DOI: 10.15587/978-617-8360-23-8.CH4

4 DEVELOPMENT OF A POLYMODEL RESOURCE MANAGEMENT COMPLEX FOR INTELLIGENT DECISION SUPPORT SYSTEMS

Andrii Shyshatskyi, Ganna Plekhova, Danylo Pliekhov, Oleksii Nalapko, Oksana Dmytriieva, Ivan Starynskyi

ABSTRACT

Intelligent decision support systems are the object of research. The problem that is solved in the research is to increase the accuracy of modeling the process of functioning of intelligent decision support systems. The development of a polymodel resource management complex of intelligent decision support systems was carried out. The originality of the research is:

– in a comprehensive description of the process of functioning of intelligent decision support systems;

– the ability to simulate both a single process that takes place in intelligent decision support systems, and to comprehensively simulate those processes that take place in them;

– in establishing the conceptual dependencies of the process of functioning of intelligent decision support systems. This allows to describe the interaction of individual models at all stages of solving calculation tasks;

– descriptions of coordination processes in hybrid intelligent decision support systems, which increase the reliability of management decision-making;

– modeling of processes for solving complex calculation tasks in intelligent decision support systems, due to the conceptual description of the specified process;

– coordination of calculation processes in intelligent decision support systems, which achieves a decrease in the number of computing resources of systems;

– comprehensive dispute resolution, due to a complex of appropriate mathematical models.

The proposed polymodel complex should be used to solve the task of managing intelligent decision support systems characterized by a high degree of complexity.

KEYWORDS

Intelligent decision support systems, complex modeling, efficiency, reliability, coordination.

Intelligent decision support systems (IDSS) are an integral component of all spheres of human social activity and are used to solve a wide range of tasks, from entertainment to highly specific ones [1–3].

The main tasks to be solved by IDSS are [3–5]:

– solving various computing tasks in the interests of a wide range of consumers, regardless of their field of application;

– storage of calculation results and also intermediate results for user needs;

– support decision-making by the persons who make them;

– provide prerequisites for intelligent decision-making.

Trends in the development of modern IDSS are aimed at solving the following tasks [4–8]:

– increasing the efficiency of processing various types of data and their reliability;

– increasing the accuracy of modeling the process of their functioning;

– maintaining a balance between efficiency and reliability of the process of solving calculation tasks, etc.

At the same time, available scientific approaches to the synthesis and functioning of IDSS have insufficient accuracy and convergence. Said related to the following reasons [1–9]:

– the essential role of the human factor in the process of primary adjustment of IDSS;

– a large number of heterogeneous sources of information, which are subject to analysis and further processing during the functioning of the IDSS;

– IDSSs function under conditions of uncertainty, which causes a delay in their processing;

– the presence of a large number of destabilizing factors affecting the functioning of IDSS, etc.

This prompts the implementation of various strategies to enhance the efficiency of the IDSS in solving calculation tasks.

One of these options is the improvement of existing (development of new) mathematical models of the functioning of intelligent decision support systems.

The analysis of works [9–62] showed that the common shortcomings of the above-mentioned studies are:

– modeling of each approach is carried out only at a separate level of IDSS functioning;

– with a complex approach, as a rule, two components of the functioning of the IDSS are considered. This does not allow for a full assessment of the impact of management decisions on their further functioning;

– the models listed above, constituting the constituent parts of the above approaches, provide weak integration into each other, which prevents them from being combined to function together;

– the above models use a different mathematical apparatus, which does not require appropriate mathematical transformations, which in turn increases computational complexity and reduces the accuracy of modeling, etc.

Intelligent decision support systems are the object of research. The problem that is solved in the research is to increase the accuracy of modeling the process of functioning of intelligent decision support systems.

The subject of the study is the process of functioning of intelligent decision support systems using a set of mathematical models of their functioning.

The hypothesis of the study is the possibility of increasing the efficiency and accuracy of the functioning of intelligent decision support systems due to the development of a set of models of their functioning.

Modeling of the proposed method was carried out in the Microsoft Visual Studio 2022 software environment (USA). The hardware of the research process is AMD Ryzen 5.

Table 4.1 shows the composition of the heterogeneous model field and the methods of presenting the models.

Table 4.1 Models included in the heterogeneous model field

Model	Class of model and its characteristics	Implementation
Artificial neural networks	Artificial neural network (ANN) (search for hidden dependencies in statistical data and prediction of plan execution) – functional element. ANN with an evolving structure. Neuron transfer function: sigmoid. The number of inputs during experiments varied from 3 to 30, and the number of outputs from 1 to 10. The number of hidden neurons ranged from 1 to 8. Neuron transfer function: sigmoid. ANN training method – as in [2]. Average training error – 9%. Training sequence – 60 test tasks	Author's algorithm written in Microsoft Visual Studio 2022. Total code volume: 250 lines
Improved genetic algorithm (GA)	Improved GA [19] for solving an optimization problem – functional element. Population of 100 chromosomes. Evolution: crossover and mutation. Selection: combination of panmixia and ranking. Fitness (in %) – when fitness is below 50%, half of the population is eliminated and regenerated. If for ten generations fitness does not change but exceeds 92%, the best individual is considered the solution	Author's algorithm written in Microsoft Visual Studio 2022. Visualization algorithm implemented. Total code volume: 300 lines
Neuro-fuzzy expert systems	Production knowledge model for finding the decisive subgraph on an AND/OR graph. Forward reasoning. Knowledge base size of functional elements – 6–48 productions, and for the IDSS element – 15 productions. Fact base – up to 15 facts. Knowledge of experts and decision-makers was extracted by protocol analysis	Author's algorithm written in Microsoft Visual Studio 2022. Forward chaining used

4.1 CONCEPTUAL MODEL OF INTELLIGENT DECISION SUPPORT SYSTEM

A conceptual model is a model of the subject domain that defines a set of concepts, properties, and characteristics for describing this domain, as well as the laws of the processes occurring within it. The conceptual model, on the one hand, delimits the subject domain as a set of objects, connections, and relationships among them, as well as the procedures for transforming these objects during problem-solving. On the other hand, it introduces the developer's subjective views in the form of their knowledge and experience – concepts – into the modeling process.

Conceptual models of entities, for example, of tasks and intelligent decision support systems (IDSS), are constructed based on a conceptual model scheme containing 11 categories of concepts C, of which the following five are used:

Definition 1. A resource is a concept denoting an object that is at the disposal of the control subject for accomplishing tasks. The set of resources is denoted as $RES = C^{res} \subseteq C$.

Definition 2. A property is everything that is not within the boundaries of a given object. It is that which, while characterizing objects, does not form new objects. The set of properties is denoted as $PR = C^{pr} \subseteq C$.

Definition 3. An action is a concept denoting relation among resources as a result of activity, actions, and behavior. The set of actions is denoted as $ACT = C^{act} \subseteq C$.

Collective effects in intelligent decision support systems (IDSS) are presented in **Table 4.2.**

Table 4.2 Collective effects in IDSS

Effect	Brief description	Positive impact	Negative impact
Adaptation	Adjustment to the external environment or its modification for effective operation of the IDSS	Expands the range of tasks solved by the IDSS	Complicates analysis of IDSS performance
Boomerang	When information is distrusted, an opposite opinion to that contained in it arises	Unreliable information is not perceived or is considered deliberately false	Reliable information from an unreliable source may be regarded as false
Wave	Dissemination of ideas within the IDSS that correspond to the interests of its members	Collective refinement of ideas	Prolonged work of experts on unpromising ideas
Homeostasis	Maintenance of system parameters within limits away from critical values	Ensures long-term viability of the IDSS	Sometimes the IDSS in borderline states generates higher-quality decisions than under normal conditions
Group Egoism	The goals of the collective are more important than those of its members or society	None	The efficiency of the collective's activity may harm society
Conformism	The common opinion is truth; the opinion of an individual is nothing	None	Hinders the emergence of new approaches to problem-solving
Fashion (Imitation)	Voluntary adoption of the viewpoints on problems established within the collective	Basis for self-learning among collective members; facilitates mutual adaptation	Reduces the likelihood of original viewpoints and approaches to problem-solving
Ringelmann Effect	As the group size increases, the individual contribution to joint work decreases	Reduces the workload on individual IDSS participants	Decreases expert motivation for effective teamwork
Self-learning	Work of IDSS participants to improve their knowledge based on experience	Maintains the knowledge of IDSS participants in an up-to-date state	The acquired knowledge may be unsystematized, nonverbalized, or erroneous
Self-organization	Relationships among experts are dynamic and change during the work process	Adaptation to the external environment; each time a new relevant method is developed. Emergence of original approaches and synergy	Complicates analysis and external management of the collective
Synergy	Attainment of a collective result that individual experts cannot achieve independently	Emergence of a qualitatively superior collective result	Possible occurrence of negative synergy (dissynergy)
Social Facilitation	Enhancement of dominant reactions in the presence of others	Accelerates solutions to simple tasks for which the individual knows the answer	In complex tasks, increases the probability of erroneous responses

Definition 4. Value is a concept or number that indicates the quantity of measurement units. The set of values is denoted by $VAL = C^{val} \subseteq C$.

Definition 5. State is a concept that denotes the manifestation of processes occurring in a resource at a certain time. The set of states is denoted by $ST = C^{st} \subseteq C$.

A set of relations R is established between the concepts of these categories.

Definition 6. A relation is that which forms a thing from given elements (properties or other things). A relation is that which, being established between things, forms new things.

The fact of a relation being established between concepts is denoted by $r^{\alpha\beta}\left(c_1^{\alpha}, c^{\beta}\right)$. It is possible to distinguish relations between different categories of concepts: $R^{\alpha\,\beta} \subseteq R$ – the set of relations between concepts from the set C^{α} and the set C^{β}, where $\alpha,\beta \in \left\{"res","pr","act","val"\right\}$.

Thus, a fragment of the conceptual model schema *sch*1 for structuring knowledge about the subject domain of the modeled task can be represented as follows

$$\begin{gathered} sch_1 = R^{res\;res}\left(RES,RES\right) \circ R^{pr\;pr}\left(PR,PR\right) \circ R^{act\;act}\left(ACT,ACT\right) \circ \\ \circ R^{val\;val}\left(VAL,VAL\right) \circ R^{st\;st}\left(ST,ST\right) \circ R^{res\;pr}\left(RES,PR\right) \circ \\ \circ R^{pr\;res}\left(PR,RES\right) \circ R^{res\;act}\left(RES,ACT\right) \circ R^{act\;res}\left(ACT,RES\right) \circ, \\ \circ R^{res\;st}\left(RES,ST\right) \circ R^{st\;res}\left(ST,RES\right) \circ R^{pr\;act}\left(PR,ACT\right) \circ \\ \circ R^{act\;pr}\left(ACT,PR\right) \circ R^{pr\;val}\left(PR,VAL\right) \circ R^{val\;pr}\left(VAL,PR\right) \circ \end{gathered} \tag{4.1}$$

where the symbol ∘ – denotes concatenation.

The micro-level conceptual model of the Intelligent Decision Support System (IDSS) can be expressed as follows

$$\widetilde{dss} = R^{res\;res}\left(prt^{dm}, env\right) \circ R^{res\;res}\left(PRT, PRT\right), \tag{4.2}$$

where prt^{dm} – the knowledge model of the decision-maker (DM); $env \in RES$ – external environment; $PRT = \left\{prt_1, \ldots, prt_n, prt^{dm}\right\}$, $PRT \subseteq RES$ – the set of participants of the IDSS, including the decision-maker (DM) prt^{dm}; $R^{res\;res}$ – the set of "resource–resource" relations among the participants of the IDSS, as well as between the decision-maker (DM) and the external environment.

In work [13], it is noted that each participant $prt \in PRT$ of the IDSS has its own objective pr^{gsu}, which may coincide with or contradict the objectives of other participants. During the discussion, the experts exchange data pr^{dat}, knowledge pr^{knw}, explanations pr^{exp} and partial solutions pr^{dec} of the joint task. Thus, they perform a set of actions related to the transmission ACT^{itr} and reception ACT^{iac} of information, a set of professional functions ACT^{prt}, and exert influence on other participants of the IDSS and members of the surrounding environment by performing actions ACT^{conf}. Each expert has their own model *resmod* of the external environment, including the control object, as well as their own set of methods RES^{met} for problem solving. Considering the heterogeneous nature of complex tasks, for their successful solution the IDSS must include experts of various specializations, with different sets of problem-solving methods, that is $RES_i^{met} \neq RES_j^{met}$, where $i, j = 1,\ldots,n$, $i \neq j$ – the index of a participant in the set PRT.

The conceptual model of an IDSS expert is expressed as follows

$$\begin{gathered} prt_i = r_1^{res\ pr}\left(prt, pr^{gsu}\right) \circ r_1^{res\ pr}\left(prt, pr^{dat}\right) \circ r_1^{res\ pr}\left(prt, pr^{knw}\right) \circ \\ \circ r_1^{res\ pr}\left(prt, pr^{\exp}\right) \circ r_1^{res\ pr}\left(prt, pr^{dec}\right) \circ r_2^{res\ act}\left(prt, ACT^{prt}\right) \circ \\ \circ r_2^{res\ act}\left(prt, ACT^{itr}\right) \circ r_2^{act\ pr}\left(ACT^{itr}, pr^{dat}\right) \circ r_2^{act\ pr}\left(ACT^{itr}, pr^{knw}\right) \circ, \\ \circ r_2^{act\ pr}\left(ACT^{itr}, pr^{\exp}\right) \circ r_2^{act\ pr}\left(ACT^{itr}, pr^{dec}\right) \circ r_2^{res\ act}\left(prt, ACT^{iac}\right) \circ \\ \circ r_2^{act\ pr}\left(ACT^{iac}, pr^{dat}\right) \circ r_2^{act\ pr}\left(ACT^{iac}, pr^{knw}\right) \circ r_2^{act\ pr}\left(ACT^{iac}, pr^{\exp}\right) \circ \\ \circ r_2^{act\ pr}\left(ACT^{iac}, pr^{dec}\right) \circ r_2^{res\ act}\left(prt, ACT^{conf}\right) \circ r_3^{res\ res}\left(prt, res^{mod}\right) \circ \\ \circ r_3^{res\ res}\left(prt, RES^{met}\right), \end{gathered} \tag{4.3}$$

where $r_1^{res\ pr}$ – the "have property" relation, which establishes the correspondence between an IDSS participant and their properties;
$r_2^{res\ act}$ – the "perform" relation, which links a subject and the action they perform;
$r_2^{act\ pr}$ – the "have property" relation, which links an action with its property;
$r_3^{res\ res}$ – the "include" relation, which links a whole and its parts.

Many relations *Rres res* in (4.2) consist of subsets of relations of various classes: cooperation $R_{coop}^{res\ res}$, competition $R_{comp}^{res\ res}$, neutrality $R_{neut}^{res\ res}$, trust $R_{trus}^{res\ res}$, pressure and conformism $R_{conf}^{res\ res}$, coordination $R_{coor}^{res\ res}$, dispute $R_{disp}^{res\ res}$, and others $R_{oth}^{res\ res}$. The subset of relations $R_{oth}^{res\ res}$ is introduced into the model to make it complete and extensible. Thus, the set $R^{res\ res}$ can be represented by the expression

$$\begin{gathered} R^{res\ res} = R_{coop}^{res\ res} \cup R_{comp}^{res\ res} \cup R_{neut}^{res\ res} \cup R_{trus}^{res\ res} \cup R_{conf}^{res\ res} \cup \\ \cup R_{coor}^{res\ res} \cup R_{disp}^{res\ res} \cup R_{oth}^{res\ res}. \end{gathered} \tag{4.4}$$

The composition of relations from the set $R^{res\ res}$ and its subsets is not known in advance and is determined during the operation of the IDSS in accordance with the interaction rules $INT \subseteq RES$ because of its self-organization. Owing to the dynamism of the links among experts and self-organization, the IDSS is capable of generating a new solution method relevant to the prevailing conditions, and the conceptual model of the IDSS as a self-organized entity, a method for solving a complex task, can be represented by the expression

$$\begin{gathered} RES_{dss}^{met} = R^{res\ res}\left(RES_1^{met}, RES_2^{met}\right) \circ \ldots \circ R^{res\ res}\left(RES_1^{met}, RES_n^{met}\right) \circ \\ \circ R^{res\ res}\left(RES_2^{met}, RES_1^{met}\right) \circ \ldots \circ R^{res\ res}\left(RES_2^{met}, RES_n^{met}\right) \circ \\ R^{res\ res}\left(RES_n^{met}, RES_1^{met}\right) \circ \ldots \circ R^{res\ res}\left(RES_n^{met}, RES_{n-1}^{met}\right), \end{gathered} \tag{4.5}$$

where the method RES_{dss}^{met}, generated by the IDSS in the process of solving a current task, represents an interconnected set of method sets RES_i^{met}, i=1,...,n, used by the experts in solving their partial tasks.

In solving the current task, the intensity and orientation of the relations $R^{res\,res}$ among the IDSS experts, and consequently among the methods they employ, change, leading to the development, in accordance with (4.5), of a new method relevant to the complex task, that is, a synergistic effect arises. The external manifestation of this effect is that the IDSS produces solutions of higher quality compared to the opinions of individual experts.

Taking the above into account, the macro-level model of the IDSS can be represented as follows

$$\widehat{dss} = \left(PRT, env, INT, \widetilde{DSS}, EFF\right), \tag{4.6}$$

where PRT – the set of IDSS participants described by the conceptual model (4.3);
env – the environment in which the IDSS operates;
INT – the set of elements structuring the interactions among experts;
$\widehat{dss}$ – set of IDSS micro-level models (4.5) corresponding to the specific functions of the experts within the IDSS and to the relations established among them;
EFF is the set of conceptual models of macro-level (collective) effects in the IDSS (**Table 4.1**): adaptation ad, boomerang bo, wave wa, homeostasis ho, group egoism ge, groupthink gt, fashion fa, Ringelmann effect re, self-learning sl, self-organization so, synergy se, and social facilitation sf. Let's consider in more detail the models of these macro-level effects.

Two types of adaptation are distinguished: passive and active. In the first case, the adapting system changes so as to perform its functions in the given environment in the best possible way. The conceptual model of such adaptation is expressed as follows

$$\begin{aligned} ad_p = {} & r_3^{res\,res}\left(dss, PRT\right) \circ r_2^{res\,act}\left(PRT, ACT^{iac}\right) \circ r_1^{act\,res}\left(ACT^{iac}, env\right) \circ \\ & \circ R_1^{res\,res}\left(\widetilde{DSS}, \widetilde{DSS}\right) \circ r_1^{res\,pr}\left(\widetilde{DSS}, PR^{cr}\right) \circ r_1^{pr\,val}\left(PR^{cr}, VAL^{cr}\right) \circ \\ & \circ r_1^{val\,val}\left(VAL^{cr}, VAL^{cr\,go}\right), \end{aligned} \tag{4.7}$$

where PR^{cr} – the set of criteria for evaluating the effectiveness of the IDSS;
VAL^{cr} – the set of values of critical parameters of the IDSS for micro-level models;
$VAL^{cr\,go}$ – the set of target values of critical parameters of the IDSS;
$r_1^{pr\,val}$ – the "have value" relation;
$r_1^{val\,val}$ – the relation of proximity between two values.

Active adaptation implies a change of the environment in order to maximize the efficiency criterion or an active search for such an environment. The conceptual model of active adaptation for the IDSS is as follows

$$\begin{aligned} ad_a = {} & r_3^{res\,res}\left(dss, PRT\right) \circ r_2^{res\,act}\left(PRT, ACT^{iac}\right) \circ r_1^{act\,res}\left(ACT^{iac}, env\right) \circ \\ & \circ R_1^{res\,res}\left(ENV, ENV\right) \circ r_1^{res\,pr}\left(\widetilde{DSS}, PR^{cr}\right) \circ r_1^{pr\,val}\left(PR^{cr}, VAL^{cr}\right) \circ \\ & \circ r_1^{val\,val}\left(VAL^{cr}, VAL^{cr\,go}\right) \circ r_2^{res\,act}\left(dss, ACT^{inf}\right) \circ r_1^{act\,res}\left(ACT^{inf}, env\right), \end{aligned} \tag{4.8}$$

where $ENV \subseteq RES$ – the set of external environments suitable for the operation of the IDSS; ACT^{inf} – the set of IDSS influences on the application environment.

The boomerang effect (bo) is the ignoring of, or identification as false, information originating from unreliable sources

$$bo = r_3^{res\ res}\left(dss,PRT\right)\circ r_2^{res\ act}\left(PRT,ACT_{trus}^{iac}\right)\circ R_{trus}^{res\ res}\left(PRT,env\right)\circ \circ R_{trus}^{res\ res}\left(PRT,PRT\right), \quad (4.9)$$

where ACT_{trus}^{iac} – a set of actions for obtaining information that considers the relations of trust among the IDSS participants, as well as between the participants and information sources from the external environment.

According to **Table 4.1**, the wave effect (wa) is a mechanism for the dissemination of ideas and objectives within the IDSS that correspond to the interests of its members, transmitted to IDSS participants primarily from the "inner circle" of the source expert. Subsequently, these participants may modify the idea and transmit it to the IDSS participants within their own "inner circle". The wave effect is formally expressed as follows

$$wa = r_3^{res\ res}\left(dss,PRT\right)\circ r_2^{res\ act}\left(PRT,ACT_{trus}^{itr}\right)\circ R_{trus}^{res\ res}\left(PRT,PRT\right), \quad (4.10)$$

where ACT_{trus}^{itr} – the set of actions for transmitting information that considers the relations of trust among the IDSS participants.

The conceptual model of homeostasis (ho) in the IDSS is expressed as follows

$$ho = r_3^{res\ res}\left(dss,PRT\right)\circ r_2^{res\ act}\left(PRT,ACT^{iac}\right)\circ r_1^{act\ res}\left(ACT^{iac},env\right)\circ \circ R_1^{res\ res}\left(\widetilde{DSS},\widetilde{DSS}\right)\circ r_1^{res\ pr}\left(\widetilde{DSS},PR^{cr}\right)\circ r_1^{pr\ val}\left(PR^{cr},VAL^{cr}\right)\circ \circ r_1^{val\ val}\left(VAL^{cr},VAL^{cr\ all}\right), \quad (4.11)$$

where $VAL^{cr\ all}$ – the set of permissible values of the critical parameters of the IDSS.

The group egoism effect (ge) consists in the IDSS disregarding the objectives of society and of individual members of the IDSS

$$ge = r_3^{res\ res}\left(dss,PRT\right)\circ r_2^{res\ act}\left(PRT,ACT^{conf}\right)\circ r_1^{act\ res}\left(ACT^{conf},PRT\right)\circ \circ r_1^{act\ res}\left(ACT^{conf},env\right)\circ R_{conf}^{res\ res}\left(PRT,PRT\right), \quad (4.12)$$

where $r_1^{act\ res}$ – the "have as object" relation, which links an action with the object toward which it is directed.

The groupthink effect (gt) is the suppression of opinions of IDSS participants that differ from the opinions of the majority of the IDSS members

$$gt = r_3^{res\ res}\left(dss,PRT\right)\circ r_2^{res\ act}\left(PRT,ACT^{conf}\right)\circ r_1^{act\ res}\left(ACT^{conf},PRT\right)\circ \circ R_{conf}^{res\ res}\left(PRT,PRT\right). \quad (4.13)$$

The fashion effect (fa) consists in the voluntary adoption of the viewpoint on a problem that has become established within the collective

$$fa = r_3^{res\ res}\left(dss, PRT\right) \circ r_2^{res\ act}\left(PRT, ACT^{iac}\right) \circ r_2^{act\ pr}\left(ACT^{iac}, PR^{dec}\right). \quad (4.14)$$

According to **Table 4.1**, the Ringelmann effect (re) is the decrease in the intensity of individual work as the group size increases

$$\begin{aligned} re = r_3^{res\ res}\left(dss, PRT\right) \circ r_2^{res\ act}\left(PRT, ACT^{prt}\right) \circ r_2^{act\ pr}\left(ACT^{prt}, PR^{efi}\right) \circ \\ \circ r_2^{act\ pr}\left(ACT^{prt}, PR^{efc}\right) \circ r_1^{pr\ pr}\left(PR^{efi}, PR^{efc}\right), \end{aligned} \quad (4.15)$$

where PR^{efi} – the efficiency of performing an action in individual work, determined individually for each IDSS and each task. In general, efficiency is understood as an indicator that considers the assessment of the speed of decision-making and the quality of proposed solutions; PR^{efc} – the efficiency of performing an action during collective work; $r_1^{pr\ pr}$ – the "be greater than" relation.

The conceptual model of decision-maker (DM) self-learning sl_{dm} is expressed as follows

$$\begin{aligned} sl_{dm} = r_3^{res\ res}\left(dss, PRT\right) \circ r_2^{res\ act}\left(PRT, ACT^{iac}\right) \circ r_1^{act\ res}\left(ACT^{iac}, env\right) \circ \\ \circ R_1^{res\ res}\left(\widetilde{DSS}, \widetilde{DSS}\right) \circ r_1^{res\ pr}\left(\widetilde{dss}, PR^{cr}\right) \circ r_1^{pr\ val}\left(PR^{cr}, VAL^{cr\ pl}\right) \circ \\ \circ r_1^{pr\ val}\left(PR^{cr}, VAL^{cr\ fct}\right) \circ r_3^{res\ res}\left(prt^{dm}, res^{fdb}\right) \circ r_1^{val\ val}\left(VAL^{cr\ pl}, VAL^{cr\ fct}\right) \circ \\ \circ r_2^{pr\ act}\left(res^{fdb}, ACT^{lrn}\right) \circ r_1^{act\ res}\left(ACT^{lrn}, res^{rul}\right) \circ r_3^{res\ res}\left(res^{rul}, res^{ienv}\right) \circ \\ \circ r_3^{res\ res}\left(res^{rul}, res^{idss}\right) \circ r_3^{res\ res}\left(res^{rul}, res^{ifct}\right), \end{aligned} \quad (4.16)$$

where $VAL^{cr\ pl}$ – the set of planned values of the IDSS efficiency criteria for the selected micro-level model $\widetilde{dss}$;
$VAL^{cr\ fct}$ – the set of actual values of the IDSS efficiency criteria for the selected micro-level model $\widetilde{dss}$;
res^{fdb} – the fuzzy knowledge base of the decision-maker (DM) for selecting micro-level IDSS models from the set $\widetilde{DSS}$;
ACT^{lrn} – learning and adjustment of the rules of the decision-maker's (DM's) fuzzy knowledge base res^{fdb};
res^{rul} – a rule of the decision-maker's (DM's) fuzzy knowledge base for selecting micro-level IDSS models from the set $\widetilde{DSS}$;
res^{ienv} – information about the external environment;
res^{idss} – information about the micro-level model $\widetilde{dss}$;
res^{ifct} – information about the actual values of the IDSS efficiency criteria corresponding to the selected model $\widetilde{dss}$.

Self-organization of the IDSS (so) is a specific effect in which the IDSS collective, without apparent external causes, creates or modifies the interrelations among participants and the organizational structures.

$$so = r_3^{res\ res}\left(dss, PRT\right) \circ r_2^{res\ act}\left(PRT, ACT^{iac}\right) \circ r_1^{act\ res}\left(ACT^{iac}, env\right) \circ \\ \circ R_1^{res\ res}\left(\widetilde{DSS}, \widetilde{DSS}\right), \quad (4.17)$$

where $r_1^{act\ res}$ – the "have as object" relation between an action and its resources;
$R_1^{res\ res}$ – the set of relations between the preceding micro-level model and the subsequent one in the course of their transformation.

The synergy effect (se) is the result of the interrelations among the IDSS participants during their collaborative work on a task, that is, the generation of an organizational structure relevant to the problem being solved. This effect in the IDSS is manifested in obtaining a collective solution of higher quality than any of the individual ones

$$se = r_3^{res\ res}\left(dss, PRT\right) \circ r_2^{res\ act}\left(PRT, ACT^{iac}\right) \circ r_1^{act\ res}\left(ACT^{iac}, env\right) \circ \\ \circ R_1^{res\ res}\left(\widetilde{DSS}, \widetilde{DSS}\right) \circ r_4^{res\ res}\left(PRT, RES^{dec}\right) \circ r_1^{act\ pr}\left(RES^{dec}, PR^{qua}\right) \circ \\ \circ r_4^{res\ res}\left(dss, res_{dss}^{dec}\right) \circ r_1^{res\ pr}\left(dss, pr_{dss}^{qua}\right) \circ r_1^{pr\ pr}\left(pr_{dss}^{qua}, PR^{qua}\right), \quad (4.18)$$

where RES^{dec} – the set of solutions to the task assigned to the IDSS, proposed by the experts as a result of individual work;
PR^{qua} – the set of quality indicators of the experts' individual solutions;
res_{dss}^{dec} – the solution produced by the IDSS as a result of the experts' collaborative work;
pr_{dss}^{qua} – the quality of the solution produced by the IDSS;
$r_4^{res\ res}$ – the relation that links an expert or the IDSS with the solution produced.

As shown in **Table 4.1**, social facilitation (SF) involves the enhancement of dominant responses in the presence of other experts; that is, it contributes to the acceleration of decision-making

$$sf = r_3^{res\ res}\left(dss, PRT\right) \circ r_2^{res\ act}\left(PRT, ACT^{prt}\right) \circ r_1^{act\ pr}\left(ACT^{prt}, PR^{spi}\right) \circ \\ \circ r_2^{act\ pr}\left(ACT^{prt}, PR^{spc}\right) \circ r_1^{pr\ pr}\left(PR^{spc}, PR^{spi}\right), \quad (4.19)$$

where PR^{spi} – the speed of performing an action during individual work; PR^{spc} – the speed of performing an action during collective work.

Analysis of expressions (4.7)–(4.19) has shown that certain macro-level effects are interrelated. For example, expressions (4.7), (4.11), (4.16), and (4.18) can be transformed using expression (4.17) as follows:

$$ad_p = so \circ r_1^{res\ pr}\left(\widetilde{DSS}, PR^{cr}\right) \circ r_1^{pr\ val}\left(PR^{cr}, VAL^{cr}\right) \circ r_1^{val\ val}\left(VAL^{cr}, VAL^{cr\ go}\right), \quad (4.20)$$

$$ho = so \circ r_1^{res\ pr}\left(\widetilde{DSS}, PR^{cr}\right) \circ r_1^{pr\ val}\left(PR^{cr}, VAL^{cr}\right) \circ r_1^{val\ val}\left(VAL^{cr}, VAL^{cr\ all}\right), \quad (4.21)$$

$$\begin{gathered} sl_{dm} = so \circ r_1^{res\ pr}\left(\widetilde{dss}, PR^{cr}\right) \circ r_1^{pr\ val}\left(PR^{cr}, VAL^{cr\ pl}\right) \circ \\ \circ r_1^{pr\ val}\left(PR^{cr}, VAL^{cr\ fct}\right) \circ r_3^{res\ res}\left(prt^{dm}, res^{fdb}\right) \circ r_1^{val\ val}\left(VAL^{cr\ pl}, VAL^{cr\ fct}\right) \circ \\ \circ r_2^{pr\ act}\left(res^{fdb}, ACT^{lrn}\right) \circ r_1^{act\ res}\left(ACT^{lrn}, res^{rul}\right) \circ r_3^{res\ res}\left(res^{rul}, res^{ienv}\right) \circ \\ \circ r_3^{res\ res}\left(res^{rul}, res^{idss}\right) \circ r_3^{res\ res}\left(res^{rul}, res^{ifct}\right); \end{gathered} \tag{4.22}$$

$$\begin{gathered} se = so \circ r_4^{res\ res}\left(PRT, RES^{dec}\right) \circ r_1^{act\ pr}\left(RES^{dec}, PR^{qua}\right) \circ \\ \circ r_4^{res\ res}\left(dss, res_{dss}^{dec}\right) \circ r_1^{res\ pr}\left(dss, pr_{dss}^{qua}\right) \circ r_1^{pr\ pr}\left(pr_{dss}^{qua}, PR^{qua}\right), \end{gathered} \tag{4.23}$$

Expressions (4.20)–(4.23) show that self-organization plays a special and fundamental role among the collective effects in the IDSS — it is the prerequisite for the emergence of other effects that positively influence the performance of the IDSS, such as adaptation, homeostasis, self-learning, and synergy [18].

4.2 COORDINATION MODELS IN HYBRID INTELLIGENT DECISION SUPPORT SYSTEMS

Coordination is a process that takes place in the IDSS during the solution of complex tasks and represents the sequence of analysis of the intermediate results of the solution of partial tasks and the issuance of controlling influences. Coordination is carried out by the decision-maker (DPR), but it can also be initiated by experts. In this work, the initiator of the coordination is DPR. The concept of "coordination" in relation to IDSS has not yet been investigated.

The study of real IDSSs determined the development of a new model for solving a complex task and a method for modeling the solution of complex tasks with the coordination of partial tasks in order to apply them to IDSS design.

4.2.1 MATHEMATICAL MODEL FOR SOLVING A COMPLEX CALCULATION TASK

Within the systems approach, tasks are traditionally considered as systems [12, 14] composed of individual interrelated subtasks that are connected and interact with one another. The order of interconnection and interaction among elements in an HIDSS (hybrid intelligent decision support system) is determined by its structure.

Let's denote the task-system as pr^{bu}, an individual task – pr^{bh}. Then $PRB^h = \left\{prb_1^h, \ldots, prb_{N_h}^h\right\}$ – the set of individual tasks included in pr^{bu}; $\widehat{PRB}^u = \left\{\widehat{prb}_1^u, \ldots, \widehat{prb}_{N_u}^u\right\}$ – the set of decompositions of tasks pr^{bu} [5]; $R^h = \left\{r_{wq} \mid w, q = 1, \ldots, N_h; q \neq w\right\}$ – the set of relations among individual tasks; N_h – the cardinality of the set PRB^h.

The model of a computational task of the IDSS can be represented as

$$prb^u =< PRB^h, \widehat{PRB}^u, R^h >, \tag{4.24}$$

and the model of each partial computational task as [5]

$$prb^h =< GL^h, DAT^h, MET^h >, \tag{4.25}$$

where GL^h – the final goal; DAT^h – input data; MET^h – conditions that specify how DAT^h are transformed into GL^h.

Model (4.24) satisfies all the properties of an IDSS:

– it consists of a set of elementary tasks PRB^h, among which relations R^h; are established; the connections are organized, which is reflected in the set of decompositions $\widehat{PRB}^u$;

– when solving the overall system task, the individual elementary tasks are predominantly isolated from the environment or its state is fixed, that is, the requirement is met that the internal connections within the system are much stronger than those with the external environment;

– a simple summation of the solutions of individual tasks does not yield a solution to the overall task as a whole [9, 10].

Model (4.25) has certain shortcomings. The main one is the inadequate representation of relations among the elements of the IDSS. Considering only the set of relations R^h among the partial tasks is insufficient. Studies of IDSSs have shown that, in most cases, experts are unable to provide professional solutions to partial tasks while taking into account the data on the complex task specified by the decision-maker (DM). Typically, there is a shortage of resources, particularly time, and errors occur in the formulation of the goal. Modification of the initial conditions of model (4.24) is impossible due to the absence of a crucial element – the image of the DM, which performs the function of a coordinator and reformulates the experts' goals depending on the situation.

The problem-solving process is thus considered as a system with a coordinator prb^k, whose function is to monitor and manage the process of solving individual partial tasks $prb_1^h, \ldots, prb_{N_h}^h$ by the experts during collective discussion. The coordinator is linked by relations $R^{hk} = \left\{ r^{kw} \mid w = 1, \ldots, N_h \right\}$ with each task prb^h in the IDSS prb^u, through which information is collected about the state of the process of solving an individual task by an expert. At certain moments in time, it also issues coordinating influences to modify the input data set – resources and goals. In this case, the model of a complex task with coordination is expressed as follows

$$prb^{uk} =< PRB^h, \widehat{PRB}^u, prb^k, R^h, R^{hk} >, \tag{4.26}$$

where prb^k – the coordinator; $R^{hk} = \left\{ r^{kw} \mid w = 1, \ldots, N_h \right\}$ – the sets of relations between the coordinator and the individual tasks.

A comparison of (4.24) and (4.26) shows that (4.26) is of a more general nature and reduces to (4.24) when the coordinator task is omitted from model (4.26), that is, in the case when the decision-maker (DM) in the IDSS does not perform coordination during the process of solving a complex task.

The coordinator element may be represented as a "coordinating task" (k-task), which should be "added" to the decomposition $\widehat{prb}^{u} \in \widehat{PRB}^{u}$ of the complex task prb^u, to adequately represent the specific features of planning tasks in the model.

Let $MET^* = \left\{ met_1, \ldots, met_{N_{MET^*}} \right\}$ – be the set of conditions. Then, a correspondence ψ_1 can be defined

$$\psi_1 : SOL_1^h \otimes SOL_2^h \otimes MET^* \to SOL^u. \tag{4.27}$$

The elements of the correspondence ψ_1 – are tuples $\left(\left(sol_{\alpha}^{h\,1} sol_{\beta}^{h\,2} met_{\gamma}\right), sol_{\eta}^{u}\right)$, where $\alpha = 1,\ldots,N_{sh1}$; $\beta = 1,\ldots,N_{sh2}$; $\gamma = 1,\ldots,N_{MET}$; $\eta = 1,\ldots,N_{su}$, with the first component being a three-component vector consisting of the solution $sol_{\alpha}^{h\,1} \in SOL_1^h$ of task prb_1^h, the solution $sol_{\beta}^{h\,2} \in SOL_2^h$ of task prb_2^h and the coordinating condition $met_{\gamma} \in MET^*$, and the second component being the solution sol_{η}^{u} of the task prb^u.

The correspondence ψ_1 is not a function; it cannot be written analytically or computed, since the coordination conditions and the results of solving individual partial tasks are most often represented in natural language.

Let, as a result of solving the partial tasks prb_1^h and prb_2^h the solutions $sol_1^{h\,1} \in SOL_1^h$, and $sol_1^{h\,2} \in SOL_2^h$, and $\left\{\left(sol_1^{h\,1}, sol_1^{h\,2}\right)\right\} \otimes MET^* \nrightarrow SOL^u$, and let, that is, the obtained solutions $sol_1^{h\,1}$, and $sol_1^{h\,2}$ for all $met_{\gamma} \in MET^*$ do not lead to the solution of task prb^u. The symbol «$\nrightarrow$» denotes the absence of a mapping from the set on the left-hand side of the symbol to the set on its right-hand side. In this case, it is necessary to re-solve tasks prb_1^h and prb_2^h. However, in the IDSS, there is often insufficient time to re-solve the tasks, so reasoning about the prb^U complex task is divided into separate, logically complete intermediate stages [13, 14], and at the end of these stages, the integrated result of solving the complex task is systematically verified – that is, an iterative process is organized. Consequently, the solutions of the partial task prb^h (the experts' lines of reasoning) are also divided into parts.

In this example, during the process of solving tasks prb_1^h and prb_2^h the following intermediate results will be obtained:

$$\begin{aligned} & sol_{11}^{h\,1} \Rightarrow sol_{12}^{h\,1} \Rightarrow \ldots \Rightarrow sol_{1s-1}^{h\,1} \Rightarrow sol_{1N_{sol}}^{h\,1} = sol_1^{h\,1}, \\ & sol_{11}^{h\,2} \Rightarrow sol_{12}^{h\,2} \Rightarrow \ldots \Rightarrow sol_{1s-1}^{h\,2} \Rightarrow sol_{1N_{sol}}^{h\,2} = sol_1^{h\,2}, \end{aligned} \tag{4.28}$$

where N_{sol} – the number of iteration steps into which the partial tasks are divided; and $sol_1^{h\,1}$ and $sol_1^{h\,2}$ – the results of solving the partial tasks prb_1^h and prb_2^h, respectively, obtained through the sequence of steps $1,\ldots, N_{sol}$.

Based on the coordinator's verification of the results obtained at a particular step, the relevance of influencing the course of solving the individual partial tasks prb_1^h prb_2^h is determined, so that the process of solving the complex task leads to the desired result – the goal. This influence is referred to as coordinating, and for simplicity, let's further denote the result of an intermediate stage without the first lower index, that is, $sol_l^{h\,1}$ and $sol_l^{h\,2}$, where $l = 1, \ldots, N_{sol}$.

Following [17], let's introduce the set of coordinating influences

$$E = \left\{ e_1^{\alpha}, \ldots, e_{N_{prt}}^{\alpha} \right\}, \tag{4.29}$$

where α – the type of coordinating influence, α=1,…,6. Let's consider each of the six types.

Integral coordination (α=1) – the decision-maker (DM) establishes various constraints (standards) on the input parameters $in_i^{h\,1} \in IN^{h\,1} \subseteq DAT^h$ of the partial task prb_1^h for a certain period of time

$$\int_0^T \left(in_i^{h\,1}(t) \right) dt = in_i^{h\,1H}, \tag{4.30}$$

where $in_i^{h\,1H}$ – the standard for the input parameter $in_i^{h\,1} \in IN^{h\,1}$, $i = 1,...,N_{inh1}$; IN^{h1} – the set of input parameters of the partial task prb_1^h; $[0,T]$ – the time interval.

Precise coordination (α = 2) imposes constraints on the input parameters of the partial task so that at each moment of time t they are equal to the specified value

$$in_i^{h\,1}(t) = in_i^{h\,1Set}, \tag{4.31}$$

where $in_i^{h\,1}(t)$ – the input parameter; $in_i^{h\,1Set}$ – the specified value of the parameter; t – an arbitrary moment in time when the fulfillment of the condition is verified $t \in \left[0,+\infty\right]$.

Interval coordination (α = 3) requires that the input parameter $in_i^{h\,1}$ of the partial task (input data) belong to a specified interval

$$in_i^{h\,1} \in \left[val_{\min}^{h\,1i}, val_{\max}^{h\,1i} \right], \tag{4.32}$$

where $val_{\min}^{h\,1i}, val_{\max}^{h\,1i}$ – the interval boundaries.

Linguistic coordination (α = 4) is a condition specified in natural language. Temporal coordination, or synchronization of the solution of partial tasks (α = 5), to determine after what period an intermediate result must be provided. $sol_l^{h\,1}$, where l = 1, ..., N_{sol} the results of solving the partial tasks are issued at certain time intervals

$$sol_l^{h\,1} \overset{\tau}{\Rightarrow} sol_{l+1}^{h\,1}, \tag{4.33}$$

where τ – the time interval after which the solution is issued; $sol_l^{h\,1}$ and $sol_{l+1}^{h\,1}$ – the results of solving the task prb_1^h after the i-th and i+1-th stages of solving the complex task, respectively.

Let's denote the situation in which the expert's line of reasoning does not change as a "null action", α = 6. For example, the decision-maker (DM) considers that it is unnecessary to influence the course of solving the partial tasks by the expert.

Since the results of solving the partial tasks are most often issued in natural language, the coordinating influences $e_1^{\alpha}, \ldots, e_{N_{prt}}^{\alpha}$ are also most often presented in the same way.

Then, taking the above into account, it is possible to establish the correspondence

$$\psi_2 : \left\{ \left(sol_l^{h\,1}, sol_l^{h\,2} \right) \right\} \otimes MET^* \to E, \tag{4.34}$$

where l = 1,..., N_{sol} –1. The maximum value of the index l is taken as N_{sol} –1, since after stage N_{sol} it is no longer possible to coordinate the solution of the partial tasks – the final result has been obtained.

The elements of the correspondence ψ_2 – are pairs $\left(\left(sol_l^{h1}, sol_l^{h2}, met_\gamma\right), e_q^\alpha\right)$, for $l = 1,\ldots, N_{sol} - 1$; $\gamma = 1,\ldots, N_{MET}$; $q = 1,\ldots, N_{prt}$, where the first component is a three-component vector consisting of the solution $sol_l^{h1} \in SOL_1^h$ of the task prb_1^h, the solution $sol_l^{h2} \in SOL_2^h$ the task prb_2^h, and the coordinating condition $met_\gamma \in MET^*$, and the second component is the coordinating influence $e_q^\alpha \in E$. Analogous to (4.26), the correspondence (4.34) is not a function. It is multivalued, since it is possible to apply to the same partial task prb^h to apply several coordinating actions $e_q^\alpha \in E$.

Since there is a limit on the number of steps, when $l = N_{sol}$, there must be a correspondence

$$\psi_3 : \left\{\left(sol_l^{h1}, sol_l^{h2}\right)\right\} \otimes MET^* \to SOL^u. \quad (4.35)$$

The elements of the correspondence ψ_3 – are pairs of the form $\left(\left(sol_l^{h1}, sol_l^{h2}, met_\gamma\right), sol_\eta^u\right)$, where $l = 1,\ldots, N_{sol} - 1$, $\gamma = 1,\ldots,N_{MET}$; $\eta = 1,\ldots,N_{su}$ with the first component being a three-component vector consisting of the solution of task, the solution $sol_l^{h1} \in SOL_1^h$ of task prb_1^h, the solution $sol_l^{h2} \in SOL_2^h$ the task prb_2^h and the coordinating condition $met_\gamma \in MET^*$, and the second component being the solution $sol_\eta^u \in SOL^u$ task met^u. If ψ_3 is absent, that is, if, as a result of the search for the elements of ψ_3, it is found that $\psi_3 = \varnothing$, then the decision-maker (DM) must modify the set of coordination conditions MET*: introduce new conditions and remove some of the old ones.

The correspondence ψ_3 is a subset of the set $\psi_1, \psi_3 \subseteq \psi_1$, since the only difference is that ψ_3 specifies the concrete results of solving tasks prb_1^h and prb_2^h.

Since not all elements of the correspondence ψ_3 have as their second component $sol_\eta^u \in SOL^u$, hat, that satisfy the objectives of solving prb^u, let's denote by DAT_{ψ_3} the set of elements of the correspondence ψ_3, which second component satisfies the objectives of solving prb^u $DAT_{\psi_3} \in \psi_3$.

Taking the above into account, and considering model (4.25), the model of the k-task can be written as follows

$$prb^k =< SOL_1^h, SOL_2^h, \psi_2, DAT_{\psi_3} >, \quad (4.36)$$

where SOL_1^h, SOL_2^h – the input data for the coordinator task prb^k, expressed as a combination of numbers, words, and expressions;

$DAT_{\psi_3} \in \psi_3$ – the final goal of solving the coordinator task prb^k;

ψ_2 – the set of conditions that specify how the coordinating influences (4.34) are formed after each step, as a result of the application of which, after the final step, DAT_{ψ_3} can be obtained.

On the basis of the above, let's give the following definition of the coordination process: an iterative (multistage) process during which, after each iteration, the decision-maker (DM) analyzes the integrated result of solving the set of partial tasks. A coordinating influence is selected for the line of reasoning of each expert so that, upon completion of the process of solving the complex task, a maximally comprehensive overall result of its solution is obtained.

It may also be noted that as the number of partial tasks increases, the relevance of coordinating their solutions grows, since the number of relations (such as information exchange, use of common variables, or common constraints) among the task elements increases combinatorially.

In the present work, the decision-maker models do not consider: B_{prof} — the base of professional knowledge; B_{theor} — the base of theoretical knowledge; B_{prec} — the case base (experience).

Let's consider how the IDSS functions according to (4.37). Let the decision-maker be given a task prb^u, which he or she reduces to partial tasks $prb_1^h,\ldots,prb_{N_h}^h$. By analyzing (4.23) and (4.35), the following conclusions can be made: GL^h is contained in B_{prec} and B_{facts} — experience combined with facts allows the expert to determine what result should be obtained; MET^h is contained in B_{prof}, B_{theor}, B_{prec}, MET_{prti}, S_{prti} and In_{prti}; DAT^h is contained in B_{facts}.

In traditional IDSSs, described, for example, in [2], each expert, prt_q, q=1,...,N_{prt} receiving his or her partial task $prt_j^h, j=1,\ldots,N_h$, finds its solution using his or her professional knowledge B_{prof} and theoretical knowledge B_{theor}. After completing the solution process, the expert provides the result $sol^{h\,j} \in SOL_j^h$, where SOL_j^h — the set of results obtained from solving the task prt_j^h, which can be represented as the correspondence ψ_4

$$\psi_4 : DAT^h \otimes B^U \to SOL^h,\ B^U = B_{prof} \cup B_{theor}. \tag{4.37}$$

The elements of the correspondence ψ_4 are tuples $\left(\left\{dat_\sigma^h\right\},\left\{b_\beta^u\right\},sol_\gamma^h\right)$, where σ = 1,..., N_{dath}; β = 1,..., N_b; γ = 1,..., N_{sh}, in which the first component is a two-component vector consisting of the list of input data $\left\{dat_\sigma^h\right\}, dat_\sigma^h \in DAT^h$ and the list of knowledge used by the expert $\left\{b_\beta^u\right\}, b_\beta^u \in B^U$ (professional knowledge — production rules; theoretical knowledge — analytical dependencies), and the second component is the result $sol_\gamma^u \in SOL^h$ of solving the task prb^h.

The correspondence ψ_4 is not a function (it cannot be represented analytically or computed by numerical methods), since the expert's knowledge and the results of solving the task element can be expressed in natural language. It is ambiguous, because with an incomplete set of input data, the expert may propose several alternative results; it is subjective, since each solution of task prb^h corresponds to at least one element from and it is not injective, as not every element of $DAT^h \otimes B^U$ corresponds to a solution of task prb^h.

Let denote the number of stages into which the experts divide the process of solving partial tasks, and let ΔN_{sol}, and sol_l^h — be the result of solving the partial task at the l-th stage, l = 1,..., N_{sol}. A time interval Δt, is allocated to each stage, since in practical tasks the total time T for solving the complex task prb^u, is strictly limited, and with Δt being constant, the number of stages is determined by the formula

$$N_{sol} = T / \Delta t. \tag{4.38}$$

It should be noted that in the process of solving a partial task prb^h, due to the coordinating influences of the decision maker, the input data DAT^h in (4.40) may be modified — additional information may be introduced, or outdated information may be replaced with new information. Let DAT_l^h the input data for the l-th stage, l = 1,...,N_{sol}. So DAT_1^h — the output data obtained from the decision maker, where $DAT_1^h = DAT^h$, and DAT_l^h, l = 2,...,N_{sol} — the output data of the subsequent stages. The index l denotes the stage number at which the output data are used. Let's define DAT_{l+1}^h — the output data of the (l+1)-th stage obtained after the coordinating influences of the decision maker concerning the modification of the data of the l-th stage.

4.2.2 CONCEPTUAL MODEL OF COORDINATION IN INTELLIGENT DECISION SUPPORT SYSTEMS

In the previous section, the coordinator model (4.36) was obtained. In an IDSS, the decision-maker (DM) functions as this element: it decomposes a complex task into a series of partial tasks, provides input data to the experts, and collects the solution results.

The drawback of existing IDSSs lies in the fact that coordination is performed only once — at the end of the problem-solving process — when the DM, after aggregating the results of solving the partial tasks into a single solution, draws a conclusion about its adequacy. If the integrated result is assessed as unsatisfactory, the possibility of solving the task anew may be lost. Therefore, it is relevant to develop IDSSs in which coordination occurs continuously throughout the process of solving a complex task.

Based on the IDSS model [6] and the model of a complex task with coordination, it is possible to construct the model of an IDSS with coordination

$$DSS = < PRT, prt^{dm}, R^{dm} >, \tag{4.39}$$

where $PRT = \{prt_q | q = 1,\dots,N_{prt}\}$ — a set of expert models; prt^{dm} — the decision-maker model; $R^{dm} = \{r^{dm\ q} |\dots,N_{prt}\}$ — the relations between the decision-maker and the experts, for example, relations of information exchange. Each expert works strictly within his or her own domain of knowledge $S_{prtq} \in S$, where S — the set of all domains of knowledge necessary for solving a complex task, and does not engage in any partial tasks outside his or her own domain $S_q \cap S_w = \varnothing$, for $q,w = 1,\dots,N_{prt}$; $q \neq w$. Based on the considerations in [5] and taking into account that in real tasks the partial tasks are solved by experts step by step, the expert model can be expressed as

$$prt_q = < B_{prof}, B_{theor}, B_{prec}, B_{facts}, MET_{prtq}, S_{prtq}, In_{prtq}, \Delta t >, \tag{4.40}$$

where B_{prof} — production base of professional knowledge; B_{theor} — production base of theoretical knowledge; B_{prec} — case base (experience); B_{facts} — fact base; MET_{prtq} — set of reasoning methods; S_{prtq} — description of the expert's domain of knowledge, for example, in mathematics this includes the description of the mathematical language, basic concepts, and operations; In_{prtq} — interpreter that ensures the execution of a sequence of rules for solving a problem based on facts and rules stored in the databases and knowledge bases; Δt — the period during which experts provide intermediate solutions.

The decision-maker model can be constructed by analogy with (4.38)

$$prt^{dm} = < B_{prof}, B_{theor}, B_{prec}, B_{facts}, B_{ext}, MET_{prtdm}, S_{prtdm}, In_{prtdm}, E, T >, \tag{4.41}$$

where B_{ext} — production knowledge base concerning how to perform reduction, aggregation, comparison, and coordination; E — the set of coordinating processes; T — the time required to solve the complex task.

Expression (4.39), in comparison with (4.38), has significant differences. The production knowledge base B_{ext} concerns how the decision-maker manages the process of solving a complex task. This knowledge comes from other experts. The set E describes how the decision-maker can coordinate the work of the experts.

The sequence scheme of the stages of the expert's work on finding a solution to the partial task π^h can be described as follows

$$DAT_l^h \otimes B^U \otimes \left\{sol_1^h\right\} \otimes, \ldots, \otimes \left\{sol_{l-1}^h\right\} \Rightarrow \left\{sol_l^h\right\},\ l = 1, \ldots, N_{sol}. \tag{4.42}$$

Output data DAT_l^h, $l = 1,\ldots,N_{sol}$ at each stage are supplemented by coordinating influences $e^{\alpha} \in E$, issued by the decision maker to the expert, which are determined based on the integrated result of the task solution prb^u at the (l–1)-th stage. In some cases, the decision maker may issue several coordinating influences to each expert. Let's assume that each expert receives one coordinating influence of a single type. Let's define the correspondence ψ_5

$$\psi_5 \left\{sol_l^u\right\} \otimes B_{ext} \to E,\ l = 1, \ldots, N_{sol} - 1. \tag{4.43}$$

The maximum value of l equals N_{sol}-1, because after N_{sol} the stage, it is no longer possible to apply coordination, since the final result has been obtained; sol_l^u – the integrated result of the task solution prb^u at the l-th stage; $E = \left\{\varepsilon_1, \ldots, \varepsilon_{N_\varepsilon}\right\}$ – a set of vectors of the form $\left(e_1^1, \ldots, e_{N_{prt}}^6\right)$, each component of which is a coordinating action for the expert, $e_q^{\alpha} \in E$, $q = 1,\ldots, N_{prt}$.

Since the knowledge about integration is included in B_{ext} the decision maker (4.40), the integrated result sol_l^u of solving the complex task prb^u can be expressed as follows

$$\left\{sol_l^{h\,1}\right\} \otimes \ldots \otimes \left\{sol_l^{h\,N_h}\right\} \otimes B_{ext} \to \left\{sol_l^u\right\}, \tag{4.44}$$

where $sol_l^{h\,1}, \ldots, sol_l^{h\,N_h}$ of solving the partial tasks $prt_1^h, \ldots, prt_{N_h}^h$ accordingly.

The elements of the correspondence ψ_5 – tuples $\left(\left(sol_l^u, \left\{b_{ext}^{\mu}\right\}\right), \varepsilon_p\right)$, so $l = 1,\ldots, N_{sol}$, $\mu = 1, \ldots, \mu_{N_\mu}$, $p = 1,\ldots, N\varepsilon$ where the first component is a two-component vector consisting of the integrated result sol_l^u solution of the task prb^u at the l-th stage and the list of the DM's knowledge used concerning how to perform comparisons, and $e \in E$ for the expert.

At the N_{sol}-th stage ($l = N_{sol}$) the vector of coordinating influences $\left(e_1^1, \ldots, e_{N_{prt}}^6\right)$, $\alpha = 6$, i.e. DM that is, the DM does not issue coordinating influences to the experts but only aggregates (performs the integration of the solutions to the prt^h tasks into a single, integrated solution sol_l^u of the complex task prt^u) the results of their work. If the obtained integrated result sol_l^u does not satisfy the DM, it must revise the initial data of the task prb^u. It is necessary to change DAT_l^h for all prt^h or change the list of its knowledge B_{ext} and the experts' knowledge B_{prof} (models (4.40) and (4.39)), and after that, initiate the repeated operation of the DSS. The correspondence ψ_5 is not a function (cannot be expressed analytically or computed), since the DM's knowledge and the integrated result of the task solution prb^u can be represented in natural language. It is unambiguous since each expert is assigned a specific coordinating influence e_q^{α}, and therefore, the correspondence ψ_5 uniquely determines only one vector $e \in E$. It is subjective, because to each vector $e \in E$ there corresponds at least one element $\left\{sol_l^u\right\} \otimes B_{ext}$, and not injective, because not every element $\left\{sol_l^u\right\} \otimes B_{ext}$ corresponds to a vector $e \in E$.

The analysis of the above-described model of the IDSS with coordination allows the following conclusion to be drawn. In this case, the errors in solving the complex task will be detected and corrected before obtaining the result of solving the complex task prb^u. Previously, this required repeated solutions.

4.2.3 MATHEMATICAL MODEL OF THE FUNCTIONAL HYBRID SYSTEM WITH COORDINATION

In [5], the following conceptual model of the IDSS, based on the automaton approach [7–9], is presented, designed for solving a complex task prb^u

$$\begin{gathered} res_A^u = R_1^{res\,met}\left(res_A^u, met^u\right) \circ R_1^{res\,pr}\left(res_A^u, pr^{ui}\right) \circ R_1^{res\,pr}\left(res_A^u, pr^{uo}\right) \circ \\ \circ R_1^{res\,st}\left(res_A^u, st^u\right) \circ R_1^{st\,st}\left(st^u(t), st^u(t+1)\right) \circ R_1^{pr\,st}\left(pr^{ui}(t), st^u(t+1)\right) \circ \\ \circ R_1^{st\,pr}\left(st^{up}(t), pr^{uo}(t)\right) \circ R_1^{res\,res}\left(RES^e, RES^e\right) \circ R_1^{pr\,pr}\left(pr^{ui}, PR^{ei}\right) \circ \\ \circ R_2^{pr\,st}\left(PR^{eo}, pr^{uo}\right), \end{gathered} \tag{4.45}$$

where t – model time, $t \in \mathbb{N}$;
$\circ$ – concatenation symbol;
res_A^u – the IDSS-aggregate as a resource for solving a heterogeneous task;
met^u – the integrated method for solving a heterogeneous task;
pr^{ui} – output data $DATu$ [5] solution of a complex task prb^u, that are transmitted to the input of one or several elements res^e, constructed according to scheme (4.45) in accordance with the decomposition $\widehat{prb}^u$ task prb^u;
pr^{uo} – the output of one or several elements res^e, constructed according to scheme (4.45) in accordance with $\widehat{prb}^u$, which is the goal GL^u of solving the task prb^u;
$st^u(t)$ – the state of the IDSS at time t;
RES^e – a nonempty set composed of elements res^e, constructed in accordance with scheme (4.45);
PR^{ei}, PR^{eo} – the set of properties "input" and "output" of the elements from RES^e accordingly;
$R_1^{st\,st}$, $R_1^{pr\,st}$, $R_1^{st\,pr}$ – relations of the functioning of the IDSS;
$R_1^{res\,res}$ – relations of integration [5] of the elements;
$R_1^{pr\,pr}$ – relations between the inputs of the IDSS and the inputs of the elements;
$R_2^{pr\,pr}$ – relations between the outputs of the elements and the outputs of the IDSS.

The element res^e models the solution of a homogeneous partial task or performs auxiliary operations, constructed according to an autonomous method met^e and possesses the properties $PR^e \subseteq PR$, the most important of which are "input" pr^{ei}, "output" pr^{eo} *i* "state" st^i. Conceptual model of an IDSS element

$$\begin{gathered} res^e = R_1^{res\,met}\left(res^e, met^e\right) \circ R_1^{res\,pr}\left(res^e, pr^{ei}\right) \circ R_1^{res\,pr}\left(res^e, pr^{eo}\right) \circ \\ \circ R_1^{res\,st}\left(res^e, st^e\right) \circ R_1^{st\,st}\left(st^e(t), st^e(t+1)\right) \circ R_1^{pr\,st}\left(pr^{ei}(t), st^e(t+1)\right) \circ \\ \circ R_1^{st\,pr}\left(st^e(t), pr^{eo}(t)\right) \end{gathered} \tag{4.46}$$

where $R_1^{st\,st}$ $R_1^{pr\,st}$, $R_1^{st\,pr}$ – the "state – state", "input – state", and "state – output" relations, respectively. Among the set of $MET^e = \left\{ met_y^e \mid y = 1,\ldots,N_{met} \right\}$ autonomous methods, it is possible to distinguish met_1^e : analytical computations, met_2^e neurocomputations, met_3^e fuzzy computations, met_4^e reasoning based on experience, evolutionary computations, met_6^e statistical computations, met_7^e and logical reasoning. If between an element res^e and an autonomous method, met_y^e a relation is established $R_1^{res\,met}\left(res^e, met_y^e\right)$, it is possible to denote the element $res^{e\,y}$.

Relations $R_1^{pr\,pr}$ $R_2^{pr\,pr}$ (4.44) are defined on sets of variables DAT^u, GL^u, and on sets of variables DAT^h, GL^h of the partial tasks included in the complex task.

In [5], three possible cases are given:

1) a set of variables for prb^u coincides with the set of variables for prb^h, so $DAT^u = DAT^h$, $GL^u = GL^h$;

2) the set of variables for prb^h – a subset of the corresponding set prb^u, so $DAT^h = DAT^u$, $GL^h = GL^u$;

3) the set of variables of a subset of the corresponding set prb^h, so $DAT^h = DAT^u$, $GL^h = GL^u$.

Since the automaton approach is used for modeling, the state of the automaton is influenced only by the input signal. The output signal depends on the state of the automaton at the previous moment of automaton time and on the input signal.

The extension of models (4.43) and (4.44) is carried out based on the following considerations. In the process of coordination, the intermediate states of the solutions to partial tasks are monitored [11]. In the adopted notations (4.43), (4.44), these states are understood as the states (solution results) of the functional elements res^e, that simulate the solutions of partial tasks prb^h. From the analysis of these states, the properties of the "input" change during coordination pr^{ei} of one or several elements res^e.

To take this fact into account, let's introduce into the conceptual model of the IDSS (4.43), (4.44) the triple $R_1^{st\,pr}\left(st^u(t), pr^{ui}(t+1)\right)$. In other words, based on the state of the IDSS $st^u(t)$ at time t, the output data change $pr^{ui}(t+1)$ for the IDSS, but already now in time t+1, that is, for the next iteration. Many $R_1^{st\,pr}$ establish relationships between the state $st^u(t)$ hybrid res_A^u (4.43) at the current model time t and the state of the inputs of one or several elements res^e at the next step.

To make the necessary change to the inputs pr^{ei} of one or several functional elements res^e for (4.44) let's introduce the triple $R_1^{st\,act}\left(st^u, act^{ek}\right)$, where $ACT^{ek} = \left\{ act_1^{ek\,\alpha},\ldots,act_{N_{prt}}^{ek\,\alpha} \right\}$ – a set of concepts denoting coordinating actions, which is identical to the set of coordinating actions E (4.30), where α – the type of coordinating influence, $\alpha = 1,\ldots,6$.

The modified conceptual model for the IDSS with coordination

$$res_A^u = res_A^u \circ R_1^{st\,pr}\left(st^u(t), pr^{ui}(t+1)\right), \tag{4.47}$$

and the modified model of the IDSS element

$$res^e = res^e \circ R_1^{st\,act}\left(st^u, act^{ek}\right). \tag{4.48}$$

Relationships $R_1^{st\,pr}$ and $R_1^{st\,act}$ are not predetermined, just as $R_1^{st\,st}$ $R_1^{pr\,st}$, $R_1^{st\,pr}$ are recorded in the course of the IDSS operation and are the result of solving the k-task prb^k (4.33).

Let's consider an example of an IDSS consisting of three elements $res_1^{e\,1}$, $res_2^{e\,6}$, $res_3^{e\,7}$ for solving partial tasks, which it is possible to call functional [5], and one coordinating (technological) element $res_k^{e\,7}$ for solving the k-task, which determines the order of interaction of the functional elements. The input of the IDSS receives the initial data DAT^u, divided among the functional elements according to the decomposition $\widehat{prb}^u \in \widehat{PRB}^u$ of solving a complex task prb^u. At the output, it is possible to obtain the results of the operation of the functional elements $res_1^{e\,1}$, $res_2^{e\,6}$, $res_3^{e\,7}$, integrated into the overall solution SOL^u of the complex task prb^u.

At each moment in time, t_l the state of all elements is recorded (polled) $res_q^{e\,y}$. After that, $res_k^{e\,7}$ based on the state $st^u(t_l)$, the IDSS issues a coordinating action $act_q^{ek\,\alpha} \in ACT^{ek}$ for each element $res_q^{e\,y}$. In the process of processing by the technological element $res_k^{e\,7}$ state $st^u\left(t_l\right)$ of the IDSS, that is, the solution of the k-task prb^k the state changes of the technological element $res_k^{e\,7}$. Moreover, the time τ', allocated for such processing, must not exceed the period after which the state of the IDSS is recorded

$$\tau' \leq T / N_{sol}, \tag{4.49}$$

where T – the time allocated for solving the complex task prb^u; N_{sol} – the total number of stages. The transitions between the states of the functional elements of the IDSS occur abruptly, since between the moments in time t_l this state $res_q^{e\,y}$ does not change.

Below is the conceptual model of the operation of the IDSS constructed according to (4.45) and (4.47)

$$\begin{gathered} st^{e\,k}\left(t_0'\right) \Rightarrow \left\{\begin{matrix} st^{e\,1}\left(t_0\right) \\ st^{e\,2}\left(t_0\right) \end{matrix}\right\} \rightarrow \left\{\begin{matrix} st^{e\,1}\left(t_1\right) \\ st^{e\,2}\left(t_1\right) \end{matrix}\right\} \Rightarrow st^{e\,k}\left(t_0'\right) \rightarrow st^{e\,k}\left(t_1'\right) \Rightarrow \\ \Rightarrow \left\{\begin{matrix} st^{e\,1}\left(t_1\right) \\ st^{e\,2}\left(t_1\right) \end{matrix}\right\} \rightarrow \left\{\begin{matrix} st^{e\,1}\left(t_2\right) \\ st^{e\,2}\left(t_2\right) \end{matrix}\right\} \Rightarrow st^{e\,k}\left(t_1'\right) \rightarrow st^{e\,k}\left(t_2'\right) \Rightarrow \ldots \Rightarrow \\ \Rightarrow \left\{\begin{matrix} st^{e\,1}\left(t_{p-1}\right) \\ st^{e\,2}\left(t_{p-1}\right) \end{matrix}\right\} \rightarrow \left\{\begin{matrix} st^{e\,1}\left(t_p\right) \\ st^{e\,2}\left(t_p\right) \end{matrix}\right\} \Rightarrow st^{e\,k}\left(t_{p-1}'\right) \rightarrow st^{e\,k}\left(t_p'\right), \end{gathered} \tag{4.50}$$

where "$\Rightarrow$" denote the relations $R^{st\,st}$, that link states from different subspaces and define the transition from one homogeneous space to others during the functioning of the IDSS; "$\rightarrow$" – the transition between states within the corresponding subspace. The transitions "$\Rightarrow$" from the subspace of the technological element $res_q^{e\,7}$ model the issuance of coordinating actions from the decision maker to the experts. And the set of transitions "$\Rightarrow$" and "$\rightarrow$" allows modeling and tracing the process of self-organization during the operation of the IDSS.

In (4.49), curly brackets denote the beginning and completion of the parallel operation of the functional elements. From the model, it is evident that after each fixation of "$\}\Rightarrow$" of states, functional element $res_q^{e\,y}$ control is transferred to the technological element $res_q^{e\,7}$, and after it changes its state, control is transferred to a group of functional elements of the IDSS.

This model is related to the conceptual model presented in [5]

$$\begin{cases} st^{e1}(t) \to st^{e1}(t+1) \to \ldots \to st^{e1}(t+n) \\ st^{e2}(t) \to st^{e2}(t+1) \to \ldots \to st^{e2}(t+n) \end{cases}. \tag{4.51}$$

The model (4.49) is based on the idea that the same homogeneous task can be solved in parallel by different functional elements of the IDSS. The relations of integration among the elements arise as internal nonverbal images in the user's memory, allowing them to compare the dynamics of modeling a complex task from different viewpoints, which makes it possible to perceive aspects that cannot be revealed through modeling with a single model. In model (4.48), another assumption is developed: the inclusion of the DM model within the mathematical model of the IDSS leads to the emergence of a self-organization effect.

4.3 CONCEPTUAL MODEL OF CONSISTENCY IN INTELLIGENT DECISION SUPPORT SYSTEMS

Consistency is understood as the degree of similarity among the goals of the IDSS participants. According to [13], a goal is a state of affairs that the decision-maker (DM) seeks to achieve, and which has a certain subjective value for them. In [3], a goal is defined as an ideal anticipation of the result of activity that acts as its regulator, while in [7] it is described as a situation or set of situations that must be achieved during the functioning of the system within a specified time frame. Generalizing these definitions, it is possible to identify the main characteristics of a goal: it represents the state of the control object, acts as a regulator of activity, has a temporal nature (a function of time), and is subjectively valuable to the DM.

Definition 7. Goal pr^{gsu} of the expert as a control subject res^{su} – state st^{pou} of the control object res^{su}, which has value (utility) for the expert pr^{csu}, that determines its activity (sequence of actions) act^{dsu}, which must be achieved within a period of time pr^{t}.

The scheme of conceptual goal models can be represented in the form of

$$\begin{gathered} pr^{gsu} = R^{res\ st}\left(res^{ou}, st^{pou}\right) \circ R^{res\ pr}\left(res^{su}, pr^{csu}\right) \circ R^{res\ act}\left(res^{ou}, act^{dsu}\right), \\ act^{dsu} = R^{act\ act}\left(ACT^{su}, ACT^{su}\right) \circ R^{act\ pr}\left(ACT^{su}, PR^{t}\right), \end{gathered} \tag{4.52}$$

where $R^{res\ st}$ – the "resource – state" relations, which assign to the control object its state;
$R^{res\ pr}$ – the "resource – property" relations, which determine the subjective usefulness of the state of the control object for the expert (the control subject);
$R^{pr\ act}$ – the "property – action" relations, which assign to the target state a sequence of actions act^{dsu};
ACT^{su} – the set of possible actions of the expert;
$R^{act\ act}$ – the "action – action" relations that determine the order of actions $act^{dsu} \in ACT^{su}$ in the sequence act^{dsu};
$R^{act\ pr}$ – the "action – property" relations between actions with CT^{su} and the time of their execution PR^{t}.

The state st^{pou} of the control object res^{ou} is determined by the values of its properties

$$st^{pou} = R^{res\ pr}\left(res^{ou}, PR^{ou}\right) \circ R^{pr\ val}\left(PR^{ou}, VAL^{ou}\right),$$

where $R^{res\ pr}$ — the "resource — property" relations, which define the set of properties of the control object, and $R^{pr\ val}$ — the "property — value" relations, where each property of the control object is associated with a set of values. One of the properties in the set Pr^{ou} may represent the time associated with the functioning of the control object. In this case, the expert's goal also becomes dynamic and changes over time.

Since, as noted above, the properties of the control object are considered variable when recording cause-and-effect relationships in one or another modeling method, several tools may be used in goal setting. This leads to the complexity of modeling decision-making when it is necessary to compare partial goals described by different methods. Such a situation arises, for example, when Pareto-optimal solutions exist, and it is necessary to select only one of them. Let's assume that there is a control object with two properties pr_1^{ou} i pr_2^{ou}, as well as two states of the control object st_1^{pou}, and st_2^{pou}, so st_1^{pou} closer to the target state, st^{pou}, than st_2^{pou}, according to the first criterion pr_1^{ou}, and st_2^{pou}, according to the second one pr_2^{ou}.

If the properties are represented by different variables (for example, stochastic and fuzzy linguistic ones) processed by different methods, it will be difficult to select one of the solutions. However, if the properties are represented by variables of the same type, it is possible to define a metric in a two-dimensional space of vectors representing the admissible states of the control object and determine the distance between st_1^{pou} and st^{pou}, and also st_2^{pou} and st^{pou}, after which they can be compared with one another. To avoid such situations, it is possible to choose a single method for representing all properties that define the state of the control object, and consequently, those used in describing the goals of the decision-maker (DM) and the experts. Analysis has shown that the apparatus of fuzzy set theory [10] is relevant for this purpose.

Definition 8. A fuzzy goal of an expert pr^{gsu} — a fuzzy set defined on the set of states of the control object $ST^{pou} \subseteq ST$, with a membership function $\mu^{pr^{gsu}}\left(st^{pou}\right)$, or, for brevity μ*gsu* (st^{pou}).

The membership function $\mu^{gsu}(st^{pou})$ takes values on the set of real numbers within the interval [0; 1]. The greater its value, the closer the state of the control object st^{pou} is to the expert's goal st^{gsu}. The state st^{pou} of the control object is described by a set of its properties $PR^{ou} = \left\{pr_1^{ou}, \ldots, pr_{N_{pr}^{ou}}^{ou}\right\}$, represented by variables belonging to one of the classes listed in [5], that is

$$\mu^{gsu}\left(st^{pou}\right) = \mu^{gsu}\left(pr_1^{ou}, \ldots, pr_{N_{pr}^{ou}}^{ou}\right). \tag{4.53}$$

The value of the membership function is determined by substituting into (4.52) the values from the set VAL^{ou} of the control object's properties corresponding to this state, that is, it is described by the expression $\mu^{gsu}\left(val_1^{ou}, \ldots, val_{N_{val}^{ou}}^{ou}\right)$.

A fuzzy goal of an expert can be represented using one of the methods for constructing membership functions of fuzzy sets considered in [7]. The choice of method is determined by the IDSS developer. Below, to describe the causal relationships between goals and the interaction relations of experts, direct methods [7] for constructing fuzzy goals are used.

When the experts' goals are formalized, pairwise comparison can be performed, and the degree of closeness can be determined. One of the options for determining the degree of closeness between experts' goals is the calculation of the Euclidean or Hamming distance between fuzzy sets [4, 5].

However, their application to determining the degree of similarity of experts' goals is problematic: they are computed only under the condition of convergence of the series or integrals used in them. Otherwise, when $val^{ou}_{\min} = -\infty$ or $val^{ou}_{\max} = \infty$ where $val^{ou}_{\min}$ and $val^{ou}_{\max}$ the minimum and maximum values of the property pr^{ou}, that describes the state st^{pou}, the distance will be equal to infinity, even if one set includes another. In this case, a measure of similarity of fuzzy goals is proposed [6, 10, 12]

$$s(A,B) = 0{,}5 \cdot \left(\frac{\int_{val^{ou}_{\min}}^{val^{ou}_{\max}} \mu^{gsu}_{A\cap B}\left(pr^{ou}\right) d\left(pr^{ou}\right)}{\int_{val^{ou}_{\min}}^{val^{ou}_{\max}} \mu^{gsu}_{A}\left(pr^{ou}\right) d\left(pr^{ou}\right)} + \frac{\int_{val^{ou}_{\min}}^{val^{ou}_{\max}} \mu^{gsu}_{A\cap B}\left(pr^{ou}\right) d\left(pr^{ou}\right)}{\int_{val^{ou}_{\min}}^{val^{ou}_{\max}} \mu^{gsu}_{B}\left(pr^{ou}\right) d\left(pr^{ou}\right)} \right). \tag{4.54}$$

Analysis shows that, unlike the Euclidean or Hamming distance, relation (4.53) should be considered a measure of similarity between fuzzy sets rather than a distance between them, since it does not satisfy some of the conditions (specifically, (4.54) and (4.55)) required of a distance function in mathematics:

$$d(X,Y) \geq 0,$$

$$d(X,Y) = d(Y,X),$$

$$d(X,Z) \leq d(X,Y) + d(Y,Z), \tag{4.55}$$

$$d(X,X) = 0. \tag{4.56}$$

After determining the measure of similarity between the experts' goals, it becomes possible to define the type of relations among them based on the level of consistency. Let's represent this as fuzzy sets on the universe of values of the similarity measure of goals s (on the set of real numbers within the interval [0;1]). The study identifies three types of relations according to the degree of consistency: competition, neutrality, and cooperation. The greater the value of the measure of similarity of the experts' goals (4.53), the closer their interaction.

Thus, the membership function of the fuzzy set "cooperation" should attain its maximum value at $s = 1$, while the membership function of the fuzzy set "competition" should attain its maximum at $s = 0$. The maximum of the membership function of the fuzzy set "neutrality" should be equidistant from these maxima, that is, located at the point $s = 0.5$. The membership functions of the fuzzy sets representing the relations of competition "*competition*" (*s*) =, of neutrality $\mu_{\text{"neutrality"}}(s) = \left(1 + \left(6 \cdot (s - 0{,}5)\right)^{8}\right)^{-1}$, and cooperation $\mu_{\text{"cooperation"}}(s) = \left(1 + \left(6 \cdot (s - 0{,}5)\right)^{8}\right)$.

Let's represent the relations between the participants of the IDSS according to the degree of consistency of the linguistic variable cl — "type of relation"

$$cl = \left\langle \beta^{cl}, T^{cl}, U^{cl}, G^{cl}, M^{cl} \right\rangle, \tag{4.57}$$

where β^{cl}= "type of relation" — the designation of the linguistic variable;
T^{cl}= {"competition"; "neutrality"; "cooperation"} — the set of names of the linguistic values of the variable (term set), which constitute the designations of the fuzzy variable;
U^{cl} =[0;1] — the domain of definition (universe) of fuzzy variables included in the definition of the linguistic variable;
$G^{cl} = \varnothing$ — a syntactic procedure that describes the process of formation of new terms from the elements of the set *T*;
$M^{cl} = \left\{ \mu_{\text{"competition"}}(s), \mu_{\text{"neutrality"}}(s), \mu_{\text{"cooperation"}}(s) \right\}$ — a semantic procedure that assigns to each term of the set *T* and to the terms formed by the procedure *G* a fuzzy set [6, 10, 12].

The value of the linguistic variable cl (type of relations) is the term with the maximum value of the membership function. To calculate it, it is necessary to determine the value of the membership function for each fuzzy set representing the relations and compare them with one another.

The fuzzy set with the maximum value of the membership function corresponds to the type of relations established between the pair of experts. It is possible to define the mapping "relation classifier" $rcl : \left(prt_i, prt_j \right) \rightarrow T^{cl}$, $ag_i, ag_j \in AG^*$, $i \neq j$, which assigns to each pair of participants of the IDSS (prt_i prt_j), one of the terms t_k^{cl} of the linguistic variable *cl*, that is, the type of relation. The mapping is defined as follows:

$$rcl : \left(prt_i, prt_j \right) = \underset{t_k^{cl} \in T^{cl}}{\operatorname{argmax}} \left(\mu_{t_k^{cl}} \left(s\left(pr_p^{gsu}, pr_q^{gsu} \right) \right) \right), \tag{4.58}$$

so $r_1^{res\ pr}\left(prt_i, pr_p^{gsu} \right), r_1^{res\ pr}\left(prt_j, pr_q^{gsu} \right), i \neq j.$

Many values of this mapping form the matrix RCL, which classifies the relations among the IDSS participants. The rows and columns of the matrix represent the participants, and the elements $rcl_{i\,j} = rcl\left(prt_i, prt_j \right)$ — the class of relations among them. This matrix is used to identify the collective decision-making situation for the complex task.

Depending on the classes of relations present in the IDSS, three collective decision-making situations (micro-level IDSS models) can be distinguished for the task:

1. The cooperation situation $\widetilde{dss}_{coop}$, when the IDSS consists of cooperative and neutral participants and there are no competitive relations.

2. The neutrality situation $\widetilde{dss}_{neut}$ occurs when all relations in the IDSS are neutral.

3. The competition situation $\widetilde{dss}_{comp}$ occurs when the IDSS contains at least one pair of experts with a competitive relationship.

In such IDSSs, neutral and cooperative participants may also be present. In the presence of cooperative participants, they are regarded as a single notional participant; in this case, all remaining participants are either competitive or neutral.

Thus, the process of self-organization based on goal analysis can be divided into two parts: identification of the current collective decision-making situation (the micro-level model of the IDSS) and selection, from the set of possible situations, of the desired collective decision-making situation that is relevant to the conditions of the given task. Taking this into account, the self-organization model (4.27) can be rewritten as follows

$$\begin{aligned} so^{goa} = {} & r_2^{res\ act}\left(dss, ACT^{sen}\right) \circ r_1^{act\ res}\left(ACT^{sen}, env\right) \circ R_1^{res\ res}\left(\widetilde{DSS}, \widetilde{DSS}\right) \circ \\ & \circ r_3^{res\ res}\left(dss, prt^{dm}\right) \circ r_2^{res\ act}\left(prt^{dm}, act_{ia}\right) \circ r_1^{act\ res}\left(act_{ia}, \widetilde{dss}_{cur}\right) \circ \\ & \circ r_2^{res\ act}\left(prt^{dm}, act_{ac}\right) \circ r_1^{act\ res}\left(act_{ac}, \widetilde{DSS}\right) \circ r_2^{act\ res}\left(act_{ac}, \widetilde{dss}_{des}\right), \end{aligned} \tag{4.59}$$

where act_{ia} – the DM's action "identification of the current collective decision situation";
act_{ac} – the DM's action "selection of the desired collective decision situation from the set of possible ones";
$\widetilde{dss}_{cur}$ – the current collective decision situation (micro-level model of the IDSS);
$\widetilde{dss}_{des}$ – the collective decision situation desired by the DM in terms of the task parameters and its knowledge about the effectiveness of a particular situation from the set $\widetilde{DSS}$ of possible in the IDSS;
$r_2^{res\ act}$ – the "performs" relation, which links a subject and the action it performs;
$r_1^{act\ res}$ – the "has as an object" relation, which links an action and its resource;
$r_2^{act\ res}$ – the "has as a result" relation, which links an action and the result of its execution.

The first stage of identification act_{ia} (4.58) collective decision situations – formalization of the experts' goals considering the definition of the fuzzy goal (4.52). After the fuzzy goals of all experts have been determined, the next stage of identification is performed, act_{ia} (4.58), collective decision situations – pairwise comparison of goals and determination of their degree of consistency using measure (4.53).

Next, the type of relations between the experts is determined according to the degree of consistency using the linguistic variable cl "type of relation" (4.56).

The final stage of identification act_{ia} (4.58) collective decision situations – recognition of the collective decision situation using the matrix CL'. Depending on the classes of relations present in the matrix CL', three collective decision-making situations are distinguished: cooperation $\widetilde{dss}_{coop}$, neutrality $\widetilde{dss}_{neut}$, and competition $\widetilde{dss}_{comp}$.

After identifying the current collective decision-making situation, the decision-maker (DM) selects act_{ac} (4.58) from the set of possible collective decision-making situations that correspond to the conditions of the given task. Depending on the task parameters and their knowledge of the effectiveness of a particular collective decision situation, the decision-maker (DM) may seek to establish one of them. This is necessary to increase the efficiency of the IDSS operation or to attempt to change it if the discussion reaches an impasse.

CONCLUSIONS

The study proposes a polymodel complex for managing the resources of intelligent decision support systems. The novelty of the proposed polymodel complex is:

– in a comprehensive description of the process of functioning of intelligent decision support systems. This allows to increase the accuracy of modeling intelligent decision support systems for subsequent management decisions;

– descriptions of both static and dynamic processes that occur in intelligent decision support systems;

– ability to simulate both a single process that takes place in intelligent decision support systems, and to comprehensively simulate those processes that take place in them;

– in establishing the conceptual dependencies of the process of functioning of intelligent decision support systems. This allows to describe the interaction of individual models at all stages of solving calculation tasks;

– descriptions of coordination processes in hybrid intelligent decision support systems, which improves the reliability of management decision-making;

– modeling of processes for solving complex calculation tasks in intelligent decision support systems, due to the conceptual description of the specified process;

– coordination of calculation processes in intelligent decision support systems, which achieves a decrease in the number of computing resources of systems;

– complex dispute resolution, due to a complex of appropriate mathematical models.

The proposed polymodel complex should be used to solve the task of resource management of intelligent decision support systems characterized by a high degree of complexity.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

USE OF ARTIFICIAL INTELLIGENCE

The authors confirm that they did not use artificial intelligence technologies in creating the submitted work.

REFERENCES

1. Dudnyk, V., Sinenko, Y., Matsyk, M., Demchenko, Y., Zhyvotovskyi, R., Repilo, I. et al. (2020). Development of a method for training artificial neural networks for intelligent decision support systems. Eastern-European Journal of Enterprise Technologies, 3 (2 (105)), 37–47. https://doi.org/10.15587/1729-4061.2020.203301

2. Sova, O., Shyshatskyi, A., Salnikova, O., Zhuk, O., Trotsko, O., Hrokholskyi, Y. (2021). Development of a method for assessment and forecasting of the radio electronic environment. EUREKA: Physics and Engineering, 4, 30–40. https://doi.org/10.21303/2461-4262.2021.001940
3. Pievtsov, H., Turinskyi, O., Zhyvotovskyi, R., Sova, O., Zvieriev, O., Lanetskii, B., Shyshatskyi, A. (2020). Development of an advanced method of finding solutions for neuro-fuzzy expert systems of analysis of the radioelectronic situation. EUREKA: Physics and Engineering, 4, 78–89. https://doi.org/10.21303/2461-4262.2020.001353
4. Zuiev, P., Zhyvotovskyi, R., Zvieriev, O., Hatsenko, S., Kuprii, V., Nakonechnyi, O. et al. (2020). Development of complex methodology of processing heterogeneous data in intelligent decision support systems. Eastern-European Journal of Enterprise Technologies, 4 (9 (106)), 14–23. https://doi.org/10.15587/1729-4061.2020.208554
5. Kuchuk, N., Mohammed, A. S., Shyshatskyi, A., Nalapko, O. (2019). The Method of Improving the Efficiency of Routes Selection in Networks of Connection with the Possibility of Self-Organization. International Journal of Advanced Trends in Computer Science and Engineering, 8 (1.2), 1–6.
6. Shyshatskyi, A., Zvieriev, O., Salnikova, O., Demchenko, Ye., Trotsko, O., Neroznak, Ye. (2020). Complex Methods of Processing Different Data in Intellectual Systems for Decision Support System. International Journal of Advanced Trends in Computer Science and Engineering, 9 (4), 5583–5590. https://doi.org/10.30534/ijatcse/2020/206942020
7. Pozna, C., Precup, R.-E., Horvath, E., Petriu, E. M. (2022). Hybrid Particle Filter–Particle Swarm Optimization Algorithm and Application to Fuzzy Controlled Servo Systems. IEEE Transactions on Fuzzy Systems, 30 (10), 4286–4297. https://doi.org/10.1109/tfuzz.2022.3146986
8. Yang, X.-S., Deb, S. (2013). Cuckoo search: recent advances and applications. Neural Computing and Applications, 24 (1), 169–174. https://doi.org/10.1007/s00521-013-1367-1
9. Mirjalili, S. (2015). The Ant Lion Optimizer. Advances in Engineering Software, 83, 80–98. https://doi.org/10.1016/j.advengsoft.2015.01.010
10. Yu, J. J. Q., Li, V. O. K. (2015). A social spider algorithm for global optimization. Applied Soft Computing, 30, 614–627. https://doi.org/10.1016/j.asoc.2015.02.014
11. Mirjalili, S., Mirjalili, S. M., Lewis, A. (2014). Grey Wolf Optimizer. Advances in Engineering Software, 69, 46–61. https://doi.org/10.1016/j.advengsoft.2013.12.007
12. Koval, V., Nechyporuk, O., Shyshatskyi, A., Nalapko, O., Shknai, O., Zhyvylo, Y. et al. (2023). Improvement of the optimization method based on the cat pack algorithm. Eastern-European Journal of Enterprise Technologies, 1 (9 (121)), 41–48. https://doi.org/10.15587/1729-4061.2023.273786
13. Gupta, E., Saxena, A. (2015). Robust generation control strategy based on Grey Wolf Optimizer. Journal of Electrical Systems, 11, 174–188.
14. Chaman-Motlagh, A. (2015). Superdefect Photonic Crystal Filter Optimization Using Grey Wolf Optimizer. IEEE Photonics Technology Letters, 27 (22), 2355–2358. https://doi.org/10.1109/lpt.2015.2464332
15. Nuaekaew, K., Artrit, P., Pholdee, N., Bureerat, S. (2017). Optimal reactive power dispatch problem using a two-archive multi-objective grey wolf optimizer. Expert Systems with Applications, 87, 79–89. https://doi.org/10.1016/j.eswa.2017.06.009

16. Koval, M., Sova, O., Orlov, O., Shyshatskyi, A., Artabaiev, Y., Shknai, O. et al. (2022). Improvement of complex resource management of special-purpose communication systems. Eastern-European Journal of Enterprise Technologies, 5 (9 (119)), 34–44. https://doi.org/10.15587/1729-4061.2022.266009
17. Ali, M., El-Hameed, M. A., Farahat, M. A. (2017). Effective parameters' identification for polymer electrolyte membrane fuel cell models using grey wolf optimizer. Renewable Energy, 111, 455–462. https://doi.org/10.1016/j.renene.2017.04.036
18. Zhang, S., Zhou, Y. (2017). Template matching using grey wolf optimizer with lateral inhibition. Optik, 130, 1229–1243. https://doi.org/10.1016/j.ijleo.2016.11.173
19. Khouni, S. E., Menacer, T. (2023). Nizar optimization algorithm: a novel metaheuristic algorithm for global optimization and engineering applications. The Journal of Supercomputing, 80 (3), 3229–3281. https://doi.org/10.1007/s11227-023-05579-4
20. Saremi, S., Mirjalili, S., Lewis, A. (2017). Grasshopper Optimisation Algorithm: Theory and application. Advances in Engineering Software, 105, 30–47. https://doi.org/10.1016/j.advengsoft.2017.01.004
21. Braik, M. S. (2021). Chameleon Swarm Algorithm: A bio-inspired optimizer for solving engineering design problems. Expert Systems with Applications, 174, 114685. https://doi.org/10.1016/j.eswa.2021.114685
22. Yapici, H., Cetinkaya, N. (2019). A new meta-heuristic optimizer: Pathfinder algorithm. Applied Soft Computing, 78, 545–568. https://doi.org/10.1016/j.asoc.2019.03.012
23. , H., Qiao, P. (2014). Pigeon-inspired optimization: a new swarm intelligence optimizer for air robot path planning. International Journal of Intelligent Computing and Cybernetics, 7 (1), 24–37. https://doi.org/10.1108/ijicc-02-2014-0005
24. Yang, X. S (2012). Flower pollination algorithm for global optimization. Unconventional computing and natural computation. Berlin, Heidelberg: Springer, 240–249. https://doi.org/10.1007/978-3-642-32894-7_27
25. Gomes, G. F., da Cunha, S. S., Ancelotti, A. C. (2018). A sunflower optimization (SFO) algorithm applied to damage identification on laminated composite plates. Engineering with Computers, 35 (2), 619–626. https://doi.org/10.1007/s00366-018-0620-8
26. Mehrabian, A. R., Lucas, C. (2006). A novel numerical optimization algorithm inspired from weed colonization. Ecological Informatics, 1 (4), 355–366. https://doi.org/10.1016/j.ecoinf.2006.07.003
27. Qi, X., Zhu, Y., Chen, H., Zhang, D., Niu, B. (2013). An idea based on plant root growth for numerical optimization. Intelligent Computing Theories and Technology. Berlin, Heidelberg: Springer, 571–578. https://doi.org/10.1007/978-3-642-39482-9_66
28. Bezuhlyi, V., Oliynyk, V., Romanenko, I., Zhuk, O., Kuzavkov, V., Borysov, O., Korobchenko, S., Ostapchuk, E., Davydenko, T., Shyshatskyi, A. (2021). Development of object state estimation method in intelligent decision support systems. Eastern-European Journal of Enterprise Technologies, 5 (3 (113)), 54–64. https://doi.org/10.15587/1729-4061.2021.239854
29. Mahdi, Q. A., Shyshatskyi, A., Prokopenko, Y., Ivakhnenko, T., Kupriyenko, D., Golian, V. et al. (2021). Development of estimation and forecasting method in intelligent decision support systems. Eastern-European Journal of Enterprise Technologies, 3 (9 (111)), 51–62. https://doi.org/10.15587/1729-4061.2021.232718

30. Sova, O., Radzivilov, H., Shyshatskyi, A., Shevchenko, D., Molodetskyi, B., Stryhun, V. et al. (2022). Development of the method of increasing the efficiency of information transfer in the special purpose networks. Eastern-European Journal of Enterprise Technologies, 3 (4 (117)), 6–14. https://doi.org/10.15587/1729-4061.2022.259727
31. Zhang, H., Zhu, Y., Chen, H. (2013). Root growth model: a novel approach to numerical function optimization and simulation of plant root system. Soft Computing, 18 (3), 521–537. https://doi.org/10.1007/s00500-013-1073-z
32. Labbi, Y., Attous, D. B., Gabbar, H. A., Mahdad, B., Zidan, A. (2016). A new rooted tree optimization algorithm for economic dispatch with valve-point effect. International Journal of Electrical Power & Energy Systems, 79, 298–311. https://doi.org/10.1016/j.ijepes.2016.01.028
33. Murase, H. (2000). Finite element inverse analysis using a photosynthetic algorithm. Computers and Electronics in Agriculture, 29 (1-2), 115–123. https://doi.org/10.1016/s0168-1699(00)00139-3
34. Zhao, S., Zhang, T., Ma, S., Chen, M. (2022). Dandelion Optimizer: A nature-inspired metaheuristic algorithm for engineering applications. Engineering Applications of Artificial Intelligence, 114, 105075. https://doi.org/10.1016/j.engappai.2022.105075
35. Paliwal, N., Srivastava, L., Pandit, M. (2020). Application of grey wolf optimization algorithm for load frequency control in multi-source single area power system. Evolutionary Intelligence, 15 (1), 563–584. https://doi.org/10.1007/s12065-020-00530-5
36. Dorigo, M., Blum, C. (2005). Ant colony optimization theory: A survey. Theoretical Computer Science, 344 (2-3), 243–278. https://doi.org/10.1016/j.tcs.2005.05.020
37. Poli, R., Kennedy, J., Blackwell, T. (2007). Particle swarm optimization. Swarm Intelligence, 1 (1), 33–57. https://doi.org/10.1007/s11721-007-0002-0
38. Bansal, J. C., Sharma, H., Jadon, S. S., Clerc, M. (2014). Spider Monkey Optimization algorithm for numerical optimization. Memetic Computing, 6 (1), 31–47. https://doi.org/10.1007/s12293-013-0128-0
39. Yeromina, N., Kurban, V., Mykus, S., Peredrii, O., Voloshchenko, O., Kosenko, V. et al. (2021). The Creation of the Database for Mobile Robots Navigation under the Conditions of Flexible Change of Flight Assignment. International Journal of Emerging Technology and Advanced Engineering, 11 (5), 37–44. https://doi.org/10.46338/ijetae0521_05
40. Maccarone, A. D., Brzorad, J. N., Stone H. M. (2008). Characteristics And Energetics Of Great Egret And Snowy Egret Foraging Flights. Waterbirds, 31 (4), 541–549. https://doi.org/10.1675/1524-4695-31.4.541
41. Ramaji, I. J., Memari, A. M. (2018). Interpretation of structural analytical models from the coordination view in building information models. Automation in Construction, 90, 117–133. https://doi.org/10.1016/j.autcon.2018.02.025
42. Pérez-González, C. J., Colebrook, M., Roda-García, J. L., Rosa-Remedios, C. B. (2019). Developing a data analytics platform to support decision making in emergency and security management. Expert Systems with Applications, 120, 167–184. https://doi.org/10.1016/j.eswa.2018.11.023
43. Chen, H. (2018). Evaluation of Personalized Service Level for Library Information Management Based on Fuzzy Analytic Hierarchy Process. Procedia Computer Science, 131, 952–958. https://doi.org/10.1016/j.procs.2018.04.233

44. Chan, H. K., Sun, X., Chung, S.-H. (2019). When should fuzzy analytic hierarchy process be used instead of analytic hierarchy process? Decision Support Systems, 125, 113114. https://doi.org/10.1016/j.dss.2019.113114
45. Osman, A. M. S. (2019). A novel big data analytics framework for smart cities. Future Generation Computer Systems, 91, 620–633. https://doi.org/10.1016/j.future.2018.06.046
46. Nechyporuk, O., Sova, O., Shyshatskyi, A., Kravchenko, S., Nalapko, O., Shknai, O. et al. (2023). Development of a method of complex analysis and multidimensional forecasting of the state of intelligence objects. Eastern-European Journal of Enterprise Technologies, 2 (4 (122)), 31–41. https://doi.org/10.15587/1729-4061.2023.276168
47. Merrikh-Bayat, F. (2015). The runner-root algorithm: A metaheuristic for solving unimodal and multimodal optimization problems inspired by runners and roots of plants in nature. Applied Soft Computing, 33, 292–303. https://doi.org/10.1016/j.asoc.2015.04.048
48. Poliarush, O., Krepych, S., Spivak, I. (2023). hybrid approach for data filtering and machine learning inside content management system. Advanced Information Systems, 7 (4), 70–74. https://doi.org/10.20998/2522-9052.2023.4.09
49. Balochian, S., Baloochian, H. (2019). Social mimic optimization algorithm and engineering applications. Expert Systems with Applications, 134, 178–191. https://doi.org/10.1016/j.eswa.2019.05.035
50. Lenord Melvix, J. S. M. (2014). Greedy Politics Optimization: Metaheuristic inspired by political strategies adopted during state assembly elections. 2014 IEEE International Advance Computing Conference (IACC), 1157–1162. https://doi.org/10.1109/iadcc.2014.6779490
51. Moosavian, N., Roodsari, B. K. (2014). Soccer League Competition Algorithm, a New Method for Solving Systems of Nonlinear Equations. International Journal of Intelligence Science, 4 (1), 7–16. https://doi.org/10.4236/ijis.2014.41002
52. Hayyolalam, V., Pourhaji Kazem, A. A. (2020). Black Widow Optimization Algorithm: A novel meta-heuristic approach for solving engineering optimization problems. Engineering Applications of Artificial Intelligence, 87, 103249. https://doi.org/10.1016/j.engappai.2019.103249
53. Abualigah, L., Yousri, D., Abd Elaziz, M., Ewees, A. A., Al-qaness, M. A. A., Gandomi, A. H. (2021). Aquila Optimizer: A novel meta-heuristic optimization algorithm. Computers & Industrial Engineering, 157, 107250. https://doi.org/10.1016/j.cie.2021.107250
54. Hodlevskyi, M., Burlakov, G. (2023). Information technology of quality improvement planning of process subsets of the spice model. Advanced Information Systems, 7 (4), 52–59. https://doi.org/10.20998/2522-9052.2023.4.06
55. Askari, Q., Younas, I., Saeed, M. (2020). Political Optimizer: A novel socio-inspired meta-heuristic for global optimization. Knowledge-Based Systems, 195, 105709. https://doi.org/10.1016/j.knosys.2020.105709
56. Mohamed, A. W., Hadi, A. A., Mohamed, A. K. (2019). Gaining-sharing knowledge based algorithm for solving optimization problems: a novel nature-inspired algorithm. International Journal of Machine Learning and Cybernetics, 11 (7), 1501–1529. https://doi.org/10.1007/s13042-019-01053-x
57. Gödri, I., Kardos, C., Pfeiffer, A., Váncza, J. (2019). Data analytics-based decision support workflow for high-mix low-volume production systems. CIRP Annals, 68 (1), 471–474. https://doi.org/10.1016/j.cirp.2019.04.001

58. Harding, J. L. (2013). Data quality in the integration and analysis of data from multiple sources: some research challenges. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XL-2/W1, 59–63. https://doi.org/10.5194/isprsarchives-xl-2-w1-59-2013
59. Orouskhani, M., Orouskhani, Y., Mansouri, M., Teshnehlab, M. (2013). A Novel Cat Swarm Optimization Algorithm for Unconstrained Optimization Problems. International Journal of Information Technology and Computer Science, 5 (11), 32–41. https://doi.org/10.5815/ijitcs.2013.11.04
60. Karaboga, D., Basturk, B. (2007). A powerful and efficient algorithm for numerical function optimization: artificial bee colony (ABC) algorithm. Journal of Global Optimization, 39 (3), 459–471. https://doi.org/10.1007/s10898-007-9149-x
61. Voznytsia, A., Sharonova, N., Babenko, V., Ostapchuk, V., Neronov, S., Feoktystov, S. et. al (2025). Development of methods for intelligent assessment of parameters in decision support systems. Eastern-European Journal of Enterprise Technologies, 4 (4 (136)), 73–82. https://doi.org/10.15587/1729-4061.2025.337528
62. Sova, O., Radzivilov, H., Shyshatskyi, A., Shvets, P., Tkachenko, V., Nevhad, S. et. al (2022). Development of a method to improve the reliability of assessing the condition of the monitoring object in special-purpose information systems. Eastern-European Journal of Enterprise Technologies, 2 (3 (116)), 6–14. https://doi.org/10.15587/1729-4061.2022.254122