Functional hybrid decision-making system for difficult formalized productive and economic problems

S Korjagin\textsuperscript{1}, A Babkin\textsuperscript{2} and P Klachek\textsuperscript{3}

\textsuperscript{1,3} Engineering and Technical Institute Baltic Federal University of Immanuel Kant
Kaliningrad, Russia
SKoryagin@kantiana.ru; pklachek@mail.ru

\textsuperscript{2} Peter the Great St. Petersburg Polytechnic University, Saint-Petersburg Russia
al-vas@mail.ru

Abstract. A steady trend of the development of modern processes in human activities (social, economic, bioengineering, medical, technological) is a complication of the tasks, which are to be tackled on different levels of administration. This is connected with growth of amount of inconsistent information, necessary for well-grounded decision making, as well as with time saving for decision making. To improve the quality of decisions taken in these conditions, intellectual decision-making systems and artificial intelligence methods, on which the procedures for the direct preparation of solutions to various tasks are shifted, are increasingly being used. The article deals with the fundamentals of the structural organization of functional hybrid intelligent decision-making systems designed to solve difficult formalizable production and economic tasks, and suggests a new cognitive approach in the development of integration and effective management of formalized and weakly formalized knowledge in decision-making systems.

1. Introduction
A steady trend of the development of modern processes in human activities (social, economic, bioengineering, medical, technological) is a complication of the tasks, which are to be tackled on different levels of administration. This is connected with growth of amount of inconsistent information, necessary for well-grounded decision making, as well as with time saving for decision making. To improve the quality of decisions taken in these conditions, intellectual decision-making systems and artificial intelligence methods, on which the procedures for the direct preparation of solutions to various tasks are shifted, are increasingly being used. At the same time, as the accumulated experience of using intellectual decision-making systems in the production and economic sphere shows [1,2,3], the quality of the solutions they develop directly depends on how much mathematical methods prevail over the heuristic methods used to prepare solutions. From this point of view, every possible set of production and economic tasks can be roughly divided into three classes [1,4-7]: formalizable, difficult formalizable and non-formalized. At the same time, the overwhelming majority of problems arising in engineering, economics, politics, medicine, biology, business, and other fields belong to the second class, which is difficult formalizable [1,4-8]. The main features of this class of problems are [1,8-15]: a large number of factors affecting the behavior of the system, regarding which the decision is made; the heterogeneity of the data in which it operates; significant a priori uncertainty that does not allow us to determine the basic laws of its behavior (acceptable for it in the mathematical and statistical sense) using traditional methods of data analysis, but it is known that such patterns exist, and the basic composition of informative variables is roughly determined, as well as other factors detailed in [1, 8-15]. Thus, there is a need to integrate mathematical methods with heuristic methods and information technologies, which leads to the idea
of hybrid systems. An important subclass of hybrid systems is hybrid intelligent systems (GIS) [1, 4-7, 10-13, 15]. A hybrid intelligent system is commonly understood as a system in which more than one method of simulating human intellectual activity is used to solve the problem [1, 4-7, 10-11]. Thus, GIS is a complex of: analytical models, expert systems, artificial neural networks, fuzzy systems, genetic algorithms, simulation statistical models [1, 4-7, 10-13].

Despite a considerable success in the field of application of hybrid intelligent systems, especially in weakly structured subject areas [1,4-7], and effective applied systems for solving difficult formalizable production and economic problems have not been created to date. The main problem is that when solving problems that are difficult to formalize, integration of two or more functional components (modeling methods) is required [1], wherefore serious problems arise (detailed in [1]) in the field of integration and control of formalizable and weakly formalized knowledge, as well as when creating application software, which requires the use of a non-standard approach [16-18].

This work is devoted to increasing the efficiency of intelligent information processing and management systems, in particular computer decision support systems, in solving difficult formalizable production and economic tasks, based on functional hybrid intelligent decision-making systems (FHDMS), which, as practice has shown [1, 4, 7], are able to successfully cope with the complexity of difficult formalizable problems and develop qualitative solutions in various subject areas [1, 4-7].

2. Materials and Methods (Model)
The main methodological elements of FHDMS are the notion of a nonhomogeneous problem-system, its homogeneous subtasks and an integrated method-system [1]. In figure 1. A non-homogeneous problem-system is presented.

![Figure 1](image)

Figure 1. Methodological basis FHDMS.

The initial, nonhomogeneous problem-system with subtasks is connected with the relations of inclusion "whole-part", which are indicated in figure 1.A. dotted line. These relations define the composition of the problem-system, which can vary within certain limits, without affecting the quality of the system. The other part of the links, already between subtasks, limits the degree of freedom between elements and does not allow one to solve some problems without others, setting the order on the cause-and-effect and time scales. A particular significance in the definition of a problem as a system has the characteristic of emergence when the properties of the system cannot be obtained by simply summing the properties of its individual elements. In other words, the problem-system must have properties that none of its component parts have in their individuality. For a nonhomogeneous problem-system, with the variability of its composition and structure, the method-system of its solution is constructed over some interrelated set of niches (autonomous operators [1, 4, 7]). Thus, FHDMS is a system that has the architecture of information exchange, input, output and functions in a nonhomogeneous state space. We call such a functioning a hybrid imitation process [1]. In figure 1.B. an example of the organization of a hybrid imitation process in FHDMS is presented, in a polymorphic regime [1]. In this mode, when modeling the problem-system, autonomous operators function simultaneously, i.e. parallel, and the user has the ability to observe changes in the state vector of FHDMS. This results in an effect well known in electronics when the same circuit is modeled as an analog device, which makes it possible to observe thermal, wave effects, and a discrete-logical device,
which allows one to study diagrams of pulse shapes and amplitudes [23-26]. The relationship of element integration here arises as internal non-verbal images in the user's memory, which, comparing the dynamics of the device from different points of view, can "see" what cannot be detected in a single-model simulation.

Figure 2. The universal architectural and technological scheme of modeling based on hybrid computational intelligence.

In [1], the concept of complex, weakly formalized, multicomponent economic systems, operating under conditions of uncertainty and difficult formalizable problems was introduced [1]. The set-theoretic representation of this class of complex systems is also realized in sources [4,7]. At present, the problem of developing methods and tools for hybrid modeling of weakly formalized, multicomponent economic systems [1] and their practical implementation for the construction of hybrid intelligent models of various types of component structures of complex economic systems remains extremely urgent. The hybrid intelligent model of complex, weakly formalized, multicomponent economic system is a model that has a universal character, functioning in real-time conditions and is based on the principles of intellectual activity of a human [1].

In figure 2. The universal architectural-technological scheme of the hybrid intelligent model of complex, weakly formalized, multicomponent economic system is given. The general formal scheme of the hybrid intelligent model of complex, weakly formalized, multicomponent economic system is given in [1]:

\[ m_{IBM}^{a} T_{a} = < M^{u}, M^{h}, T_{x}, I^{nc} > \]

(1)

Where:

- \( M^{u} = \{ m_{1}^{u}, \ldots, m_{N_{u}}^{u} \} \) - a set of basic model structures [1];
- \( M^{h} = \{ m_{1}^{h}, \ldots, m_{N_{h}}^{h} \} \) - a set of complementary model structures, \( \forall m_{i}^{u} \exists M^{h} = \{ m_{1}^{h}, \ldots, m_{N_{h}}^{h} \} \), where \( i = 1, \ldots, N_{u} \), \( \forall i (N_{h} = \text{var}) \), \( m_{i}^{h} \in M^{u} \) [2,6];
- \( T_{x} \) - a table of hybrid strategies [1];
- \( I^{su} \) - the interpreter representing the four processes [2,6]:

\[ I^{BH} = \{ I^{1}, I^{2}, I^{3}, I^{4} \} \], where:

- \( I^{1} \) — the process of studying the hybrid correlation of basic and complementary model structures;
- \( I^{2} \) - the selection process in accordance with \( T_{x} \) the method of hybrid computational intelligence [1];
- \( I^{3} \) — the development process in accordance with
the hybrid computational intelligence method of the hybrid computational model; $I^4$ — process of selecting or developing a hybrid computational scheme.

In figure 3. The FHDMS model for complex, weakly formalized, multicomponent economic system is proposed, which assumes the realization on the basis of (1) the model of the collective decision-making process [1] peculiar to the large class of complex, weakly formalized, multicomponent economic system.

![Figure 3. Model FHDMS in complex, weakly formalized, multicomponent economic system.](image)

An essential advantage of the proposed approach was the possibility of a rapid transition to the automated development process of FHDMS based on multi-agent systems (MAS) [1,4,7,9]. In figure 4. the FHDMS architecture based on MAS is presented, which was considered in detail in [1].

![Figure 4. Architecture of FHDMS based on multi-agent systems, 1 - Logical agent, 2 - Fuzzy agent, 3 - Agent converter, 4 - Linguistic agent, 5 - System model, 6 - Search agent solutions 4, 7 - Search agent solutions 3, 8 - Search agent solutions 2, 9 - Search agent solutions 1, 10 - Interface agent, 11 - Agent decision-making, 12 - Agent middleman, 13 - Analysis agent, 14 - Stochastic agent.](image)

3. Results and Discussion
Approbation of the proposed solutions was carried out using the example of creating an intelligent control system for the technological process of drilling oil and gas [1]. One of the most promising technologies for thermal recovery of heavy oils and natural bitumen in a system of horizontal wells is the process of Steam Assisted Gravity Drainage [1]. An important significance for the implementation of this technology is the choice of optimal parameters of the coolant injected into the formation. The heat content of the steam depends on its dryness. The dependence of the radius of the zone of heating of the inter-well space is established as a function of the injection time of the steam for different values of dryness [19-21]. Thus, the fulfillment of the requirements arising from the established regularity of heat exchange between the reservoir and surrounding rocks is of great practical importance for increasing the technological efficiency of developing deposits with hard-to-recover oil reserves. Controlling the performance, as well as the quality of the steam generated by them, significantly increases the possibility of optimizing operating modes.

World experience testifies to the possibility of effective development of deposits of heavy oils and bitumen by mining, open-pit method and surface wells, in such countries as Russia, Canada, Venezuela, China, etc. [1]. In Russia, the experience of developing deposits of heavy oils and natural bitumen has been accumulated in Tatarstan, Udmurtia, the Republic of Komi and other oil-producing regions. Feasibility and economic efficiency of the development of deposits of heavy oils and natural bitumen is determined by the geological and physical conditions of their occurrence, physical and chemical characteristics, reservoir data, as well as the results of their processing.

One of the most promising technologies for thermal recovery of heavy oils and natural bitumen in a system of horizontal wells is the process of Steam Assisted Gravity Drainage (SAGD) [1], currently used in Canada, Venezuela, the USA. In addition to the classical method of SAGD technology, there are several of its various modifications, allowing for the possibility of taking into account the features of the geological and physical properties of reservoirs, and the regulation of the development of oil fields currently being implemented in Russia (Tatarstan, Komi Republic).

The essence of the technology lies in the formation of a "steam chamber" by injecting steam into the upper horizontal well end and taking out the oily liquid through the lower horizontal end of the production well. The zone of oil displacement is constantly increasing and the flow of oil spreads to the roof of the formation, and then it expands horizontally, merging with the heated zones located around the neighboring wells [22-24, 30]. Thus, at the boundary of the steam chamber, the steam condenses when the heat of the inactive oil is transferred, and the heated oil is displaced by its own weight and the condensed steam from the top to the bottom, that is, the performance of the plant is influenced by two factors - gravity drainage and pressure displacement.

To optimally form a steam chamber, it is necessary to preheat the interwell space for several months by circulating the steam in both wells. As a result, conductive heating of the bottomhole formation zone is carried out, the viscosity of the oil is reduced and the hydrodynamic connection between the wells is improved.

In accordance with (1), based on the method of knowledge genesis [1], a hybrid computational model was developed for calculating the required volume of steam, which when performing pumping at the preheating stage, takes into account the geological characteristics of the experimental section [1]:

\[ Q = \left( \frac{2\pi (T_3 - T_n) z \lambda F}{\sqrt{2 \pi \rho_c \kappa_c}} \right) \left( \frac{\rho n}{\rho_c} \right) \left( z^3 \right) \left( \frac{X_3 - X^*}{0.29} \right) \]

Where: \( Q \) - the steam flow rate at pumping, \( \pi \) - the mathematical constant, \( T_3 \) - the temperature of the steam at the bottom of the well, \( T_n \) - the initial temperature of the formation, \( z \) - the length of the heated section, \( \lambda F \) - the thermal conductivity of the soil, \( X_3 \) - the dryness of the steam at the bottom of the well, \( X^* \) - the dryness of the steam at the collar, \( \rho_c \) - the density of the formation frame, \( C_r \) - the latent heat of vaporization, \( C_{ck} \) - specific heat of the formation frame, \( \rho_n \) - the
vapor density, $t^*$ - the time measured from the beginning of the circulation of the working agent inside the pipeline, the, \( a_{of}^3 = \alpha_{of} \cdot C_r \cdot C_{ck} \cdot \rho_n \), $Y(I, \text{ mathematical degree), } KB, F^H, F^{TS}, F^Y, f \), \( f = \) the classical fuzzy system [2].

An important indicator, both at the preheating stage and during the formation of the steam chamber, is the choice of the optimal parameters of the coolant pumped into the reservoir. Water vapor, which has a greater enthalpy (heat content) compared to hot water, provides a higher oil recovery. The change in the enthalpy of saturated water vapor depends both on temperature and pressure, and on its dryness. The higher the dryness at the same pressure and temperature, the greater the heat content, i.e., the more qualitative the steam, the faster and the more heat-efficient it is possible to realize warming of the inter-well space and the further process of realizing the Steam-Assisted Gravity Drainage.

In accordance with (1), based on the method of knowledge genesis [1], a hybrid computational model was developed for calculating the radius of heating of the inter-well space, depending on the pumping period for different values of dryness [1]:

\[
 r = \left( \frac{QC_r X_3 \rho_n t}{\pi (C_r X_3 \rho_n + C_{ck} \rho_{ck} (T_3 - T_1))} \right)^{a_{of}^3} \tag{3}
\]

Where: $r$ - radius of formation heating, $t$ - time of steam pumping, $m$ - formation porosity, $h$ - distance between wells, $\beta$ - coefficient of anisotropy of the reservoir, \( a_{nr}^3 = m, h, \beta \), $Y(I, \text{ mathematical degree), } KB, F^H, F^{TS}, F^Y, f \), \( f = \) classical fuzzy system [1].

Currently, in collaboration with leading specialists of the Harvard School of Engineering and Applied Sciences, the development of innovative FHDMS is being carried out with the technological process of drilling oil and gas [1] (figures 4, 5).

![Figure 5. Architecture of innovative FHDMS in the technological process of drilling oil and gas [1].](image-url)
Figure 6. An example of modelling, based on (2.3), optimal volumes and modes of injection of steam into the well [1].

Preliminary tests of the FHDMS prototype used in the oil and gas drilling process at the Alpine oil field in the USA, Alaska, showed a perspective and massive opportunities of the suggested approach, (see section 2: Methods and Materials), and the developed prototype FHDMS [1].

4. Conclusion
Opening the way to a new scientific discipline - knowledge engineering, a group of scientists led by J. Weizenbaum (USA) put forward the hypothesis that a person is good at solving problems through his professional knowledge. The problems are enough to be transferred to a computer, so that it can solve practical problems. Thus, expert systems appeared. Another hypothesis can be put forward - a person solves complex problems well thanks to collective efforts in decision support systems, and for a computer to solve such problems, it is necessary to learn how to simulate in its memory the work of the group of people over a practical problem. In this way, hybrid intelligent systems were created, in particular functional hybrid intelligent systems. They are the focus of this article.

For the first time in the field of methodological support for the creation of functional hybrid intelligent decision-making systems, which as the practice has shown in [1,4-7,10-13], are capable to successfully cope with the complexity of difficult formalizable production and economic tasks and develop qualitative solutions in various subject areas [1 , 4-7,10-13]. This promising approach is conceived by the authors on the "border" of hybrid systems, synergetic artificial intelligence, neuro and psychophysiology, philosophy, cybernetics and centers around self-organization of groups of people that develop and make decisions in complex situations [15].

Currently, FHDMS has been successfully applied in the modeling of complex systems and the solution of complexes of applied production and economic problems, in agriculture, engineering, aircraft building, water ecosystems, etc. [1,4,7,9]. Work in this area is actively continuing.

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