjust the development of the simulated situation in order to obtain new knowledge about the nature of the processes being studied, as well as to train specialists in working with new systems.

On the other hand, system dynamics has a significant limitation — limited modeling accuracy and the impossibility of its a priori estimation (an indirect characteristic of accuracy can be provided by analyzing the model's sensitivity to changes in individual parameters of the systems under study). In addition, developing a good dynamic model is often more expensive than creating analytical models and is time consuming. Nevertheless, system dynamics is one of the most widely used methods for solving the problems of synthesis and analysis of complex systems.

J. Forrester formulated the basic principles of the system dynamics method, which allow him to be considered as a method, despite the absence of a rigorous theoretical justification (14). And although it seems to people with a high mathematical background that system dynamics is a brute force technique, nevertheless, this method is the most common tool in the hands of a scientist involved in the problems of research and management of complex systems. J. D. Sterman refers to Weston's research [20], which examined the 1000 largest US firms in terms of analyzing the suitability of certain methods for in-house planning. The results of this study are shown in tab. 1.

Table 1. Methods most commonly used in corporate planning

Methods	Frequency of using	Percent
Simulation	60	29
Linear programming	43	21
Theory of scheduling	28	14
Inventory theory	24	12
Nonlinear programming	16	8
Dynamic programming	8	4
Integer programming	7	3
Queueing theory	7	3
Other	12	6

The system dynamics method is based on four principles that determine the effectiveness of the method [14, 15].

The first principle: the dynamics of the behavior of an arbitrarily complex process can be reduced to a change in the values of some "levels", and the changes themselves can be regulated by flows filling or exhausting the levels.

The level accumulates the total amount of the studied "product", which is the result of flows entering and leaving it, the values of which are added or subtracted from the level. System levels fully describe the state of the system at any given time. The values of the levels are the information necessary for making decisions and justifying the control actions on the system. Levels provide the system with inertia and a "memory" of states; they create delays between the inflow and outflow as a cause and effect.

Changes in levels are caused by the corresponding flows.

A level can have a fixed value, or it can be controlled as a function of level values. Also the flow has a direction.

Thus, the totality of levels and flows implementing a model of the dynamics of the behavior of an "arbitrarily complex process" will be a system very similar to a water supply system consisting of various containers and pipes connecting them. But instead of physically simulating the dynamics of the system's behavior with the help of "water supply", it's convenient to use mathematical descriptions of the elements of the system dynamics model for this purpose, and to simulate the processes taking place in the system under study, use numerical methods for integrating these equations.

The concepts of levels and flows are present in many areas of human knowledge. Here are some examples: in mathematics these are integrals and derivatives, in physics these are stable states and transitions, in chemistry these are reagents, reaction products and chemical reactions themselves, in economics these are levels (e.g. welfare) and flows (e.g. labor force), in accounting these are stocks and flows (financial and material), in medicine these are the state of the body and the spread of infection, and so on. This list can be continued for a very long time, which indicates the obviousness of the proposed system dynamics principle proposed by J. Forrester [15].

The second principle: all changes in any system are determined by "feedback loops". The feedback loop is a closed chain of interactions that connects the original action with its result, which changes the characteristics of the surrounding conditions, and which, in turn, are "information" that causes changes.

The third principle: feedback loops in any system are often connected non-linearly. Essentially, this means that information about system levels through feedback indirectly affects levels in a disproportionate and sometimes difficult to predict mode

The fourth principle: system dynamics is a purely pragmatic apparatus that is able to most adequately reflect the nontrivial behavior of a network of interacting flows and feedbacks. It is advisable to apply it only when traditional approaches are ineffective, when the behavior of objects cannot be accurately mathematically described and only rough estimates are possible

The widespread use of system dynamics as a method of solving problems in various fields of human activity is becoming increasingly apparent. Therefore, despite the lack of mathematical elegance, system dynamics is one of the most widely used methods used to solve research and control problems.

But the construction of a composite model from them in the case when the object of study is a complex system becomes difficult. Therefore, the main focus of the research was on the search for ways to formalize and automate this process. Conceptual modeling was chosen as a vehicle for this. The conceptual model is used to move from the knowledge of experts to their uniform formal description. After that, a formal synthesis of the system dynamics model becomes possible [21].

The use of conceptual model for the formalization and integration of collective expert knowledge is presented in detail in our research [22].

3 Synthesis of System Dynamics Models based on Conceptual Patterns Technology

Based on the proposed technology [5], a single conceptual model of the cognitive structure of the operator was obtained, combining the formalized knowledge of an expert group in the form of one or more tree structures, which further provides a formal synthesis of systems dynamics models.

The conceptual model is implemented in the form of a knowledge base consisting of declarative and procedural knowledge [6].

In order to solve the problems formulated, declarative knowledge is highlighted as follows:

– tree of goals of the professional activity of the operator *Tr*, contains a decomposition of the global goal and the material relations between them, taking into account the view of the problem of each expert;

– the set of patterns *A*;

– the set of instances of patterns *E*;

– the directories *V = {Vk, W}*.

The set concepts and terms are denoted by *V*. (The base contains information of domain, for example, different coefficients and constants. The set of norms and constants is denoted *W*.)

In turn, the goal tree can be formally written as the union of the set of vertices of all decomposition levels and the set of primitives — vertices for which no further splitting is performed:

$$Tr = \bigcup_{k=1}^{n_k} V^k \bigcup L$$

where k is the hierarchy level,

n_k is the number of vertices of the goal tree at the k-th level of the hierarchy.

$V^k = \bigcup_{l=1}^{m} V_l^{k-1}$ is the set, that is union of the vertices of the lower level, where m is the number of lower vertices for the given vertex.

The set *L* is the set of primitives of the conceptual model. The selection of these vertices into a separate set is due to the presence of a group of special inference procedures that perform actions only on elements from this set.

The pattern [7] implies a certain structure having a steady-state structure and a set of input, output parameters and initial values. In this paper, the pattern is implemented as a construct in the language of system diagrams.

Formally, a pattern can be represented by the following entry in the language of theory of sets:

$$P = \{St, Fn, X, Y, I\},$$

where *St* is the pattern structure, *Fn* is the pattern operation law, *X* is the set of pattern input parameters, *Y* is the set of pattern output parameters , *I* is the set of initial values.

In this paper, the pattern is considered as a “black box” with input and output parameters (Fig. 1.).

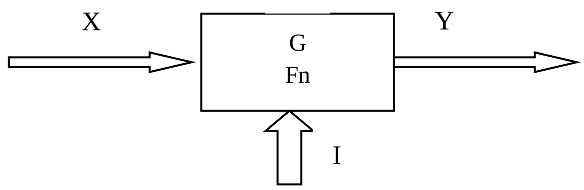

Fig. 1. The formal pattern “black box”.

You must distinguish the pattern from the pattern instance. A pattern instance is a filled pattern that contains information not only about the composition and structure of the pattern, but also the specific values of the input, output and initial parameters of the pattern and, in addition, each instance is addressed (corresponds) to one of the primitives of the goal tree.

The declarative knowledge base contains facts that include: a set of pattern, mapped by experts to primitives, the goal tree itself, a set of auxiliary variables, reference books containing textual knowledge about the subject area under study.

Procedural knowledge of experts is implemented in the knowledge base in the form of inference procedures that allow for formalizing the process of synthesizing a dynamic model. The input of the procedures is the declarative knowledge of the knowledge base; the output is obtained fragments of system-dynamic models. Inference procedures are mappings of the structure of the conceptual model to the structure of dynamic models.

The knowledge base contains three groups of inference procedures:

1. Inference procedures that define covering actions for each model template. We will call them matching procedures.
2. Inference procedures that determine the material relationships between patterns in a dynamic model.
3. Inference procedures that determine the informational relationships between patterns in a dynamic model.

By sequentially performing these procedures, we obtain a composite model:

1) The conclusive procedures *D* and *d* determine covered operations for each pattern, i.e. how it (matches) opposites to the primitive of the goal tree.

   a) The direct procedure for matching the primitive to the pattern.

The task of this procedure is to cover the primitive of the goal tree of the concept model by pattern, specifically, by instance of pattern.

Let Tr be a set of top points of the goal tree of the concept model, $L \subset Tr$ – a set of finite leaves – primitives, then procedure D can be defined as a mapping of the set of primitives to the set of instances.

$$D : L \to A , \quad (1)$$

what is more, $\forall l_i \in L \ \exists a_j \in A$: $f_i = Fn_j$, $i = \overline{1,m}$, $j = \overline{1,k}$,

where f_i is the goal of the primitive, Fn_j is the goal of pattern functioning (operation),

m is the number of primitives of the goal tree of the conceptual model,

k is the number of pattern instances.

That is, for any primitive there is an instance of the pattern covering it, if the law of the functioning of the pattern covers (satisfies) the goal (s) of the primitive.

Thus, the matching process is based on the functional coverage of the primitive goal by pattern $(f_i=Fn_j)$.

b) The procedure for specifying an instance.

To determine this procedure, it is necessary to introduce additional sets:

Let E be a set of all instances in the model, and A is a set of all patterns.

The procedure d can generally be represented as a mapping of multiple patterns to multiple terms and norms.

$$d: \ D(L) \rightarrow V \cup W , \tag{2}$$

what is more,

$\forall a_i \in A \ \exists e_j \in E$: $(\forall s \in St_i \rightarrow v \in V)$ and $(\forall c \in I_i \rightarrow w \in W)$, $i = \overline{1,n}$, $j = \overline{1,k}$,

where n is the number of patterns in the system, k is the number of instances in the system.

That is, for any pattern from a set of model patterns, there is an instance only when each element of the pattern structure contains a corresponding element of a set of concepts and terms and when each initial value of the pattern is given a value from the norm base - a set of coefficients and constants W.

In other words, the task procedure fills the model patterns with specific content, which is taken from the directories (reference information), thereby creating many model instances.

2) The inference procedure that defines the material relationships between the instances of the patterns.

In this context, material relations are meant the linking of individual instances via the flows. Not only material resources, but also abstract objects can be transmitted through the flows in system dynamics. However, here a fundamental difference from the information connection between the patterns, which will be discussed below, is emphasized.

At this paper, the instance of pattern is the system-dynamic model that has its own structure and content (compound), input and output parameters. The flows are as input and output parameters, which can “inflow/outflow” (to/from), in other words, to be taken and to be provided as parameters to other patterns.

The main purpose of the above proposed withdrawal procedures is the formation of a new “higher level” submodel based on already formed “lower level” submodels in accordance with the hierarchy of goals.

Graphically, these procedures can be represented as shown in Fig. 2.

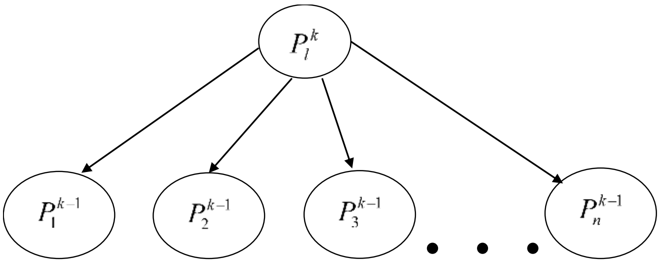

Fig. 2. The fragment of the goal tree.

Let P_1^{k-1}, …, P_n^{k-1} are known patterns, h. e., functionally cover the corresponding vertices of the goal tree.

It is necessary to determine the rules for inferencing the sub model from these patterns, which covers parent vertex of the pattern tree P_l^k functionally. Where k is an hierarchy level of the goal tree vertex, $l = 1,\dots,n_k$, n_k is the number of vertices at the k-*th* hierarchy level.

In the general case, the parent vertex $P_l^k = \{< P_i^{k-1}, P_j^{k-1} >\}$, that is, represent a set of pairwise ordered pairs of its child vertices. Our task is to determine the binding procedure:

$$P_l^k = \varphi(\overline{P}_l^k) = \varphi(P_1^{k-1}, P_2^{k-1}, \dots, P_{n_{k-1}}^{k-1}) \tag{3}$$

In the general case, with the requirement that all patterns become instances after they are filled, the procedure φ can be represented as a mapping of a subset of instances to the product of the same subset of itself.

$$\varphi : E_l \to E_l \times E_l \text{, where } E_l \subset E \text{,} \tag{4}$$

what is more, $\forall e_i \in E_l \ \exists \ e_j \in E_l$: $< ei, ej > \in E_l \times E_l$, $i, j = \overline{1, n_k}$, n_k is the number of patterns in E_l: (n_k < n).

So, scheme of mapping φ_k may be represented as a matrix φ_k ($n_k \times n_k$), rows and columns that match instances of model patterns. The values of the elements of this matrix represent the presence of relationships between existing models of models at the k-th hierarchy level.

Before describing the principles of matrix construction φ_k ($n_k \times n_k$), it is necessary to mention about union types between patterns. Two connection types are considered in this paper.

1. The series connection.

Here the output data, in our case represented by the flows, of one pattern is the input of another (Fig. 3.). An explanation should be made here that the case when the input and output data are vectors is considered in the paper. For this reason, for simplicity of constructing the synthesis algorithm, situations are taken into account when the dimensions of the output and input vectors coincide, and the remaining cases are discarded.

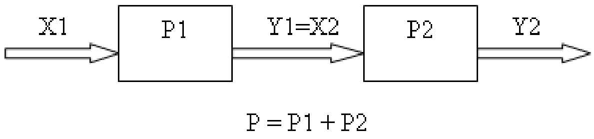

Fig. 3. The example of a series connection of patterns.

2. The parallel connection.

In this type of union patterns, both patterns are included in the “higher level” model, and their input and output parameters are not connected in any way. In this case, only information relations between two patterns can occur, and the simultaneous modeling of these patterns is implied (Fig. 4).

To define a formal relationship between two patterns, redefine the standard notation for arithmetic operations: + - serial connection, * - parallel connection.

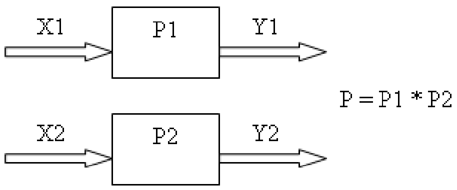

Fig. 4. The example of parallel connection of patterns.

Therefore, the notation $P = P1 + P2$ means that $\forall y_i \in Y1 \ \ \exists x_j \in X2 : y_i = x_j$, $i = \overline{1,m},\ j = \overline{1,n}$, n is the number of input parameters of the pattern $P2$, m is the number of output parameters of $P1$, actually $n = m$ (in this case).

Define the matrix k ($n_k \times n_k$).

$$\varphi_k = \begin{cases} 2, \text{ if } e_i * e_j \\ M_{ij}, \text{ if } e_i + e_j \\ 0, \text{ if } i = j \text{ if no connection between patterns} \end{cases} \tag{5}$$

where $i = 1, j = 1,\ldots, n_k$,

e_i , e_j – instances of patterns k-th level, if parent vertex is κ+1 level,

M_{ij} – the matrix of conjugation of the input and output parameters of two copies.

In the trivial case, when each instance is supposed to have one input and output parameter, they do as follows: if there is a serial connection between the patterns, then the current matrix element will be equal to 1.

In the nontrivial case, the element M_{ij} is also a matrix

$$M_{ij} = B_{tp} = \begin{cases} 0, \text{if } y_t \neq x_p \\ 1, \text{if } y_t = x_p \end{cases} \quad (6)$$

where $t = 1$, $p = 1, \ldots, m$, m – the number of input/ output parameters of patterns.

Thus, using the procedure described above, the material interconnection of the model patterns is established between themselves, that is, the relationship due to flows.

1) Inference procedures that determine the information relations of the system-dynamic model.

In system-dynamic models, in addition to material relations realized through the flows, information relations are widespread, the main purpose of which is to transmit information about values between model elements during the simulation process.

In the proposed approach, three types of information relations are considered depending on the type of interaction objects: the relationship between the structure elements of two patterns, the relationship between the auxiliary variable and the structure element of the pattern, the relationship between the structure element of the pattern and the auxiliary variable.

a) An inference procedure that defines informational relationships between structural elements of two instances of patterns.

Let $E_l \subset E$ be a subset of the set of model instances and contain instances covering all the child vertices of the parent vertex P_l^k of the goal tree (k is the hierarchy level, l is the vertex index at this level).

There after a mapping

$$\psi : E_l \rightarrow E_l \times E_l,\ E_l \subset E , \quad (7)$$

moreover $\exists\, e_i \in E_l\ \exists\, e_j \in E_l$:

$< e_i, e_j > \in E_l \times E_l$, $i, j = \overline{1, n_k}$, n_k is the number of patterns in E_l

$\exists\, s_p \in St_i \in e_i\ \exists\, s_t \in St_j \in e_j : < s_p, s_t > \in St_i \times St_j \subset E_l \times E_l$,

where $s \in [1; m_i]$ and $p \in [1; m_j]$, m_i and m_j – the number of elements of the structure in instances e_i and e_j respectively.

The first statement says that there is an information connection between two copies of the set E_l, and the second indicates between which elements of the structure of the copies this connection is established.

Consequently, the operator ψ can be represented as a mapping of a subset of the set of instances to the Cartesian product of this set by itself, indicating the elements of the structure of the instances between which an information relation is established in the general case.

The scheme of mapping ψ can be represented as a square matrix $\psi(n_k \times n_k)$, the rows and columns of which correspond to elements of the set E_l. The values of the elements of this matrix are determined by the presence of a connection between the corresponding instances of this set.

$$\psi_{ij} = \begin{cases} B_{ij}, \text{if } e_i \in E_l \ \exists e_j \in E_l :< e_i, e_j > \in E_l \times E_l, i, j = 1, n_k \\ 0, \text{if not} \end{cases} \tag{8}$$

In turn, the element B_{ij} of the matrix $\psi (n_k \times n_k)$ is also the matrix B ($m_i \times m_i$), where m_i and m_j are the number of structural elements in instances e_i and e_j, respectively. The form of this matrix can be determined as follows:

$$B_{p,t} = \begin{cases} 1, \text{if } s_p \in St_i \subset e_i \ \exists s_t \in St_j \subset e_j :< s_p, s_t > \in St_i \times St_j \\ 0, \text{if not} \end{cases} \tag{9}$$

b) The inference procedure that defines the information relations between auxiliary variables and instances of model patterns is defined as the mapping of the set of auxiliary variables Vk obtained by adding expert knowledge about the modeling object to the product of this set with the set of instances of model E_l, which is a subset of the set of all instances of model E.

In the process of practical work on building system dynamic models based on patterns, the fact was revealed that to build an adequate model some patterns are not always enough. For this reason, many auxiliary variables have been introduced into the conceptual model. The main purpose of these objects is to supplement the model built on the basis of patterns with expert comments (estimates).

Let Vk is the set of auxiliary variables of the model, and E_l is the subset of instances of the model, thereafter

$$R1 : Vk \to Vk \times E_l, \ E_l \subset E \tag{10}$$

$$\text{moreover, } \forall v_i \in Vk \ \exists e_j \in E_l : < v_i, e_j > \in Vk \times E_l, \tag{11}$$

where $i = 1,\ldots,k$, k is the number of auxiliary variables of the model,

$j = \overline{1, n_k}$, n_k is the number of patterns in E_l

Taking into account that each instance has its own internal structure and any element of the structure, i.e. $e_j = <St_j, Fn_j, X_j, Y_j, I_j>$, then statement (11) can be written in the following form:

$$\forall v_i \in Vk \ \exists e_j \in E_1 | \ \exists s_k \in St_j : < v_i, s_k > \in Vk \times St_j \subset Vk \times E_l \tag{12}$$

The scheme of mapping $R1$ can be represented as a square matrix $R1$ ($k \times n_k$), the rows of which correspond to elements of the set of auxiliary elements Vk and columns correspond to elements of the set E_l.

The values of the elements of this matrix are determined by the presence of a connection between the corresponding elements of these sets.

$$R1_{ij} = \begin{cases} A_{ij}, \text{if } v_i \in Vk \ \exists e_j \in E_1 :< v_i, e_j > \in Vk \times E_1 \\ 0, \text{ if not} \end{cases} \tag{13}$$

In turn, an element A_{ij} of the matrix $R1$ ($k \times n_k$) is vector A (m_j) also, where m_j is the number of elements of the instance structure e_j. The form of this vector is defined as follows:

$$A_t = \begin{cases} 1, \text{if } v_i \in Vk\ \exists s_t \in St_j \in e_j :< v_i, s_t > \in Vk \times St_j \\ 0, \text{ if not} \end{cases} \tag{14}$$

c) An inference procedure that defines the information links between the elements of the structure of the pattern and auxiliary variables. It is defined as a mapping of the set of instances of the model E_l, which is a subset of the set of all instances of the model E to the product of this set with the set of auxiliary variables of the model Vk.

$$R2 : E_l \to E_l \times Vk,\ \ E_l \subset \mathrm{E} \tag{15}$$

$$\text{moreover } \exists\ e_i \in E_l\ \exists\ v_j \in Vk : < e_i\ , v_j > \in E_l \times Vk, \tag{16}$$

where $i = \overline{1, n_k}$, n_k – the number of patterns in E_l , $j = 1,...,k$, k is the number of auxiliary variables of the model.

Taking in account, that each instance has its own internal structure and any element of the structure can act as a parameter of information communication, i.e. $e_i = <St_i , Fn_i, X_i , Y_i , I_i>$, then statement (16) can be written in the following form:

$$\exists\ (e_i \in E_l \mid \exists\ s_k \in St_i\ )\ \exists\ v_i \in Vk\ : < s_k , v_i > \in\ St_j \times Vk \subset E_l \times V_k \tag{17}$$

The scheme of mapping $R2$ can be represented as a square matrix $R2$ ($n_k \times k$), the columns of which correspond to elements of the set of auxiliary elements Vk, and rows correspond to elements of the set E_l. The values of the elements of this matrix are determined by the presence of a connection between the corresponding elements of these sets:

$$R2_{ij} = \begin{cases} C_{ij}, \text{if } e_i \in E_l\ \exists v_j \in Vk :< e_i, v_j > \in E_l \times Vk \\ 0, \text{ if not} \end{cases} \tag{18}$$

In turn the element C_{ij} of the matrix $R1$ ($k \times n_k$) is a vector also, where m_i is the number of elements of instance structure e_i. The form of this vector is define as follows:

$$C_t = \begin{cases} 1, \text{if } \ s_t \in St_i \in e_i \exists v_j \in Vk :< s_t, v_j > \in St_j \times Vk \\ 0, \text{ if not} \end{cases} \tag{19}$$

Application of the given procedures to the corresponding sets of declarative knowledge provides a formal synthesis of the composition and structure of the dynamic model, adequate to the declarative knowledge of the knowledge base, which is the implementation of the conceptual model of the studied subject area.

4 Evaluation of Accuracy of a Composite Model

A technique for quantifying the accuracy of recurrent dynamic models implemented in instrumental environments using standard integration methods is proposed by V. V. Bystrov [7, 8].

The simulation errors considered below are by their nature approximation errors and, at the stage of creating corresponding models, they can be attributed to method errors. As a basic approach to quantifying errors, the method of the reference model was used in the following modification, directly oriented to simulation modeling.

Assuming that:

1. the studied dynamic model M is a precisely known and unambiguously determined composition of relatively independent submodels;

$$M = K\{\, M_i \mid i \in I \,\} \tag{20}$$

2. for each of the M_i sub-models named in paragraph (1), a reference linear recurrent model

$$< M_i\,;\ \Delta T_i > \text{ is known, } \ i \in I\,;$$

3. the only sources of error for the compositional model under investigation are:

   a) deviation of the system-wide time from the elementary cycles of the sub-models;
   b) the integration method used.

An additional essential assumption for the proposed approach is the assumption about the smoothness of the nominal characteristic function of errors within the real error band of each of the used submodels M_i, $i \in I$. In practice, this assumption allows the real error curves of submodels within the error band to be replaced by the smoothed (in other words, properly filtered) curve.

It should also be noted that the reasons for errors specified in paragraph (3) are additive. The circumstance specified here allows instead of a set of reference models $< M_i\,; \Delta T_i >$, $i \in I$, for each integration method, simply consider the corresponding cumulative nominal error functions (CNEF).

In the considered method of estimating the methodological error of recurrent dynamic models for the construction of CNEF, linear, parabolic, cubic approximation of functions were used. For each type of approximation, optimization theorems are proved, on the basis of which an analysis of methodological errors is constructed, which made it possible to carry out and substantiate the correctness of the choice of the optimal integration step for composite dynamic models. The statements of the theorems are given below. The proof of the theorems was carried out using the mathematical apparatus and methods of the theory of extreme problems, namely, linear programming, since the problem of studying methodological errors can be reduced to the problem of finding extreme points of the generalized error function of the composite model.

The system time is considered to be a valid value from the interval [0, 1], which is achieved by simple normalization of the values of the elementary cycles of the submodels, i.e. scaling with the coefficient

$$\frac{1}{\max\limits_{i\in I} \Delta T_i}$$

of the set $\{\Delta T_i \mid i \in I\}$ characteristic cycles of submodels. In addition, it is further considered $i=\overline{1,2}$, that this will avoid the need for a detailed account of the "inversion" points for the error curves of the submodels on the set of values of the reduced cycles.

Thus,

$$\frac{1}{\max\limits_{i\in I} \Delta T_i} * \min_{i\in I} \Delta T_i = a \le b = 1$$

the normalized cycles of submodels, with the corresponding error functions $f_1(t)$ and $f_2(t)$.

Theorem 1. If CNEF $f_i(t)$, $i=\overline{1,2}$, decomposition elements $\{M_1; M_2\}$ of the dynamic model M are linear with respect to t, then the optimal value $\Delta T*$ of the system time minimizing the error of approximation of M coincides with one of the boundaries of the interval $[a, b]$.

Theorem 2. The pair composition of recurrent dynamic models with the same type of CNEF of the form (21) achieves the smallest approximation error for

$$\Delta T = \frac{k_1 a + k_2 b}{k_1 + k_2} \quad \text{and} \quad \begin{cases} f_1(t) = k_1 (t-a)^2 \\ f_2(t) = k_2 (t-b)^2 \end{cases} \tag{21}$$

Theorem 3: The set of optimal system time values for a pair composition of recurrent dynamic models that have the same type of CNEF type (22) is non-empty and contains at least one point of the set

.

$$\left\{ \frac{(k_1 a - k_2 b) + (b-a)\sqrt{k_1 k_2}}{k_1 - k_2} ; \frac{(k_1 a - k_2 b) - (b-a)\sqrt{k_1 k_2}}{k_1 - k_2} \right\} \quad \text{and}$$

$$\begin{cases} f_1(t) = k_1 (t-a)^3 \\ f_2(t) = k_2 (b-t)^3 \end{cases} \tag{22}$$

Theorems 2 and 3 allow for generalization the results obtained to multiple compositions of recurrent submodels possessing linear CNEF. The empirical method of differentiation of the branches of the CNEF intermediate models can be used as the basis for the formation of the composite error function.

5 Conclusion

For the purpose of studying the cognitive structures of a human operator of ergatic systems, an information technology has been developed for the conceptual synthesis of simulation models (cognitive structures). The technology is based on the use of conceptual modeling. The implementation of the conceptual model in the form of a knowledge base provides for the autonomous use of expert knowledge for the automated synthesis of simulation models. Formal procedures that provide synthesis based on the conceptual model of the corresponding simulation model from a set of patterns. A technique for the quantitative assessment of accuracy is proposed, which makes it possible to optimize the choice of the integration step for composite simulation models built from patterns.

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References

1. Petukhov I., Steshina, L, Kurasov, P, Tanryverdiev, I.: Decision Support System for Assessment of Vocational Aptitude of Man-machine Systems Operators. In: IEEE 8th Int. Conf. on Intelligent Systems IS'16, Sofia, Bulgaria, pp. 778-84 (2016).
2. Petukhov, I. V.: Decision support system in assessing the professional suitability of the operator of ergatic systems (for example, transport and technological machines) DSc Thesis (Ufa:USATU), 411 pages (2013).
3. Man-machine system. Soviet encyclopedic dictionary, Sovetskaya Entsyklopedia, Moscow, 1226 pages (1980).
4. Mukhin, V. I.: Research of Control Systems. Analysis and Synthesis of Control Systems, "Examen", Moscow, 383 pages (2003).
5. Bozhok, A. M., Draganov, B. Kh.: On the ergonomics of agricultural vehicles. Energetika i avtomatika: electronic scientific journal 3 (2010). http://www.nbuv.gov.ua/e-journals/eia/2010_3/10bameav.pdf
6. Morozova, V. A.: The Technology of Using Expert Systems for Automated Control of Energy-Eco-Efficient Processes in Metallurgy. In: All-Russian Scientific and Practical Conference on Automation Systems in Education, Science and Production, Novokuznetsk, SibGIU, pp. 18 – 22 (2007).
7. Piskoppel, A. A., Shchedrovitsky, L. P. 1982 from the "man-machine" system to the "sociotechnical" system. Psychology 3 pp 15 – 25 (1982).

8. Pyatibratov, A. P., Abdel-wahed, M. Kh.: Conceptual provisions for assessing the reliability and fault tolerance of a distributed local computer network (DLCN). University Open Education: Scientific and Practical Journal 5, 52-56 (2006).
9. Belov, P. G.: Theoretical Foundations of the Management of Technological Risk. Abstract of DSc, STC PS, Moscow, 32 pages (2007).
10. Magid, S. I., Arkhipova, E. N., Muzyka, L. P.: The reliability of personnel is one of the main guarantees of energy security. Reliability and safety of energy 1, 22 – 33 (2008).
11. Pulikovsky, K. B.: Priority to the quality of training, Vocational Training and Certification of Employees of Organizations Supervised by Rostekhnadzor. Labor Safety in Industry 7, 2-8 (2006).
12. Velev., D, Zlateva, P.: Augmented and Virtual Reality Application in Disaster Preparedness Training for Society Resilience. In: 18th International Multidisciplinary Scientific GeoConference (SGEM 2018), vol. 4.3, pp 195-202 (2018).
13. Hollangel, E.: Human reliability assessment in context. Nuclear engineering and technology 37(2), 159-66 (2005).
14. Forrester, J. W.: Industrial Dynamics, Portland, OR: Productivity Press, 464 pages (1961).
15. Forrester, J. W.: Urban Dynamics, Portland, OR: Productivity Press, 285 pages (1969).
16. Forrester, J. W. , Senge, P. M.: Tests for Building Confidence in System Dynamics Models. In Legasto Jr. A .A. (Ed.) System Dynamics. Studies in the Management Sciences, New York, North-Holland, pp. 209-228 (1980).
17. Roberts, N., Andersen, D., Deal, R., Garet, M., Shaffer, W.: Introduction to Computer Simulation: A System Dynamics Modeling Approach, Portland, OR, Productivity Press, 562 pages (1983).
18. Shannon, R.: Systems Simulation: The Art and Science, “Mir”, Moscow, 417 pages (1978).
19. Pavlovsky, Yu. N.: Course of Lectures: Simulation Models and Systems. “Phasis”, Moscow, 122 pages (1998).
20. Sterman, J. D.: Business Dynamics: Systems Thinking and Modeling for a Complex Word. Irwin/ McGraw-Hill, Boston, MA, 768 pages (2000).
21. Gorokhov, A. V.: Synthesis and analysis of models of system dynamics of regionalsocial and economic development. DSc Thesis, ISA RAS, Moscow, (2003).
22. Gorokhov, A. V., Petukhov, I. V., Steshina, L. A.: The Integration Technology for Collective Expert Knowledge in the Tasks of Developing Scenarios for Vocational Guidance and Employees’ Rehabilitation Eurasia. Journal of Mathematics, Science and Technology Education 13 (11), 7517-7526 (2017). doi:10.12973/ejmste/80012.
23. Putilov, V. A., Gorokhov, A. V.: System dynamics of regional development. Research Center “Pazori”, Murmansk, 306 pages (2002).
24. Bystrov, V. V.: The organization of the knowledge base in the automation of the synthesis of dynamic models of complex systems. Vestnik Pomorskiy University 6, 111-118 (2006).
25. Bystrov, V. V., Gorokhov, A. V.: Information technology of conceptual synthesis of dynamic models of complex systems. Information technologies in regional development 7, 69-77 (2007).