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METHODOLOGY OF CONTROL SYSTEM DEVELOPMENT FOR BIOLOGICAL SYSTEMS UNDER INFORMATION INSUFFICIENCY

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ABSTRACT

Multiparameter control of complex biological systems requires collaboration of experts from different branches. Methodology for the case of insufficient information about the biological system is divided into three stages: 1) model development of biological system as a biological control system (BCS) including verification of the model, 2) model development of artificial control system (ACS), which satisfy the set of control targets and is optimised accordingly the set of efficiency criteria, 3) adaptation of ACS parameters to ensure harmless collaboration of BCS and ACS taking into account the dynamics of the transition processes. Methodology contains different applications of topological modelling, expert surveys, dynamic modelling and model verifying using experimental data. Methodology is described in form of algorithms for each of three stages of methodology.

INTRODUCTION

The simulation of biological system from the system control viewpoint is related to several problems that are not characteristic for technical systems. In the case of biological systems there is no unambiguous information on the principles of the construction, relations of causes – consequences and interaction with the environment because this system has not been constructed by a man for particular targets by the means selected by a man. This factor restricts the possibilities of application of the simulation methods of the technical systems.

Besides that the analysis of stability during transition processes widely applied in the control systems of the technical systems has not been adapted until now for the peculiarities of the control of the biological systems. Control of the biological system means the modification of the parameters of the environment where it is located. And the biological system reacts to any deviation in the environment parameters as the biological control system to compensate the changes taking place. Thus there is a task of balancing two control systems: one control system (usually several mutually linked loops) is the biological control system (BCS) of the biological system itself, and the other control system is the artificial control system (ACS) which has been created by a man for the control of the first one. Consequently also the analysis of the transition processes is required.

During last years a new agricultural industry has been defined – Precision Agriculture (PA) (Laurs, 2004, Vilde et al., 2004, Domeika and Kurlavicius, 2004), which is based upon the computer control of the agricultural processes extending even to the individual control over the animals and plants depending on their conditions and the defined goals of the control. This tendency indicates growing demand for complex control systems in industry.

The approaches to the modelling of the biological systems found in the literature are quite specific and focused on particular directions because the term of simulation in the biology is very wide (Antamonov, 1977, Lisenkov, 1979; Renshaw, 1995). In the literature no methodology or algorithms of the simulation or research of the biological systems from the viewpoint of the control including transitional processes have been found.

Goal of the paper is to create the methodology for the development of the computer control for the biological system under the conditions of incomplete information on the regularity of the operation of the biological system. Methodology has to provide the correspondence of control system to the criteria of efficiency and harmlessness.

The goal of the paper shall be reached by performing the following tasks in sequence:

1. To develop the methodology for the development of a static and dynamic model of the BCS of biological system.

2. To develop the methodology of the development of the ACS of the biological system including the

determination of the percentage of the ACS loop, which is optimal based upon the efficiency criteria.

3. To develop the methodology for ensuring the harmlessness of the collaboration of BCS and ACS (competition of the two control loops), taking into account the dynamics of the transition processes.

DEVELOPMENT OF MODEL OF THE BIOLOGICAL CONTROL SYSTEM (BCS)

The operation of the set of the parameters B of the biological system existent in the nature under the conditions of set of environmental parameters V can be described in the form of the model

$$M_b = F_b(b_1,...b_k,...b_K;\ v_1,...,v_s,...v_S;\ t), \qquad (1)$$
$$b_k \in B,\ v_s \in V,\ B \cap V = \varnothing,$$

where $b_1...b_k$ – the variables characterising the biological system (internal control loop) belong to the set of the parameters B of the biological system,
$v_1...v_s$ – the variables characterising the environment, belong to the set of the parameters V characterising the environment,
t – time.

Reproduction and metabolism is a common feature of all the biological systems. The description of these processes can be used as the initial point for the simulation when the biological system is viewed in totality as a population.

When a process within the biological system or its part is viewed, the food, energy, heat, time or other balance can be used as the initial data. These can be viewed independently of each other or in relation.

As it is necessary to take into consideration many functional correlation's relating the variables of the biological system $b_1..b_K$ to the variables of the biological system and environment $b_1..b_K$ and $v_1..v_S$, the initial model is developed by means of the topological modelling. In this stage of the development of the model cooperation of the experts of the biological system and knowledge engineers is necessary.

The algorithm for the development of the BCS model M_b is shown in Figure 1. The description of the operations contained in the algorithm (**in bold**) has been provided for every step of the algorithm.

Definition of control targets is intended for the specialisation of the model from the point of view of control system to be developed.

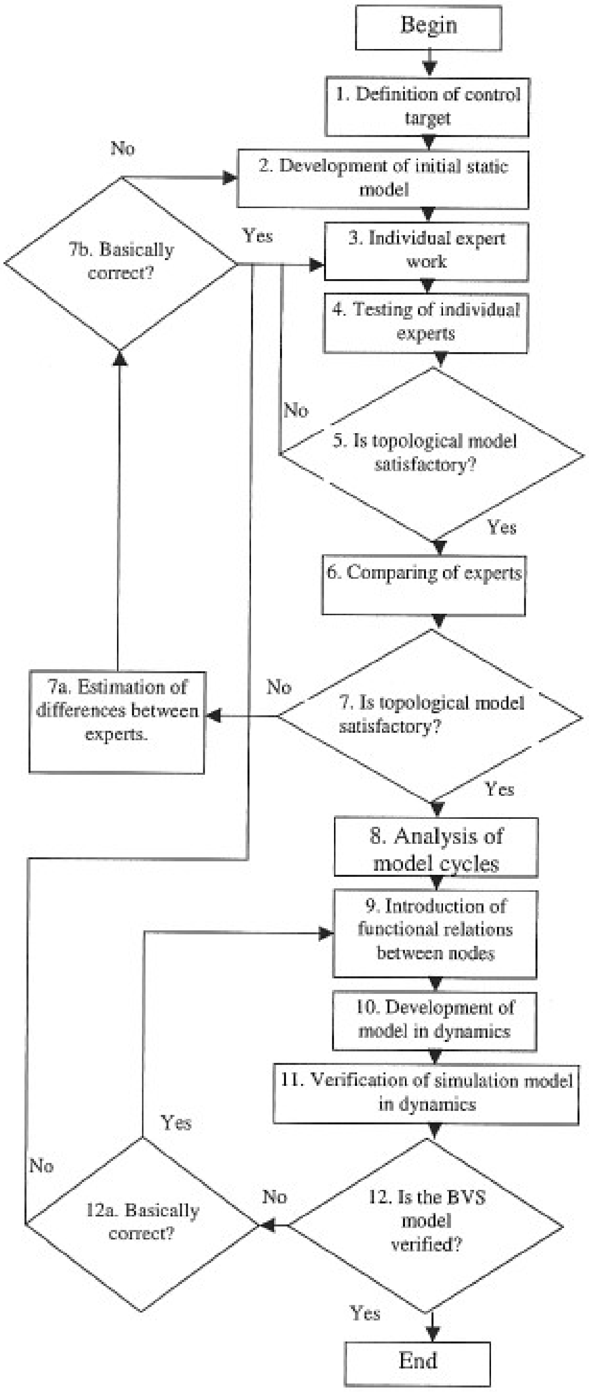

Figure 1: Algorithm of BCS Development.

The control task is being solved to satisfy the set of control targets $G\{g_1,...,g_q\}$

$$G = F_g(b_k,\ v_s,\ t), \qquad (2)$$

where k=1,K; s=1,S.

The control targets G can be clearly defined in the definition of the control task, or these should be reduced to the particular parameters characterising the system when the targets have been defined generally. Further detailed study of the system will be devoted only to the processes related to the control target thus permitting to reduce the extent of the model to the minimum required. The development of the model starts with the application of the topological simulation (Osis, 1967). Use of topological modelling is caused by its flexibility regarding implementation of changes. That is very important in circumstances of insufficient amount of information, which requires possibility of easy and quick structure change of the model. **The initial static topological model** is the first iteration of the following topological model

$$M_t=F_t(b_1,\ldots b_k,\ldots b_K;\ v_1,\ldots,v_s,\ldots v_S). \qquad (3)$$

It is necessary as the basis for further statements by the experts at the stage of the expert survey. The initial model is developed referring to the data in the literature or with the participation of some of the experts to be invited later on.

Further improvement of the model is done by the experts introducing the changes to the model M_t (Stalidzāns and Markovičs, 2000). Incidence matrix and the topological model as the kinds of the information reflection are applied for making the model more precise by experts in iterative process first individually (cycle: **individual expert work, testing individual experts, satisfactory model**). Individual expert work is followed by **comparing of experts**. If the result is not **satisfactory model** and after **estimation of differences between experts** does not appear **basically correct** the initial topological model can be changed.

The evaluation of the information provided by the experts based upon the level of the concord of the experts is made depending on the type of the survey: direct estimation or comparison of pairs.

In case of the direct estimation of the parameters the level of concord of the experts is evaluated based upon the concordation coefficient W_t (Kendall, 1955, Djakova and Krug, 1966) in compliance to the following formula:

$$W_t=\frac{12\sum_{i=1}^{n}\left\{\sum_{j=1}^{m}r_{ij}-\frac{1}{2}m(n+1)\right\}^2}{m^2(n^3-n)}, \qquad (4)$$

where n - number of estimated objects in the group,
m – number of experts,
r_{ij} – rank of object i accordingly to estimation of expert j.

In case of the comparison of the pairs the level of concord of the experts is determined based upon the concordation rate W_p in compliance to the following formula (Kendall, 1955, Djakova and Krug, 1966):

$$W_p=\frac{4(\sum\partial_{lk}-m\sum\partial_{lk}+C_m^2C_s^2)}{m(m-1)s(s-1)} \qquad (5)$$

where ∂_{lk} - numbers in the table of pair comparison;
l=1,...s; k=1,...s – indexes of comparable objects;
s – number of comparable objects;
m – number of experts;
$C_m^{\ 2}$ – number of conformities from m each 2;
$C_s^{\ 2}$ – number of conformities from s each 2.

The value of the concordation coefficients W_t and W_p varies within the scale $0 \le W \le 1$, and W=0 of there is no relation between the ranks and it is 1, if all the experts have rated the objects the same. The value $W \ge 0{,}5$ can be considered as a statement that the concord between the experts is sufficiently high. In case when the concordation coefficients are satisfactory the obtained average values or the weight rates can be used.

When the number of the experts m is small the role of every expert increases. Consequently the inaccuracy of any single expert's view strongly influence the average arithmetic value. Another methodology for obtaining the resulting assessment is applied for the prevention of this effect. It is known that the essence of the evaluation by the experts is obtaining an unknown value as an incidental value the distribution of which is judged based upon the individual evaluations by the experts. Thus the initial data massive of the experts' views should be processed based upon the mathematical statistics concepts. In case when the number of experts is small the average arithmetic value is not the best way for obtaining the resulting assessments.

Therefore the evaluation of every i parameter should be defined as the mathematic expectation of the average value C which is calculation on iterative bases where the formula for q iteration is (Voronin, 1974).

$$C_q=\frac{\sum_{j=1}^{m}C_j\exp\left[-\frac{1}{2\partial^2}(C_{q-1}-C_j)^2\right]}{\sum_{j=1}^{m}\exp\left[-\frac{1}{2\partial^2}(C_{q-1}-C_j)^2\right]} \qquad (6)$$

where C_j – evaluation of expert j of the object i,
C_{q-1}- result of previous iteration,
q=1,...,μ - iterations,
∂ - standard deviation,
m – number of experts.

On the first iteration it is recommended to apply the average arithmetic value

$$C_1 = \frac{1}{m}\sum_{j=1}^{m} C_j \cdot \qquad (7)$$

Then in compliance to the procedure of iterations the exact value should be found. The iterative process has been completed when the changes of the value between iterations are lower than the permitted error.

Following the development of the topological model **the analysis of the cycles of the model** should be performed defining the particular BCS loops in the biological system itself.

If the experts think that the topological model M_t sufficiently well depicts the relation of the biological system and the environment parameters the study of the system should be continued in the dynamics and **the introduction of the functional relations between the nodes** is required. The topological model developed for the application case (the model for the microclimate control of wintered bee colony) can be seen in Figure 2.

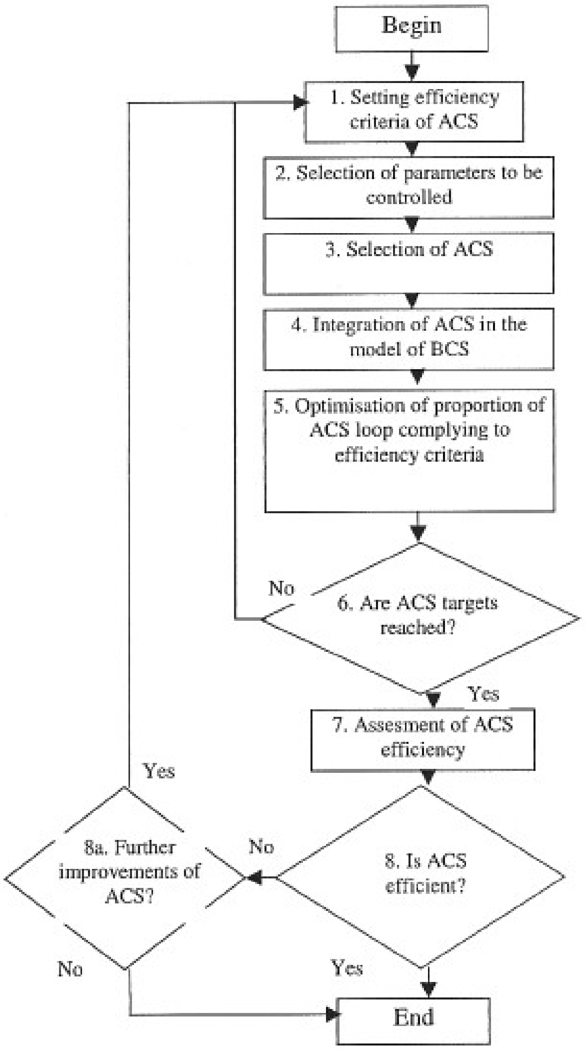

Figure 2: Algorithm of ACS development.

The static topological model $M_t=F_t(b_1,...b_k,...b_K; v_1,...,v_s,...v_S)$ has to be homomorphly changed into the dynamic model $M_b=F_b(b_1,...b_k,...b_K; v_1,...,v_s,...v_S;t)$. That can be done applying the dynamic simulation software package *Powersim Constructor 2.51*. Advantages of *Powersim Constructor 2.51* dynamic modelling software are determined by its flexibility in relation to the changes in a model, simple user interface and possibility to connect with the *Microsoft Excel* program for information exchange.

Under the conditions when sufficient information on the relations between the nodes is not available the surely known data, which can be expressed in the form of equation become the most valuable basic information of the model. These can become the tools for turning down the low quality data as deficient. Instead of the unknown relations between the nodes it is necessary to introduce very approximate functions initially and they can be updated in the process of simulation.

Development of the simulation model in dynamics (model M_b) comprises one of the most important stages of the work - tuning the model on which the level of similarity of the model to the simulated processes in the biological system depends.

Verification of the simulation model in dynamics should be performed using the data collected in the field experiments.

The verification operation is intended for checking the correctness of the simulated data of the model. It is necessary to minimise the deviations of the model from the measurements obtained in the field experiments $M_l= F_l(b_1,...b_k,...b_K; v_1,...,v_s,...v_S; t)$.

$$\Delta_{ver} \geq |M_b - M_l| = F_b(b_k,v_s,t) - F_l(b_k,v_s,t), \qquad (8)$$

where Δ_{ver} – difference between the field measurements M_l and the system model M_b,
k=1,K; s=1,S.

The maximum permitted verification error δ_{mver} can be specified separately for every parameter of the set B:

$$\delta_{ver\,i} \geq |F_b(b_k) - F_l(b_k)|, \ k=1,K. \qquad (9)$$

It is necessary to attempt to minimise the deviations from the measurements performed in the nature paying major attention to the comparison of the tendencies (growth, decrease, stagnation). When the difference between the test data M_l and the model data M_b has become lower than the permitted Δ_{ver}, the **BCS model verification** has been performed and the model of the biological system $M_b= F_b(b_1,...b_k,...b_K; v_1,...,v_s,...v_S; t)$ can be considered as established. In the further operations this will replace the biological system.

Verification is done by software *Powersim Solver 2.0*, which works with model created on *Powersim Constructor 2.51*. It provides model flexibility and changes done in the BCS model does not need to be changed for *Powersim Solver 2.0*.

DEVELOPMENT OF THE ARTIFICIAL CONTROL SYSTEM (ACS).

For the purpose of implementing the control of the biological system - collaboration with BCS - it is necessary to establish ACS, which would be able to control the first one.

ACS usually is a technical system the structure of which depends on the task set for it (minimisation, maximisation, prevention of fluctuations, or the combination of these tasks for the sets of the parameters of the biological system).

The control task is being solved to satisfy the set of the control targets $G\{g_1,...,g_q\}$ by ACS that is described by its model

$$M_c=F_c(c_1,\ldots c_z,\ldots c_Z;\ b_1,\ldots b_k,\ldots b_K;\ v_1,\ldots,v_s,\ldots v_S;\ t),\quad (10)$$

where c_z – ACS parameters ($z=1,Z$),

without getting into detail of the transitional processes which would require a more detailed analysis of the system. By this part of methodology in essence has to established whether the introduction of the ACS can be useful assuming that there will be no difficulties in the transitional processes. Algorithm of ACS development is described in Figure 2.

The criteria of efficiency of ACS are set in the task definition or with the help of experts.

There is a set of possible solutions of the ACS establishment X. Its permitted solutions x_i , $i=1,\ldots,n$ form the set of the permitted solutions D_x.

The efficiency of every solution or its efficiency is assessed based upon the scalar criteria y_j, $j=1,\ldots,m$, which jointly form the efficiency vector

$$Y=(y_1,\ldots,y_j,\ldots,y_m).\quad (11)$$

Most often the Y components are the criteria of economic character combined with the criteria of other kinds. A few examples of the possible criteria which can be defined simultaneously: minimisation of the human work force, ecology, minimum time to reach the target, minimum deviations from the target value, etc.

The selection of the parameters to be controlled is determined mostly by the technical possibilities – the measurability of the parameter and possibility to influence it, as well as the set of the control targets G and the efficiency vector Y.

The aim of **the selection of ACS** is to define the technical means to be able to control and supervise the selected parameters.
It is necessary to **integrate ACS in the model of BCS** to perform the simulations of the efficiency of its introduction. In this stage the model can be sufficiently simple because more detailed analysis of it will take place if it turns out that the implementation is useful.

Optimisation of the proportion of the ACS loop in compliance to the efficiency criteria usually is related to the search for compromises because not everything a man can do for reaching the control targets complies with the criteria of efficiency in the particular case.
The efficiency vector Y is related to the resolutions with the help of the reflection function

$$F(X)=X\rightarrow Y,\quad (12)$$

which can be set analytically, statistically or heuristically. The optimum solution X^o should be found which would satisfy two conditions:

1. the solution should be feasible, i.e. it should belong to the set of the permitted solutions D_x,
2. the solution should be the best in the meaning that it should optimise the vector of efficiency Y(X).

The general form of the optimisation model is as follows (Borisovs, 1972):

$$X^o = F^{-1}[\text{opt } Y(x)],\quad X\in D_x,\quad (13)$$

where opt – the optimisation operator of the efficiency vector,
F^{-1}– reverse reflection $Y\rightarrow X$.

The classic vectorial optimisation theory is related to 3 problems.

First of them is the selection of the optimisation principles which determines in what respect the optimum resolution X^o is better than all the other permitted resolutions. In the model it means deciphering the essence of the optimisation vector *opt* leading to the scalar criterion, which, in turn, is the function of the local criteria.

The second problem is rationing of the local criteria.

The third problem is related to the evaluation of the weight coefficients Λ of the local criteria $\Lambda=\{\lambda_j\}$, $j=1,\ldots,m$.

When the optimum resolution X^o is found the optimum ACS model M_c^o is defined.

The optimisation of the efficiency is performed based upon the proportion X of the ACS loop, which is expressed as percentage. The target of the ACS usually it to take over, ease or promote a function of the biological system for the purpose of satisfying some particular targets. Assuming that the maximum technically possible effect of ACS is 100% of the proportion of the ACS loop (X=100%) and the case when the ACS is not introduced at all is X=0%, it is possible to optimise efficiency of the system implementation. In case of one or several consistent criteria the optimum can be found by simple methods.

A more difficult compromise solution should be searched for in cases when the quality of every single local solution is assessed based upon several (at least two) criteria which are mutually conflicting, i.e. when the assessment of the solution becomes higher based upon one criterion it decreases based upon the other. It is a vectorial optimisation situation well known in the technical sciences when the global optimum should be searched for as a compromise solution.

"Fair compromise" optimisation method can be used for searching for the compromise (Borisov, 1972 and Jemeljanov, 1973).

Following the optimisation of the proportion of the ACS loop (finding the ACS model M_c^o corresponding to X^o) the collaboration of BCS and ACS should be analysed again by performing simulations with the optimised ACS (M_c^o), to establish whether the target set for **ACS has been reached**.

Following the **assessment of ACS efficiency** of the optimised it can turn out that **further improvement of ACS** is necessary. In opposite case **ACS is effective** and development of ACS and optimisation of its efficiency is completed.

ENSURING OF COLLABORATION HARMLESSNESS OF BCS AND ACS

When the implementation of the ACS has turned out to be useful it is necessary to ensure the harmless operation of the BCS and ACS to reach the control target and not to damage or destroy the system to be controlled in the transitional processes. The algorithm is shown in Figure 3.

For the purpose of evaluating the control process it is necessary **to combine BCS and ACS models in the real time including the transition processes**.

Following the combination of the models the **simulations with sets of extreme real external impacts** is necessary. The extreme external impact for the purpose of transfer processes are the cases when the environment parameters V varies with maximum speed and thus requires also a fast reaction of the BCS which in natural conditions in most cases can ensure the survival of the system.

During control of the biological system ACS must be correctly designed for extreme changes of the external parameters. The system must not be damaged during collaboration of BCS and ACS.

The permitted range of the changes of the system parameters under the natural conditions, i.e. without the influence from ACS may be set as the criteria of **ACS harmlessness** of the system to be controlled $J=\{j_1,\ldots j_h\}$. Restrictions can be set also in the definition of the task:

$$J = F_j (b_k). \quad (14)$$

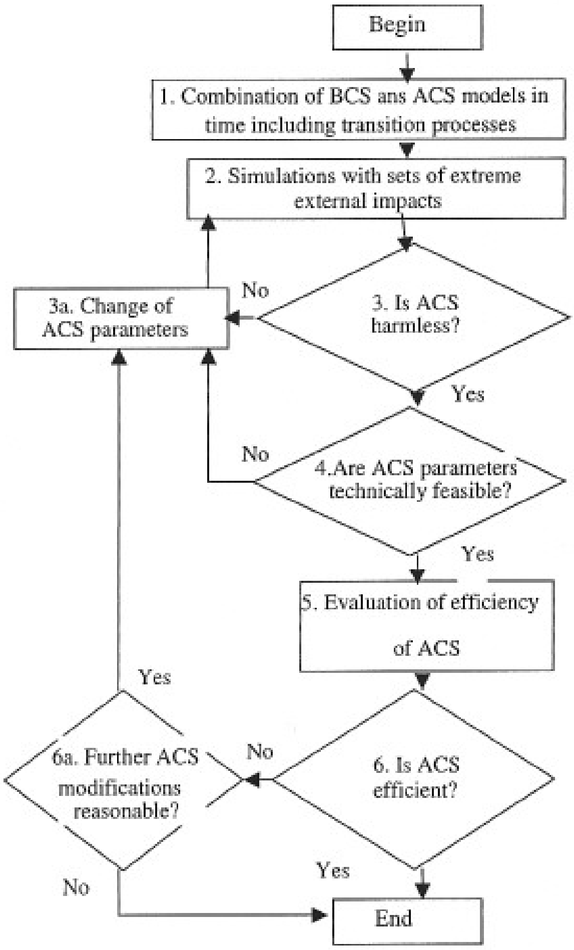

Figure 3: Algorithm for Coordination of the Collaboration of BCS and ACS.

If simulations with sets of extreme external impact does not extend outside the range of the system parameters seen under the natural conditions the collaboration between BCS and ACS can be considered as harmless. Of course, the criteria of harmlessness can differ in their interpretation depending on the specific of the task because even killing the biological system can be set as a task for ACS (for instance: pest control).

In case when the criteria of harmlessness are not satisfied it is necessary to **change the ACS parameters** until the system generally complies with the harmlessness criteria on the level of simulations. Following the ensuring of the harmlessness it is necessary to check whether the new **ACS parameters are technically feasible**. When it is necessary to change the parameters of ACS for reaching the parameters found in the simulations a repeated **evaluation of the efficiency of corrected ACS** is necessary taking into account the performed corrections. The possible results of the **ACS efficiency** evaluation can be as follows 1) **further ACS modification** attempts are necessary to reach the harmlessness and efficiency of the system, 2) the conclusion that the task cannot be fulfilled and further search is not efficient, or 3) the conclusion that the complete task of ACS development has been fulfilled.

CONCLUSIONS

Methodology and its algorithms for the development of the computer control for the biological system under the conditions of incomplete information on the regularity of the operation of the biological system is developed. Methodology provides the correspondence of control system to the criteria of efficiency and harmlessness.
The following tasks have been fulfilled:

1. The methodology for the development of the static and dynamic model of the biological system has been developed.

2. The methodology for the development of the model of target-orientated computer control of the biological system has been developed. The methodology includes the determination of the optimal implementation percentage of the ACS loop based upon the efficiency criteria.

3. The methodology for the provision of the harmlessness of the collaboration of the BCS and ACS (competition of two control loops) has been developed. The harmlessness of the transfer processes under the dynamic conditions is tested in the situations when parameters change with the highest speed and the fluctuations in the transitional process reach their maximum values.

Practical value and further research

1. The established methodology of the development of the computer control for the biological systems can be applied in practice as the area of its application per the types of the biological systems is very wide and the methodology pays special attention to the conditions of insufficient information. That is very often the case in practical research or industry.

2. The described principles of the establishment of the model of the biological system can be applied in practice for solving the forecasting tasks also without the implementation of the control system.

3. The methodology is able to include the most up-to-date science facts on the system to be simulated and this is ensured by the flexibility of both – the topological simulation and the applied dynamic simulation software package.

4. The methodology for the control of one biological system with the help of another biological system thus not applying the artificial system established by a man can turn out to be an interesting direction, for example, biological pest control.

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