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FORMATION AND DEVELOPMENT OF SELF-ORGANIZING INTELLIGENT TECHNOLOGIES OF INDUCTIVE MODELING

Introduction. *Effective solution of control and decision-making tasks in complex systems should use the results of mathematical modeling. To construct adequate predictive models, many modern methods and tools are available which may be generally based on two principal approaches: theory-driven (deductive) and data-driven (inductive) ones. The data-driven methods are basic for solving typical tacks of data mining; they implement an inductive process of transition from particular data to models generalizing the data. Among all such methods, very notable are those being developed within the area of GMDH-based inductive modeling founded several decades ago by academician O.H. Ivakhnenko.*

The purpose of this paper *is analysing the background of the GMDH invention by Ivakhnenko and the evolution of model self-organization ideas, methods and tools during the half-century historical period of successful development of the inductive modeling methodology.*

Results. *Professor Ivakhnenko acquired broad knowledge in the areas of automatic control, engineering cybernetics and emerging neuroscience initiated by the idea of perceptron. These were those prerequisites which helped Ivakhnenko to synthesize his original self-organizing approach to solving tasks of constructing models of objects and processes on the basis of experimental data. The paper tracks evolution of scientific ideas and views of Ivakhnenko and main achievements in development of GMDH during the period 1968-1997. Contributions of researchers from different countries to the GMDH modification and application are characterized. Results of further developments of inductive modeling methods and tools in the ITIM department are presented and the most promising prospects of investigations in this field are indicated.*

Conclusions. *Main prerequisites facilitating the creation of the GMDH by O.H. Ivakhnenko were analysed, basic fundamental, technological and applied achievements of the half-century development of inductive modeling both in Ukraine and abroad were characterized, as well as the most prospective ways of further research were formulated.*

Keywords**:** *mathematical modeling, data-driven modeling, model self-organization, GMDH, inductive modeling, noise-immune modeling, information technology, case study.*

INTRODUCTION

Effective solution of control and decision-making tasks in complex systems should use the results of mathematical modeling. To construct adequate predictive models, many modern methods and tools may be used which generally can be based on two principal approaches: theory-driven or deductive and data-driven or inductive ones. The data-driven methods are basic for solving tacks of data mining; they implement an inductive process of transition from particular data to models generalizing the data.

Among all data-driven methods, very notable are those being developed in the area of inductive modeling based on the Group Method of Data Handling (GMDH) [1-4]. For the scientific school of inductive modeling, founded several decades ago by Professor Oleksiy Hryhorovych Ivakhnenko, the year 2018 is reach for a few remarkable jubilees:

– **105** years of Ivakhnenko's birthday (1913),

– **80** years of his first published article (1938),

– **75** years ago he defended the thesis for the title Candidate of Engineering Science (1943),

– **50** years of his the very first article on the worldwide-known GMDH (1968),

– **15** years ago he was elected Academician of NAS of Ukraine (2003),

– **20** years ago, the Department for Information Technologies of Inductive Modeling (ITIM) was established at the IRTC ITS of the NAS and MES of Ukraine.

Taking into account the central item in this list, namely the ***half-century jubilee*** of the GMDH origination, which is the main methodological base of Inductive Modeling, it is reasonable to look through the historical period of formation and development of this scientific direction. Accordingly, this article is intended to analyze the following aspects:

– attempt to understand which sum of acquired knowledge helps Ivakhnenko to approach in 1968 to the creation of GMDH as a self-organizing method of modeling from experimental data;

– examination of main achievements in development of this induction-based method during long period from 1968 to 1997;

– appraisal the contribution of researchers from different countries into evolution of the method;

– explanation of main developments of the ITIM Department in further progress of the theory, tools and applications of the GMDH-based inductive modeling during last 20 years, presenting the modern stage of functioning the inductive modeling school;

– foresight of forthcoming prospects in development of the subject-area of inductive modeling.

These aspects are comprehensively reflected below in the article and they differ its matter from the known surveys [1–4] dealing with analysis of various periods of GMDH and inductive modeling development.

EVOLUTION OF SCIENTIFIC IDEAS AND VIEWS OF O.H. IVAKHNENKO PRIOR TO THE "GMDH ERA"

Scientific and administrative career. After defending in 1954 the thesis for the degree Doctor of Engineering Sciences in Kiev Polytechnic Institute and receiving in 1956 the academic title Professor, O.H. Ivakhnenko has became Head of laboratory "Automatic control of manufacturing processes" at the Institute of Electrical Engineering of the Academy of Sciences of the Ukrainian SSR (1956–1962) reorganized later into the Department of Engineering Cybernetics at the same institute (1962–1963). In 1961, Ivakhnenko was elected the Corresponding member of the AS of UkrSSR.

In 1963, he with all members of his team has moved to the Institute of Cybernetics of the Academy of Sciences being invited by the Academician V.M. Glushkov, and worked there long time as Head of the Department of Combined Control Systems (1963–1989). After retirement of Ivakhnenko in 1989 from the leading position, the Department was reorganized into the Laboratory of modeling after experimental data headed by his disciple PhD G.I. Krotov. In 1995, all the laboratories in the NASU were closed up, and this team worked in another department as autonomous scientific group.

Based on this group, the Department for Information Technologies of Inductive Modeling (ITIM) was established in 1998 at the IRTC ITS of the NAS and MES of Ukraine headed by his disciple and follower DSc. V.S. Stepashko, and Professor Ivakhnenko worked there as a Directorate Adviser. In 2003, in the year of his 90th anniversary, O.H. Ivakhnenko was elected Academician of the NAS of Ukraine for outstanding achievements in the development of computer science and artificial intelligence in Ukraine. He fruitfully worked at the department up to 2007 when he passed away.

Main stages of the scientific activity. Oleksiy Hryhorovych was an outstanding scientist in the fields of automatic control, cybernetics and informatics whose research results in various areas had received worldwide recognition. The fact is that Ivakhnenko always proves the validity of his views both theoretically and also by the actual results, namely devices, operating systems and specific applied tasks solved and it was impossible to not acknowledge such evidences of rightness of his viewpoint.

Electroautomatics. Prior to the period of the 1960s, the main achievements of O.H. Ivakhnenko concern areas of electroautomatics and the invariance theory: he has developed a new principle of automatic speed control of alternating current motors using magnetic amplifiers, asynchronous motors by the difference of voltage and current etc. [5].

Combined systems of automatic control. O.H. Ivakhnenko developed the theoretical basis of invariant automatic control systems that operate by the principle of compensation of the measured disturbances. He is the author of a new for automatic control theory *principle of combined control* based on the negative feedback with respect to the controlled variable and the positive (compounding) feedforward by controlled disturbances. This principle allowed for the first time to create real invariant systems of automatic control for asynchronous motors speed [6].

Control systems with self-tuning, self-learning, pattern recognition and forecasting. O.H. Ivakhnenko proposed to use a variety of devices and methods of self-tuning in combined control systems. He published in 1959 the very first in the former USSR monograph on engineering cybernetics [7] where the *cybernetic control systems* are considered which differ from the *conventional automation systems* by the presence of automatic self-modification, self-adaptation and self-tuning of characteristics when external and internal influences change. This book brought him international recognition and was reprinted in English and some other European and Asian languages. He was invited to give lectures in Europe and the USA; the "father of cybernetics" Norbert Wiener visited Kyiv in 1962 at his invitation.

In 1960th, working at the Institute of Cybernetics, O.H. Ivakhnenko started to use principles of self-learning, pattern recognition and forecasting when designing control devices. Under his leadership, the recognition system "Alpha" was constructed which demonstrated the self-learning process at first time in the world. His monograph "Cybernetic forecasting devices" [8] was re-released in English, Polish, German and Chinese.

The sum of this broad and diverse knowledge acquired by him personally and supplemented by deep understanding the possibilities of the perceptron introduced by Frank Rosenblatt [9] were those prerequisites which help Ivakhnenko to synthesize his original self-organizing approach to solving tasks of constructing models of objects and processes on the basis of experimental data. This development gave start to new, long and very fruitful period of his scientific creativity.

MAIN ACHIEVEMENTS IN DEVELOPMENT OF GMDH DURING THE PERIOD 1968-1997

Heuristic self-organization of models. The very first article [10] on the group method of data handling (GMDH) published in 1968 in Ukrainian journal “Avtomatyka”, reprinted in the USA [11] and followed by publications [12, 13] abroad, signified the beginning of the most fruitful stage in the creative scientific work of O.H. Ivakhnenko. It is worth to no note that in Ukrainian language this method is called «Метод групового урахування аргументів» (МГУА), and direct translation would give an accordant and correct English equivalent “Method of Group Using of Arguments” (MGUA). But when translating the article [10] in the USA journal “Soviet automatic control”, the reprinted version of “Avtomatyka”, a specific name “Group Method of Data Handling” was introduced and the abbreviation GMDH is now world-wide known as the method, explicitly associated with its creator.

With these publications, a new scientific area has emerged that was named at first by Ivakhnenko as “heuristic self-organization of models” [14]. This name had several modifications later: “self-organization of models from experimental data”, further “inductive self-organization of models” [15], then “inductive learning algorithms” [16], and finally, from the 1998, simply “inductive modeling” (see below). Active development of this area was determined by brilliant scientific intuition of the author and his original scientific hypotheses. Since 1968, this new scientific field is steadily and successfully developing being recognized, adopted and used by researchers around the world.

Generally speaking, the task of inductive modeling consists in an automated data-based construction of a mathematical model, approaching an unknown regularity of functioning the simulated object or process. GMDH is an original self-organizing inductive method of modeling from experimental data, or structure and parametric identification of forecasting models, first of all of polynomial type, under uncertainty conditions. It is notable for application of the following main principles for solving optimization tasks of parameter estimation and structure determination:

– automatic generation of groups of model variants with various complexity;

– inductive way of model construction with evolution from simple to more complex model structures;

– evaluation of the model quality by external criteria based on the division of a dataset into at least two parts: the first one is used for parameter estimation and the second for criteria calculation;

– non-final decisions during the evolutionary modeling process: at any stage or iteration, not unique the best model is selected but a subset of best ones;

– successive selection of models of optimum complexity with respect to minimal values of the external criteria.

GMDH is intended for automatic building a mathematical model that reproduces the unknown regularity of operation of the investigated object information on which is implicitly contained in the available data sample (table). After the modern terminology this is an original means of data mining.

The method effectiveness was repeatedly confirmed by the solution of various of practical problems of modeling complex objects and processes in areas of ecology, economy, engineering, technology, hydrometeorology, etc. [14–16]. In parallel, researches were conducted on the development and application of self-organization algorithms in pattern recognition tasks [17].

General characteristic of the model self-organizing task. As a rule, GMDH deals with building models in the class of functions linear in parameters. Let us be given a data sample $W=[X\,y]$ of n observations over m input variables $X=[x_{ij}], i=\overline{1,n}, j=\overline{1,m}$, and one output $y=(y_1,...,y_n)^T$. Suppose that we may build a set Φ of various models of the form

$$\hat{y}_f = f(X,\hat{\theta}_f),\ f\in\Phi, \tag{1}$$

using the data set W, where the parameter estimation $\hat{\theta}_f$ for each $f\in\Phi$ is the solution of a task of continuous minimization of an error criterion $QR(\cdot)$:

$$\hat{\theta}_f = arg \min_{\theta_f\in R^{s_f}} QR(X,y,\theta_f) \tag{2}$$

where s_f is the complexity of the model (1), or the number of unknown parameters of the model.

Consequently, the problem of the best model constructing from the given experimental data consists then generally in finding the minimum of a given criterion $CR(\cdot)$ on the discrete set Φ of models of different structures:

$$f^* = arg \min_{f\in\Phi} CR(X,y,f) \tag{3}$$

The two criteria $QR(\cdot)$ and $CR(\cdot)$ are called in the GMDH theory as *internal* and *external* ones respectively. They should be different, $QR(\cdot)\neq CR(\cdot)$, because in another case the task (3) has trivial solution: f^* corresponds to the model of maximum complexity $s_{\max}$. It is evident especially in the case of linear functions, when the task (2) is solved using the Least squares method (LSM) for estimation of parameters, and the LSM is a monotonically decreasing function of the number of parameters.

To ensure the condition $QR(\cdot) \neq CR(\cdot)$, in GMDH the data division into at least two parts is used:

$$W = \begin{bmatrix} A \\ B \end{bmatrix} = \begin{bmatrix} X_A y_A \\ X_B y_B \end{bmatrix}, \tag{4}$$

then the internal criterion has the form $QR(X_A, y_A, \theta_f)$ when the external one $CR(X_B, y_B, \hat{\theta}_{Af})$: they are evidently different, and the task (3) is not trivial.

In general, the process of solving the problems of structural and parametric identification (1–3) includes the following main stages:

1) setting a data sample and a priori information;

2) the choice or assignment of a class of basic functions and the respective transformation of data;

3) generation of different model structures in this class;

4) estimation of parameters of generated structures by an internal criterion $QR(\theta_f)$ and formation of the set Φ ;

5) minimization of a given external criterion *CR*(*f*) and selection of the optimal model *f**;

6) checking the adequacy of the model obtained;

7) completion of the process and/or the use of the model.

This means that each modeling method including GMDH can be described with the help of four main components: a) class of basic functions, b) structure generator, c) method for estimating parameters, and d) criterion for model selection. As far as GMDH is dealing mainly with model classes linear in parameters, the use of LSM-estimator is the best option. Hence, there is a need to analyze the formulas for external criteria and the types of model structure generators in GMDH algorithms.

One can use two main external criteria for model selection based on the sample division (4). The first one is called the *regularity* criterion which for linear models equals to the model error on the data subset *B* when parameters were estimated on the subset *A*:

$$AR_B(X_B, y_B, \hat{\theta}_A) = \left\| y_B - X_B \hat{\theta}_A \right\|^2 . \tag{5}$$

And another one is the unbiasedness criterion, evaluating the difference between outputs of two models of the same structure with parameters estimated on the parts *A* and *B*:

$$CB = \left\| X_W \hat{\theta}_A - X_W \hat{\theta}_B \right\|^2 . \tag{6}$$

Main types of GMDH algorithms. Any of the GMDH algorithms realizes some kind of a self-organizing process of sequential generation of more and more complex models in an inductive manner: any next such complication takes into account results of the previous stage of model building and may by based on both adding some new members to the previous model structures and combining them using some superposition function called "*partial description*". This self-organizing process of model complication stops when the minimum value of a given external criterion is reached.

Consequently, all the GMDH algorithms are generally divided into two big separate groups: the *sorting-out* [18] and *iterational* [19] ones that differ from each other by the methods of model structures generation and the procedures of search of minimum of a selection criterion based on a data sample division into two or more parts.

Sorting-out GMDH algorithms. The first type algorithms generate models of various structures in a given set of basic functions like members of polynomial of a preset power or lag terms of an autoregression model. They all are based on the *exhaustive* or *directed* search of the model of optimal complexity.

The most known *combinatorial algorithm* is called COMBI [20] generating all possible model structures:

$$y_v = X_v \hat{\theta}_v,\ v = 1,\ldots,2^m, \tag{7}$$

where the decimal number v is assigned a binary structure vector d_v, in which units indicate the presence of arguments, when zeros their absence. Here, the number of models being compared and forming the set Φ equals to 2^m and the exhaustive search is effective only up to approximately $m = 30$ because of exponential growth of calculations.

The purpose of the *directed search* methods is to find the global minimum of the selection criterion, i.e. the result of an exhaustive search, by significantly smaller calculations. They are runnable with hundreds of arguments, e.g. the multistage algorithm MULTI [21] which uses a special step-by-step evolving procedure of the type

$$\hat{y}_s^l = (X_{s-1}^i \mid x_s^j)\hat{\theta}_s,\ s = \overline{1,m},\ i,l = \overline{1,F_{s-1}}, \tag{8}$$

where s is the stage number (and the structure complexity); F_s — number of the best structures (freedom of choice) at the stage s; j is the index of an argument vector being added to the matrix X_{s-1}^i. In this case, a subset $\Phi_s \subseteq \Phi$ is analyzed, with a high probability containing the result of a complete search. This algorithm has the polynomial complexity of order m^3.

Iterative GMDH algorithms. The second type algorithms, being classical, are based on the nature inspired idea of biological selection with pairwise account of features. According to the principle of operation, the iterative GMDH algorithms are similar to methods of optimization using successive approaching, but the principle of indecisive solutions (freedom of choice F) is here substantially used. Depending on the method of successive approaching, they may be divided into two main groups: *multilayered* and *relaxational* ones.

The conventional is the so-called multilayered algorithm [11–13] which starting from late 1990$^{\text{th}}$ is commonly called in the current literature as *multilayered iterative algorithm* MIA GMDH. It is the algorithm that was initially created in 1968 by Ivakhnenko and named *multilayered algorithm* MGUA/GMDH.

It has the perceptron-like architecture and constructs hierarchical network-type models through an iterational procedure of step-by-step complicating model structures: a partial model of a current layer/iteration is a polynomial of any pair of models of the previous layer.

The MIA GMDH was constructed by the analogy with the biological selection of living organisms: the complication of models from r-th layer to (r+1)-th occurs due to the "crossing" of all possible pairs from F best models of the previous layer. Typically, the MIA partial description is of the form:

$$y_l^{r+1} = f_l(y_i^r, y_j^r),\ r = 0,1,...;\ i,j = \overline{1,F};\ l = \overline{1,C_F^2}\ , \tag{9}$$

where second order polynomial is usually used, but bilinear or even linear one may be applied as well. The iterative process of model complication stops after the criterion CR starts to increase.

During 1970th, there were developed a lot of various modifications of the classical algorithm; the most original among them are: multilayered algorithm with orthogonalization of arguments [22], linear CML [23] and nonlinear GN [24] algorithms. They were generally dissimilar but had common features separating them from the classical type algorithm: they have the only two-member partial descriptions and the use of initial arguments on each layer of selection. A GMDH procedure of such type (based on adding initial arguments to the intermediate ones) is called now *relaxational iterative algorithm* RIA GMDH.

In GMDH algorithms of the RIA type, models are complicated on each layer by "crossing" the best models of the previous layer with the initial arguments, and a partial description of the following modification:

$$y_l^{r+1} = f_l(y_i^r, x_k),\ i = \overline{1,F};\ k = \overline{1,m}\ , \tag{10}$$

which may be used with quadratic, bilinear or linear polynomial.

Such kind of descriptions was introduced in [22–24] in the form $y_l^{r+1} = y_i^r + \varphi(x_k),\ i = \overline{1,F};\ k = \overline{1,m}$ to avoid some known drawbacks of the MIA GMDH: e.g., they help to exclude the possibility of losing relevant arguments.

In general, iterative GMDH algorithms are operable at $m > 1000$, and they allow constructing models even in degenerate problems when $n < m$. Historically the very name of GMDH is associated primarily with them.

Expressions (7–10) represent in a simplified form the four main types of structure generators in GMDH algorithms. All of them build models that are linear in parameters but generally non-linear in inputs. Typical GMDH applications are modeling of nonlinear systems, forecasting complex processes, function approximation, recognition, classification, clustering and others.

Control with optimization of forecast. In 1970th, O.H. Ivakhnenko had developed a new method of control with the forecast optimization [25] (optimization on a sliding finite interval) which was fundamentally necessary in control problems of environmental systems as the tasks with predicted disturbances. A control system with such an optimizer is a combined one: in the implemented control action the requirements are taken into account of both stabilization of the output value and advanced compensation of the measured disturbance that attaches intelligent features to the control system. Such an approach called currently "predictive control" had started to develop only in the late 1980th.

Noise-immune modeling. In early 1980th O.H. Ivakhnenko had established an organic analogy between the tasks of model construction from noisy data and signal passing through a noisy channel [26]. This had made it possible, using Kotelnikov's ideas on the noise-immune receiver of signals, to suggest the so called "ideal criterion" for modeling tasks that enabled to proof theoretically better forecasting capabilities of "non-physical" models [27] and to build fundamentals of the noise-immune modeling theory [18]. The basic result of the theory: the complexity of optimum model depends on the level of uncertainty — the higher it is the simpler (more «robust») is to be the optimum model.

Two-level predictive models. For modeling of dynamics of cyclic processes, in particular economic and ecological, O.H. Ivakhnenko suggested a method for construction of multilevel forecast systems [25]. The theoretical base of the two-level modeling was presented in [18], and an appropriate algorithm for construction of two-level difference models for cyclicities of the "cycle-time" type was described in [28]: the variables of upper (cycle-averaged) and lower (time-averaged) levels in their balance relationship are thus considered.

Non-parametric forecasting. O.H. Ivakhnenko developed original non-parametric approaches to forecasting complex processes: correlation predictive models; a reverse transformation of the transition probabilities matrix into forecast [29]; a method of the group *analogues complexing* [30].

Ideas of systems analysis and clustering. An algorithm of *objective system analysis* (OSA) is intended for determination of inputs and outputs variables among all measured ones and building the system of difference equations of an object dynamics [31]. An algorithm of the *objective computer clusterization* (OCC) solves the tasks of clustering with the use of self-organization of the quantity and composition of clusters [32].

Modeling with other basic functions. O.H. Ivakhnenko promoted evolving new algorithms of model construction in such model classes: *harmonic models* of oscillatory processes in the form of sum of harmonics with aliquant frequencies [33]; nonlinear *additive-multiplicative models* with automatic determination of non-integer degrees of input variables [34]; etc.

Analysis of selection criteria, optimal complexity of models. In the GMDH theory, the scope is first of all on analysis of selective properties of external criteria which is carried out within the framework of the noise-immune modeling theory. The initial results [26, 27, 18] were supplemented in [35, 36] by studies of so-called J-optimality (J-criterion is another name for the "ideal" one [27]).

Theoretical results regarding the problem of convergence analysis of iterative GMDH algorithms one can find in [37, 23, 19]. Another important aspect of the GMDH theory was concerned the analysis of asymptotic properties of external criteria [38, 39]. Main results of O.H. Ivakhnenko and his colleagues during 1980th are reflected both in the domestic books [18, 19] and abroad [16].

GMDH as the polynomial neural network. In 1990th, the typical MIA GMDH procedure was interpreted as an original architecture of a neural net called *polynomial neural network* (PNN). The point is that the originality of GMDH as a neuronet consists in self-organization of both its structure and parameters. To the explicit advantages of GMDH we can refer automatic formation of a network structure, simplicity and speed of parameters adjustment as well as the possibility to "fold" the adjusted network directly into an explicit mathematical expression ready to be used for solving tasks of simulation, prediction, control and decision making.

To illustrate the originality of the MIA GMDH as an automatically constructed PNN architecture, Fig. 1 represents a very simple example of the network state (for the case of 4 input arguments): a) after stopping the forward iterative process of the best model f^* building, and b) the resulting trained GMDH network after backward tuning. As the result of the net self-organization, the argument x_2 appears to be redundant. As it is evident, the tuned net may be easily reduced to direct formula $f^* = f(x_1, x_3, x_4)$.

Neuronet with active neurons. A typical "GMDH neuron" in the form of quadratic polynomial of two arguments can be called as "passive" because any of the neurons have the same fixed structure, i.e. the PNN GMDH is *homogeneous* net. In the 1990th, Ivakhnenko proposed a new type of GMDH network with *active neurons* [40] or a *heterogeneous* network in which any of the neurons is in turn also a GMDH algorithm, due to that the structure of such neuron is optimized. As a result, all neurons can get different structures increasing the flexibility of configuring the network to a specific task. Networks of such type are also called as "*twice multilayered*" ones [41].

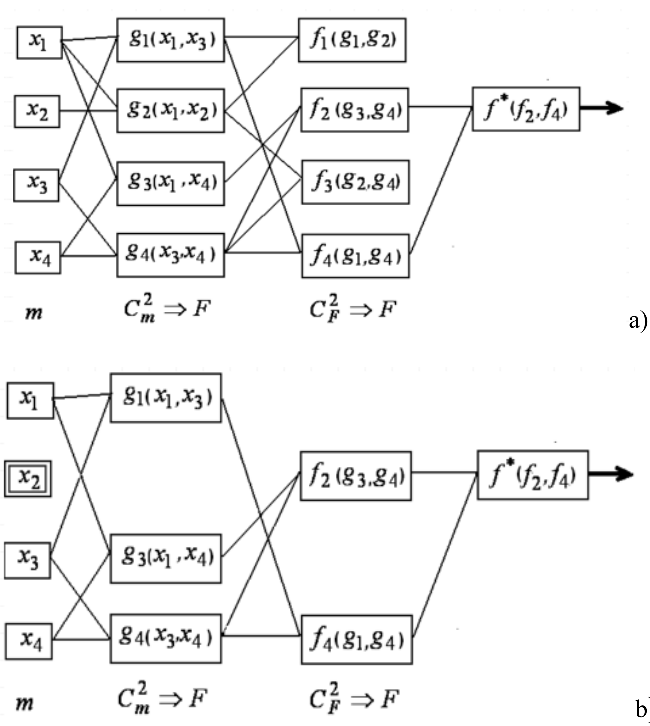

Fig. 1. An example of self-organization of the GMDH net architecture

DEVELOPMENT OF IVAKHNENKO'S IDEAS BY RESEARCHERS OF THE WORLD

Scientific results of O.H. Ivakhnenko are widely known in Ukraine and abroad: more than 40 books and 500 scientific papers were published by him, many of which, in the first place books, was republished in English, German, Polish, Bulgarian, Romanian and Chinese (11 monographs published abroad). Graphic evidence of the global recognition of merits of this method and its author was the publication in 1984 in the United States of the monograph of American and Japanese researchers on theoretical and applied aspects of GMDH [42] dedicated to the 70th anniversary of the GMDH author.

Hybrid GMDH-type algorithms and neural networks. New and efficient architectures of neuronets are recently intensively developed on the basis of hybridization of GMDH procedures and various approaches of computational intelligence and nature-inspired solutions: particle swarm optimization [43], RBF [44], genetic selection and cloning [45], immune systems [46] etc. Several variants of hybridization are implemented in the GMDH-based architecture called GAME [47].

Fuzzy and interval approaches in inductive modeling. For the real tasks with fuzzy variables there have developed corresponding algorithms: Multi-layer hybrid fuzzy PNN [48]; Fuzzy GMDH [49] based on the classical structure MIA GMDH; GMDH-like cascade wavelet-neuro-fuzzy network [50]. For another case of initial assumption on interval-given input data, a method [51] has elaborated.

Algorithms based on paralleling operations. There are several effective realizations of both iterative [52] and combinatorial [53] algorithms with implemented parallel computations.

Ensembling-based prediction. The core idea in the GAME method [54] is a kind of non-parametric procedures for predicting processes using not a separate model but a weighted average of assemblage of several predictions obtained by various GMDH-type algorithms.

Automated data preprocessing. An advanced idea is suggested in [55] to build some kind of automated means for data preprocessing enabling to enhance the accuracy of classification.

Modeling tasks with multiple outputs. New analytical and applied results were obtained for the task of inductive modeling of multidimensional systems with many outputs [56].

Inductive algorithms for classification, recognition, clusterization. Essential part of real-world problems requires application of special methods of pattern recognition in wide sense. Among current developments in the inductive modeling field there are many methods and tools dealing with tasks of such type, for instance [47, 57].

Software tools based on GMDH. There are several examples of computer tools for modeling complex systems completely based on GMDH and/or GMDH-type algorithms. The software complex KnowledgeMiner of commercial destination and its recent highly advanced realization [58] contains iterative and several non-parametric GMDH algorithms for fully automatic building and analyzing forecasting models. Another variant of commercial software is GMDHshell [59] based on COMBI and MIA GMDH algorithms. The technology FAKE GAME [47] is intended for construction, investigation and application of inductive evolutionary algorithms of different architectures.

Real-world applications of inductive modeling. During the whole period of GMDH evolution this method demonstrated good performance when solving modeling problems for complex processes and systems of different nature in environment, economy, finance, hydrology, technology, robotics, sociology, biology, medicine, and others. Many examples of such modeling results can be found on the ITIM department site [60] in papers presented at conferences and workshops on inductive modeling as well as in the annual issue of collected papers "Inductive modeling of complex systems".

FURTHER DEVELOPMENTS OF INDUCTIVE MODELING METHODS AND TOOLS IN THE ITIM DEPARTMENT

In 1998, precisely 20 years ago, when the Department for information technologies of inductive modeling (ITIM) was established at the IRTC ITS of NAS of Ukraine, the scientific direction created by O.H. Ivakhnenko obtained its short name «Inductive Modeling» being now generally accepted for scientific forums, articles and books in Ukraine and abroad. This department is the only one in the world which is professionally dealing with the theoretical, technological and applied investigations in this field. Its activity presents the modern stage of functioning the Inductive modeling school and provides the coordination of studies in this area by annually holding International Conferences and Workshops on IM as well as Summer schools for young researchers devoted to issues of the GMDH theory, algorithms and applications. These events take place both in Ukraine and abroad and involve researchers of many countries.

The ***research strategy*** of the department covers the full life cycle of a scientific research: the methodology of modeling from data samples; the theory of inductive construction of models of optimal complexity; algorithmization of high-performance modeling tools; intellectualization of technologies of constructing models; computer experiments to evaluate the effectiveness of developed technologies; solving real problems of modeling and forecasting; applied implementation of the developed software tools in monitoring, control and decision support systems.

The term ***inductive modeling*** is defined as a self-organizing process of evolutional transition from initial data to mathematical models reflecting some functioning patterns of the modeled objects and systems implicitly contained in the available experimental, observational or statistical information under the uncertainty conditions [5]. Instead of the traditional deductive way of solution of modeling tasks «from general theory — to particular model», inductive approach is based on the intensive use of computers as the way «from particular data – to general model».

Main scientific results of the ITIM department may be characterized as follows.

Theory of inductive modeling. Detailed outcomes concerning conditions of constructing models of optimal complexity were presented in [61] using so called method of critical variances. This main analytical instrument of the inductive modeling theory has made it possible to prove that GMDH is the method of construction of models with minimum variance of the forecasting error. GMDH process enables an automatic adaptation of the optimal model to the level of informativity of a noisy data sample. This makes it possible to classify GMDH as an effective method of data mining and computational intelligence, since it is aimed at automatic search and description of regularities with the choice of structure and parameters of linear, nonlinear, difference and other models based on data samples under condition of uncertainty and incompleteness of a priory information.

Enhanced and optimized GMDH algorithms. An original two-criterion method of redefinition (additional determination) the optimal model choice was elaborated in [62] which enhances the reliability of model building from data.

High-performance sorting-out GMDH algorithms were designed and implemented based on *recurrent* calculations [63], *paralleling* operations [64], *sequential selection* of informative *variables* [65], and *genetic* procedures of model construction [66]. They all allow enhancing the dimensionality of the real-world problems being solved.

New hybrid architectures of iterative GMDH algorithms were constructed as a generalization of algorithmic structures of multilayered, relaxational and combinatorial types, based on which the *generalized iterative algorithm* GIA GMDH [67] was developed as a neural network with active neurons in the form of the COMBI algorithm for automatic adjustment of a neuron complexity.

The *generalized relaxational iterative algorithm* GRIA GMDH was developed based on the use of high-speed recurrent computations of parameters and external criteria during the multilayer procedure, which allows solving inductive modeling problems from high-dimension data [68].

Theoretical foundations of *intelligent modeling* of complex processes, e.g. socioeconomic ones, under conditions of incompleteness and uncertainty of a priori information are developed based on the use of knowledge bases, means of inductive data analysis and intelligent user interface [69].

An original approach to substantial enhancing the effectiveness of sorting-out GMDH algorithms is based on combined implementation of *recurrent and parallel calculations* [70].

Developed instrumental tools. Generally all GMDH-based means allow solving typical tasks of data mining, knowledge discovery and business intelligence. The following tools have been developed:

– complex of software tools [71] for designing, researching and applying modeling methods, conducting experiments on testing modeling methods and their components (model classes, generators of model structures, methods for estimating parameters and models selection criteria).

– software package ASTRID-GIA [72] for inductive modeling of complex systems based on various iterative GMDH algorithms makes it possible to use the generalized algorithm GIA GMDH and all its special cases [69] in online access mode both over the Internet and in the local network.

– computer system of *automated structure and parameter identification* ASPIS [73] for building predictive models on the basis of the high-speed generalized relaxational iteration algorithm GRIA GMDH [68] for solving big data problems.

– software tool for modeling and predicting complex *interrelated processes* on the basis of recurrent-and-parallel GMDH algorithms in the class of dynamic models of vector autoregression [74];

– management decisions informational support system MDISS for solving problems of estimation, analysis and forecasting of the state of complex systems of interrelated socio-economic processes with the purpose of making reasonable managerial decisions [75].

Many of the mentioned above results of ITIM department are reflected in the three monographs dealing with: elaboration, computer-based research and practical application of high-performance sorting-out GMDH algorithms [76]; design, theoretical study, numerical testing and application of the GMDH algorithms of the relaxational type [77]; development and investigation of the generalized iterative algorithm GIA GMDH, construction the interactive software package ASTRID-GIA [78].

Basic application results. Various tasks of modeling of complex systems and processes of different nature have been solved, in particular:

– dynamics of interdependent indicators of the energy and investment areas in the class of vector autoregression models for a short-term forecast [74, 75];

– dependence of the sputtering (disruption) coefficient of a spacecraft surface under action of ionized gas jets on the physical properties of the surface coating [76];

– predicting the results of testing blood samples with medicines to determine the most effective for a patient; construction of classifiers for the differential diagnostics of blood diseases [77].

– quantitative assessment of the impact of sea water pollution with bitumoid substances on the total number of species of benthic organisms in the Sevastopol bays [78];

– modeling of the quantity of microorganisms in the soil depending on weather factors and the dose of contamination with heavy metals [79].

PROSPECTS OF RESEARCH DEVELOPMENT IN THE FIELD OF INDUCTIVE MODELING

The most promising ***directions of the research development*** may be indicated as follows:

– theory of intellectualization of inductive modeling tools using paradigms of neural networks with active neurons and hybrid architectures of GMDH with evolutionary and multiagent methods;

– theory and high-performance structures of the sorting-out GMDH algorithms on the basis of recurrent-and-parallel and evolutionary calculations;

– methodology, theory and intelligent algorithms for inductive solving tasks of classification and clustering for detecting regularities and automatic analysis of big data;

– intelligent technologies for informational support of making decisions in systems of various nature on the basis of instrumental means of interactive synthesis of inductive modeling algorithms;

– optimal preprocessing procedures to improve the modeling results;

– non-parametric modeling and forecasting based on waited averaging of model ensembles;

– knowledge-based intelligent user interface with strong support and control of user’s activity;

– application of the developed means of intelligent modeling in applied problems of analysis and forecast of socioeconomic, ecological and technological processes;

– theory and application of tools for informational support of the decision-making based on inductive modeling methods and algorithms;

– knowledge discovery based on inductive procedures of automated content analysis of messages on Internet, in social networks and textual sources;

It should be noted that the research community dealing with the problem of Deep Learning [80] has recognized that the GMDH created in 1968 by Ivakhnenko is the very first example of a deep learning network with self-organization of its structure, parameters and depth. This fact opens new and very promising prospects for further research developments in the field of inductive modeling.

CONCLUSIONS

An enormous amount of articles has been published during the 50-years period in the world on the subject of GMDH-based inductive modeling. In this article, structured information was presented on historical aspects of the formation and development of inductive modeling as original scientific direction in Ukraine and abroad, including the ITIM department. Main prerequisites facilitating the creation of the GMDH by O.H. Ivakhnenko were analyzed, basic fundamental, technological and applied achievements of the half-century development of inductive modeling both in Ukraine and abroad were characterized, as well as the most prospective ways of further research were formulated.

GMDH as the main instrument of inductive modeling is an original and effective means of solving a wide range of problems of artificial intelligence. The structure of GMDH is interpreted as a neural network whose originality consists in the self-organization of both its structure and parameters, and it is defined as a kind of architecture of deep learning. Inductive modeling theory refers to the most modern methods of data mining, computation intelligence and soft computing. GMDH-based self-organizing inductive modeling tools represent an original and efficient facility for solving a wide range of artificial intelligence problems including identification and forecast, pattern recognition and clusterization, data mining and search for regularities.

The main objective of scientific research of the ITIM department is developing theoretical and applied bases of designing intelligent tools and technologies for inductive modeling of dynamics of complex interrelated processes based on statistical data for informational support of management decisions in digital economy systems. This objective corresponds to the dominating world trends in the development of technologies for high performance computing, deep learning and big data analysis.

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ФОРМУВАННЯ І РОЗВИТОК САМООРГАНІЗОВНИХ ІНТЕЛЕКТУАЛЬНИХ ТЕХНОЛОГІЙ ІНДУКТИВНОГО МОДЕЛЮВАННЯ

Вступ. Ефективне розв’язання завдань керування та прийняття рішень у складних системах має використовувати результати математичного моделювання. Для побудови адекватних прогнозних моделей є багато сучасних методів та інструментів, які, як правило, базуються на двох основних підходах: керовані теорією (дедуктивні) та керовані даними (індуктивні). Методи, керовані даними, є основними для розв’язання типових задач аналізу даних; вони реалізують індуктивний процес переходу від конкретних даних до моделей, що узагальнюють ці дані. Серед усіх таких методів досить примітними є ті, що розробляються в рамках індуктивного моделювання на основі методу групового урахування аргументів (МГУА), створеного кілька десятиліть тому академіком О.Г. Івахненком.

Метою дослідження є аналіз передумов винайдення МГУА О.Г. Івахненком та еволюції ідей, методів та інструментів самоорганізації моделей протягом піввікового історичного періоду успішного розвитку методології індуктивного моделювання.

Результати. Знання, набуті О.Г. Івахненком у галузях автоматичного керування, інженерної кібернетики та зароджуваної нейронауки, ініційованої ідеями персептрона, були тими передумовами, які допомогли йому синтезувати оригінальний самоорганізовний підхід до розв’язання завдань побудови моделей об'єктів і процесів на основі експериментальних даних. У роботі проаналізовано еволюцію наукових ідей та основні досягнення у розвитку МГУА в період 1968–1997 років. Охарактеризовано внесок науковців з різних країн у модифікацію та застосування МГУА. Наведено результати подальшого розроблення методів та інструментів індуктивного моделювання у відділі інформаційних технологій індуктивного моделювання і вказано найперспективніші напрями досліджень у цій галузі.

Висновки. Проаналізовано основні передумови, що сприяли створенню МГУА О.Г. Івахненком, охарактеризовано основні фундаментальні, технологічні та прикладні досягнення півстолітнього розвитку індуктивного моделювання як в Україні, так і за кордоном, а також сформульовано найбільш перспективні шляхи подальших досліджень.

Ключові слова: *математичне моделювання, моделювання на основі даних, самоорганізація моделі, МГУА, індуктивне моделювання, завадостійке моделювання, інформаційні технології, прикладне дослідження.*

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ФОРМИРОВАНИЕ И РАЗВИТИЕ САМООРГАНИЗУЮЩИХСЯ ИНТЕЛЛЕКТУАЛЬНЫХ ТЕХНОЛОГИЙ ИНДУКТИВНОГО МОДЕЛИРОВАНИЯ

Целью работы является анализ эволюции идей, методов и инструментов самоорганизации моделей в течение полувекового исторического периода успешного развития методологии индуктивного моделирования. Проанализированы основные предпосылки создания академиком А.Г. Ивахненко метода группового учета аргументов (МГУА), исследуется эволюция его научных идей и взглядов, а также основные достижения в развитии МГУА в период 1968–1997 годов. Охарактеризован вклад исследователей разных стран в модификацию и применение МГУА. Приведены результаты дальнейших разработок методов и инструментов индуктивного моделирования в отделе Информационных технологий индуктивного моделирования и указаны наиболее перспективные направления исследований в этой области.

Ключевые слова: *математическое моделирование, моделирование на основе данных, самоорганизация модели, МГУА, индуктивное моделирование, помехоустойчивое моделирование, информационные технологии, прикладное исследование.*