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A System Approach to the Regional Sustainable Management

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Abstract. A system approach to the regional sustainable management based on game theoretic models and information technologies is considered. A notion of the regional active system is specified. The author's approach uses hierarchical dynamical game theoretic models formalizing and integrating many different aspects of the control in active systems. A concept of the regional sustainable development is added by the requirement of system compatibility. Sustainable development means that a human activity should provide sufficiently high values of indicators of the social-economic development, and in the same time sustain an environmental equilibrium. Formally, all indicators of the state of a regional socio-ecological-economic system must belong to a given range. In turn, system compatibility means that interests of the active agents should be considered by the Center in a maximal degree for the achievement of the Center's purposes. For a quantitative measurement of the system compatibility based on the proposed model an index of system compatibility is used. Administrative and economic control mechanisms providing the system compatibility are described. On the regional level the problem of coordination of interests has the following specific features. First, a regional administration which should be a leader of SD, in a higher degree is interested in the approval from the federal center that estimates the regional activity by other criteria. Second, the principal control levers, both legislative and economic, are also situated in the federal level. Third, the municipal districts that should provide a practical implementation of the requirements of homeostasis, have not enough resources for it. A hierarchical structure of the model system in this domain is considered. A practical implementation of the methodology of sustainable management on the regional level requires a regional information-analytical system, the structure of which is proposed.

Key words: computer simulation, game theoretic modeling, homeostasis, regional development, sustainable management, system approach, system compatibility.

1. INTRODUCTION

System approach and its applications were extremely popular in 1960-1980s [25]. Since that time up to the moment this approach has been developed not so actively though the system methodology is not completely exhausted [6].

It should be noticed that a system, complex approach was always used by Russian scientists starting from Michael Lomonosov. Vassily Dokuchaev, Kliment Timiryazev, Dmitry Mendeleev, Konstantin Tsiolkovsky, Alexander Chizhevsky, Alexander Bogdanov and especially Vladimir Vernadsky belong to that glorious cohort. A great role in the system research based on mathematical modeling was played by works of Andrey Kolmogorov, Leonid Kantorovich, Andrey Lyapunov, Nikita Moisseev, Alexander Samarsky, Sergey Kurdyumov and many others.

An essential contribution to the system methodology was made by the notion of active system proposed by Vladimir Burkov and his school in the Institute of Control Sciences [5]. This notion formalizes relations in active systems of different nature including human beings (organizational, economic, social systems). An active system consists of active elements (agents) having their own objectives and interests and possibilities to achieve them. As a rule, one of the agents is separated as the Center reflecting the objectives and interests of the whole system. The interests of the agents and the Center do not coincide but are not also antagonistic that allows for some trade-off solutions acceptable for everybody.

An informational interaction of the agents with the Center and each other may include a strategic manipulation (a deliberate misrepresentation of the reported information in private purposes). The main problem of the theory of active systems is a concordance of the interests of the Center (the whole system) and the active agents as elements of the system. For this purpose special administrative, economic, and informational control mechanisms are used [17]. Close ideas are developed in the information theory of hierarchical systems [8], theory of incentives and mechanism design [1,12].

A widely spread since 1980s concept of sustainable development has also a system character. Thus, a key approach of "three pillars" in the analysis and implementation of the sustainable development requires to consider social, economic, and environmental factors in their totality as a whole system. It should be also noticed an important idea that a global sustainable development is formed by the sum of local efforts in this direction [21].

An important class of active systems is generated by territorial formations. Here the problem of coordination of private and public interests is also of the main importance and may be formulated in terms of state - regions, regions - municipal districts, municipal districts - economic agents depending on the level of consideration. In Russia this problem was especially essential in 1990s in the connection with the development of federalism, and it is still actual [15,16].

The author's approach to the analysis of regional active systems is based on the general complex theory of sustainable management in active systems [20]. The approach uses hierarchical dynamical game theoretic models formalizing and integrating all the named aspects. The complexity of these models and big data volumes make necessary an application of modern information technologies of the research support. The regional management is an example of the possible applications of the developed universal theory.

The rest of the paper is organized as follows. In the section 2 a notion of a regional active system is considered. A specified concept of the regional sustainable development with consideration of the condition of system compatibility is proposed in the section 3. In the section 4 mechanisms of system compatibility and monitoring on the regional level are described. In the section 5 a hierarchical structure of the model system of the sustainable management is considered. Section 6 concludes.

2. A REGIONAL ACTIVE SYSTEM

A general structure of the regional active system is presented in Fig.1.

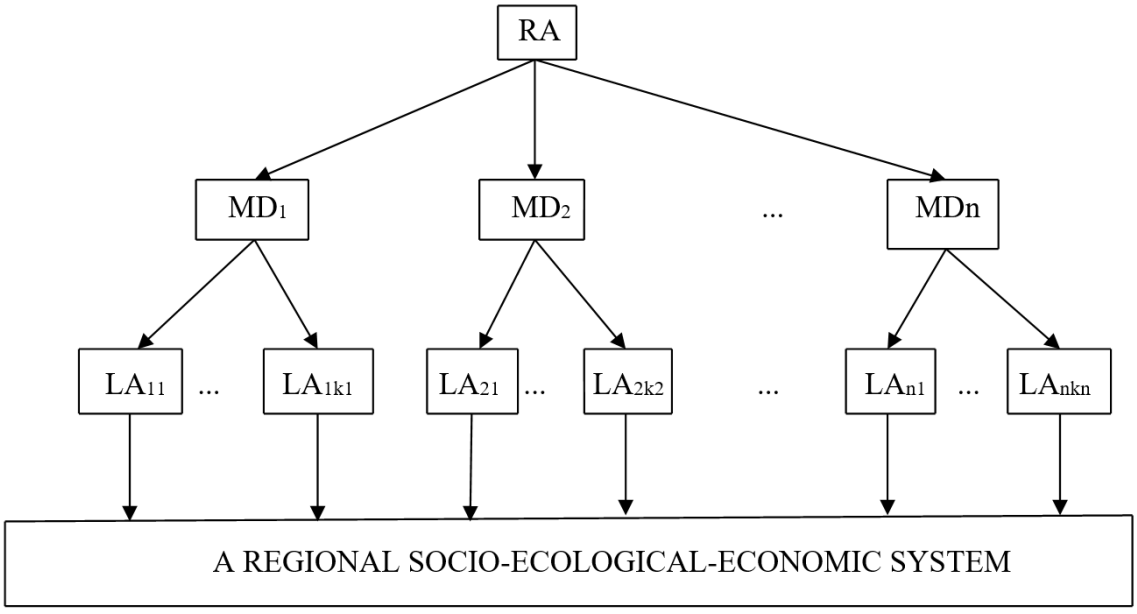

Fig.1 A Regional Active System

On the higher control level a regional administration (RA, Center) is situated. The middle control level is presented by municipal districts (MD). A more complicated variant is also possible when urban municipal formations and their districts are considered separately. The lower control level is formed by local active agents (LA): enterprises, organizations, firms, individual entrepreneurs. The control object is the regional socio-ecological-economic system considered as a hierarchically controlled dynamic system [20].

In the majority of cases LA are economic agents having certain financial, human, and other resources and tending to maximize their income (profit). However, non-commercial organizations and local control agencies can also be considered as LA having non-economic objectives. Economic LA can have social and ecological objectives too.

MDs solve the problems of social-economic development of the respective territories with consideration of the environmental requirements using certain budget resources [15].

The objectives and possibilities of RA are structurally similar to the ones of MD but differ from them by the volume and sources of financing [16]. RA can establish its own laws, and have additional means of influence to MD and LA.

A control object is characterized by three groups of indicators describing the social sphere, economic potential, and environmental state respectively. For determination of the specific values of the indicators the data of official statistics are used which may be complemented by expert estimates. Notice that only LAs exert a direct influence to the regional socio-ecological-economic system. The higher control levels just create some administrative, legislative, and economic framing conditions of the influence.

The laws of change of the state indicators due to natural factors and LA's impact are described by dynamic balance relations. The left hand side contains a new value of the indicator, the right hand side contains an old one plus increase minus decrease generated by the considered processes.

It is more appropriate to set the problems of sustainable management in an infinite period of time. However, a finite, long enough period may be more acceptable in practice. Some discount rate should reflect a relation between incomes and expenses in different moments of time.

Most typical political technologies of regional elites include:

- a concentration of financial resources;
- a power pressure to the opponents;
- an establishment of control and strategic partnership with the most powerful regional economic agents;
- using of information flows from the federal center for the protection of the elites' interests;
- negotiation process with the political leaders;
- a direct or indirect control on the information flows and media, an active construction of a positive image of the regional administration by media;
- a formation of the regional mythology;
- a harder selection of the new candidates to the regional elites [13].

Technically, the administrative controls of RA and MD include legislative restrictions of the activity of subordinated control agents (norms, quotas, quality standards). The economic controls represent tax rates, parameters of privileges, subsidies, grants.

The laws of state dynamics are determined by natural processes and social-economic activity. For their description specific models of the mathematical ecology and economics, and dynamic forecasting models of the regional level are used [18].

The respective three-level game theoretic model of regional control has the form

$$J_0 = \sum_{t=1}^{T} e^{-\rho t} g_0(r^t, s^t, p^t, q^t, u^t, x^t) \to \max \tag{1}$$

$$r^t \in R; \quad s^t \in S; \tag{2}$$

$$J_i = \sum_{t=1}^{T} e^{-\rho t} g_i(r_i^t, p_i^t, q_i^t, u_i^t, x^t) \to \max \tag{3}$$

$$p_i^t \in P_i(r_i^t); \quad q_i^t \in Q_i(s_i^t); \tag{4}$$

$$J_{ij} = \sum_{t=1}^{T} e^{-\rho t} g_{ij}(r_i^t, p_{ij}^t, u_i^t, x^t) \to \max \tag{5}$$

$$u_{ij}^t \in U_{ij}(s_i^t, q_{ij}^t); \; j = 1,...k_i; \; i = 1,..., n; \tag{6}$$

$$x^{t+1} = x^t + f(x^t, u^t), \quad x^0 = x_0; \tag{7}$$

$$r^t = (r_1^t,..., r_n^t); \; s^t = (s_1^t,..., s_n^t);$$

$$p^t = (p_1^t,..., p_n^t); \; q^t = (q_1^t,..., q_n^t); \; p_i^t = (p_{i1}^t,..., p_{ik_i}^t); \; q_i^t = (q_{i1}^t,..., q_{ik_i}^t);$$

$$u^t = (u_1^t,..., u_n^t) = (u_{11}^t,..., u_{1k_1}^t,..., u_{n1}^t,..., u_{nk_n}^t).$$

Here T is a period of consideration (in years); ρ is a discount rate; J_0, J_i, J_{ij} and g_0, g_i, g_{ij} - summary and current payoff functions of RA, MDs, and LAs respectively; r^t, s^t are economic and administrative controls of RA in the year t; R, S are the respective sets of feasible controls; p_i^t, q_i^t are economic and administrative controls of the i-th MD in the year t; P_i, Q_i are the respective sets of feasible controls; u_{ij}^t is a control of the ij-th LA in the year t; U_{ij} is the respective set of feasible controls; x^t is a state vector of the regional socio-ecological-economic system in the year t; x_0 - a vector of initial values of the state indicators on a base year; f - a set of models that describe the state dynamics; n - a number of MDs; k_i - a number of LAs in the i-th MD.

The model (1)-(7) represents a hierarchical differential game, a discrete form of which is oriented to simulation analysis based on the scenario method [14]. Solutions of the game (1)-(7) are understood in the sense of Stackelberg [3]. As a rule, the RA chooses only s^t while r^t is fixed (administrative control, or compulsion) or vice versa (economic control, or impulsion). Similarly, given s^t or r^t the MD_i choose q_i^t while p_i^t are fixed or vice versa. At last, given q_i^t and p_i^t as well as s^t and r^t the LA_{ij} choose their control parameters u_{ij}^t. In fact, simulation modeling is almost unique possibility to solve the game (1)-(7) in the general setup. Some simplified versions may be investigated by means of standard techniques like Hamilton-Jacobi-Bellman equations or Pontryagin' s maximum principle together with numerical methods.

3. SUSTAINABLE DEVELOPMENT

A serious attention to the problem of sustainable development (SD) was attracted by the report “Our Common Future” (1987) prepared by the UN World Commission on Environment and Development, known as “Brundtland Commission”. Conclusions of the Brundtland Report formed a base for the decisions of the UN Conference on Environment and Development (Rio de Janeiro, 1992). The Brundtland Report defines sustainable development as the development which satisfies the needs of present generation and does not undermine the possibility of future generations to satisfy their needs [21, p.43]. The Declaration on Environment and Development accepted at the Rio-92 Conference includes 27 principles, such as principle 3 “A right to the development should be realized to provide a just satisfaction of the needs of the present and future generations in the domains of development and environment” and principle 4 “To provide the sustainable development an environmental protection should be an integral part of the development process and cannot be considered without it”.

In spite of the active discussion of the concept of sustainable development and a number of accepted official documents, a unity in the definition and interpretation of the notion is still absent. Already in the early work [23] more than 60 definitions of sustainable development given by different authors are cited.

The general transformations of the environmental scene are shown in Table 1 [26, p.84].

Table 1 **Evolution of the views on SD in 1970 - 2000s**

Environmental policies	**1970-1980s**	**2010**
Iconic policy instrument	Command and control	Collaborative and market-based instruments
Key group relied upon	Government	Government and stakeholders
Dominant mode of action	Work with industry, mostly through technology	Work with industry and consumers, through technology, economy, finance
Knowledge about the environment	Superficial, or limited to specialists	Extensive, diffused in many realms of society
Discourse on green issues	View of green as important (before 1973) and then as rather marginal	Acknowledgment of the seriousness of some problems: a trend of "going green" and resulting business opportunities
Social issues	Superficial or neglected concerns	Concerns for environmental justice and the influence of environmental degradation on poverty

Based on the initial notion of SD of the society it is possible to say about SD of any active system [20]. According to the existing approach, the main role in SD is played by the notion of homeostasis. It means that a human activity should provide sufficiently high values of indicators of the social-economic development, and in the same time sustain an environmental equilibrium. Formally, all indicators of the state of a regional socio-ecological-economic system must belong to a given range that can be written as the condition

$$\forall t = 1,...,T \quad x^t \in X^* . \tag{8}$$

A stronger formulation is also possible when the condition of homeostasis is treated as an asymptotic approximation of the values of indicators to their ideal values [20].

It seems that the main problem of the practical implementation of the concept of SD consists in the absence of interested and plenipotentiary agents of the implementation. The criteria used by acting politicians not always coincide with the conditions of homeostasis of the territories governed by them. That's why the concepts of transition to SD accepted by many countries and regions remain only as declarations in a great part. It should be noticed in the same time that from an objective point of view all politicians who wish to enlist the support of the population and secure the power for a long time, should be interested in the conditions of homeostasis.

It concerns also the owners of companies thinking about conservation of their family business for many generations. On the level of a firm the considered problem is tightly connected with strategic delegation (see [24]), i.e. sharing of the powers between owners, top-managers, and managers of lower levels. As for territories, the problem is in the distribution of resources and powers between federal, regional, and local agents of power and control (the problem of federalism).

It is especially important that the values of SD be shared by active agents of the lower level whose activity has a direct impact to the state of a controlled system. That's why the concept of homeostasis, playing a key role in the traditional approach to SD, should necessarily be complemented by a requirement of system compatibility [2,7]. It means that interests of the

active agents should be considered by the Center in a maximal degree for the achievement of the Center's purposes.

For a quantitative measurement of the system compatibility based on the model (1) - (7) it is expedient to use an index of system compatibility in the form

$$SCI = J_0^{\max} - J_0^*, \tag{9}$$

where

$$J_0^{\max} = \max_{\substack{r\in R\\ s\in S}} \max_{\substack{p\in P(r)\\ q\in Q(s)}} \max_{u\in U(p,q)} J_0(r,s,p,q,u,x); \tag{10}$$

$$J_0^* = \max_{\substack{r\in R\\ s\in S}} \min_{p,q\in NE(r,s)} \min_{u\in NE(p,q)} J_0(r,s,p,q,u,x). \tag{11}$$

The substrahend in the formula (9) gives a guaranteed payoff of the Center in the worst Nash equilibrium in the game of agents regulated by her, and the minuend shows her payoff in the case of complete cooperation of the agents with the Center (globally maximal value of the payoff in the team solution). The value $SCI = 0$ indicates the complete (ideal) system compatibility. This approach generalizes an idea of the price of anarchy proposed for network games [22], and its development in other works [4]. An indicator of the ideal compatibility is proposed in [8] as well.

Given (9) a requirement of the system compatibility is expressed by the condition

$$SCI \le SCI^*, \tag{12}$$

where SCI^* is an expert threshold value of the system compatibility index. The condition (12) may be used additionally after the solution of the game (1)-(7) with phase constraints (8) to check whether the system compatibility holds.

The relations (1)-(12) determine a holistic formal description of the problem of sustainable management in any active system [19].

On the regional level the problem of coordination of interests has the following specific features. First, a regional administration which should be a leader of SD, in a higher degree is interested in the approval from the federal center that estimates the regional activity by other criteria. Second, the principal control levers, both legislative and economic, are also situated in the federal level. Third, the municipal districts that should provide a practical implementation of the requirements of homeostasis, have not enough resources for it.

Thus, the problem of coordination of interests on the regional level has a special importance and deserves a detailed investigation by means of systems analysis, mathematical modeling, and information technologies.

4. CONTROL MECHANISMS

In the case of a low system compatibility ($SCI >> 0$) the Center should use special control mechanisms to provide it. To develop a classification of the control mechanisms three attributes characterizing the Center's strategy can be used:

1) absence/presence of a feedback of the Center's strategy on the state of a controlled dynamic system (CDS). This attribute has two basic values: open-loop strategies (OL) which depend only on the instant of time t, and closed-loop strategies (CL) which depend on the game position $(t, x(t))$ [3];

2) absence/presence of a feedback of the Center's strategy on the agents' strategies. In the first case we deal with Stackelberg games (ST), and games of the second type we propose to call Germeier games (GER), or incentive Stackelberg games [9-11];

3) methods of hierarchical control. Here we differentiate compulsion, when the leader influences the followers' sets of feasible strategies, and impulsion, when she influences the followers' payoff functionals [20]. So, in the case of compulsion the leader chooses s^t in the

higher control level and q^t in the middle control level while impulsion means the respective choice of r^t and p^t.

A classification of the control mechanisms on example of the Russian traffic rules (RTR) is given in Table 2. Here an illustrative active system is considered. In this system the Center is the federal state that establishes RTR and the penalties for their violation exposed in the Administrative Codex (AC) and the Criminal Codex (CC); an active agent is a driver and his vehicle; a controlled object is a road and its environment. The respective clauses of the legislative documents are presented in brackets. Administrative control mechanisms explicitly forbid some driver's actions, and economic ones charge penalties for their violation.

From the mathematical point of view, a type of the Center's control mechanism determines an information structure of the difference game (1) - (7). For example, A/ST/CL is a Stackelberg game in closed-loop strategies in which the Center restricts the agents' sets of feasible strategies. The solutions of respective differential games are defined in [20].

Table 2 **Classification of the control mechanisms on example of the Russian traffic rules**

	ST/OL	ST/CL	GER/OL	GER/CL
Administrative mechanisms	It is forbidden to injure or pollute a road cover (1.5 RTR)	In populated areas it is allowed to drive a vehicle with the speed not more than 60 km/h (10.2 RTR)	It is forbidden to drive a vehicle with a working brake system disrepair (2.3.1 RTR)	It is forbidden to drive a vehicle with not burning (absent) head-lights and back marker lights in the dark period (2.3.1 RTR)
Economic mechanisms	Absence of an insurance policy - 800 roubles (12.37 p.2 AC)	Exceeding of the allowed speed: more than 20, but not more than 40 km/h - 500 r. (12.9 p.2 AC); more than 40, but not more than 60 km/h - 1000-1500 r. (12.9 p.3 AC)	Driving a vehicle by a driver in the state of intoxication - 30000 r. (12.8 p.3 AC), repeatedly 200000 - 300000 r. (CC 264)	Non-compliance of the requirement to stop before the stop line: first time - 800 r. (12.12. p.2 AC); repeatedly - 5000 r. (12.12 p.3 AC)

A very important role in the practical implementation of the control mechanisms is played by the monitoring system that provides to the control agents information about the state of the object and therefore ensures a feedback. A general form of the monitoring in a simplified hierarchically controlled dynamic system with one agent is shown in Fig. 2 [20].

Here x_{SL} is a Center's information about the state of CDS; x_{FSL} is a Center's information about the impact of the agent on CDS; x_{FL} is a Center's information about the agent's state; x_{SF} is the agent's information about the state of CDS.

In conformity with a regional active system the presented model can be used both on the level RA - MD, and on the level MD - LA (see Fig. 1). In the former case CDS is treated as a socio-ecological-economic system of the respective MD, and in the latter one as a part of that system controlled by the given LA. A union of those systems forms a regional monitoring system, the visual presentation of which is huge. The information is collected by means of official statistics which can be complemented by special sample audits and expert estimates.

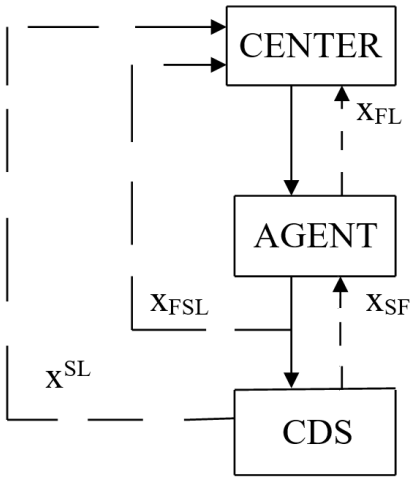

Fig.2 Monitoring in a hierarchically controlled dynamic system (HCDS)

5. HIERARCHICAL STRUCTURE OF THE MODEL SYSTEM

The regional level has an intermediate position in the structure of state control (Fig. 3).

Here FC corresponds to RA in Fig. 1, RA_i corresponds to MD_i, and MD_{ij} corresponds to LA_{ij}. The dynamics of a regional socio-ecological-economic system is described by a system of non-linear equations (7), and the interests of agents and their possibilities by the relations (1)-(6).

The respective system connections are presented in Table 3.

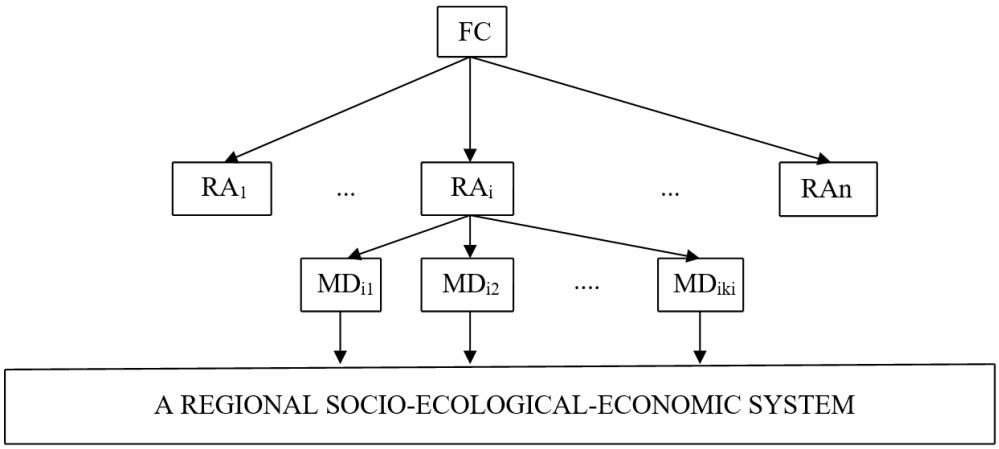

Fig.3 Hierarchical Structure of the Model System

Table 3 Connections of the regional control level with federal and local levels

	Inputs	Outputs
FC	Federal laws and instructions Informal directions of the federal power Federal budget financing	Tax revenues to the federal budget Information about the state of the socio-ecological-economic system of a region (indicators of the official statistics)
MD	Tax revenues to the regional budget Information about the state of the socio-ecological-economic system of a region by separate MD	Regional laws and instructions Informal directions of the regional administration Regional financing of the local budgets

A practical implementation of the methodology of sustainable management on the regional level requires a regional information-analytical system, the structure of which is shown in Fig.4.

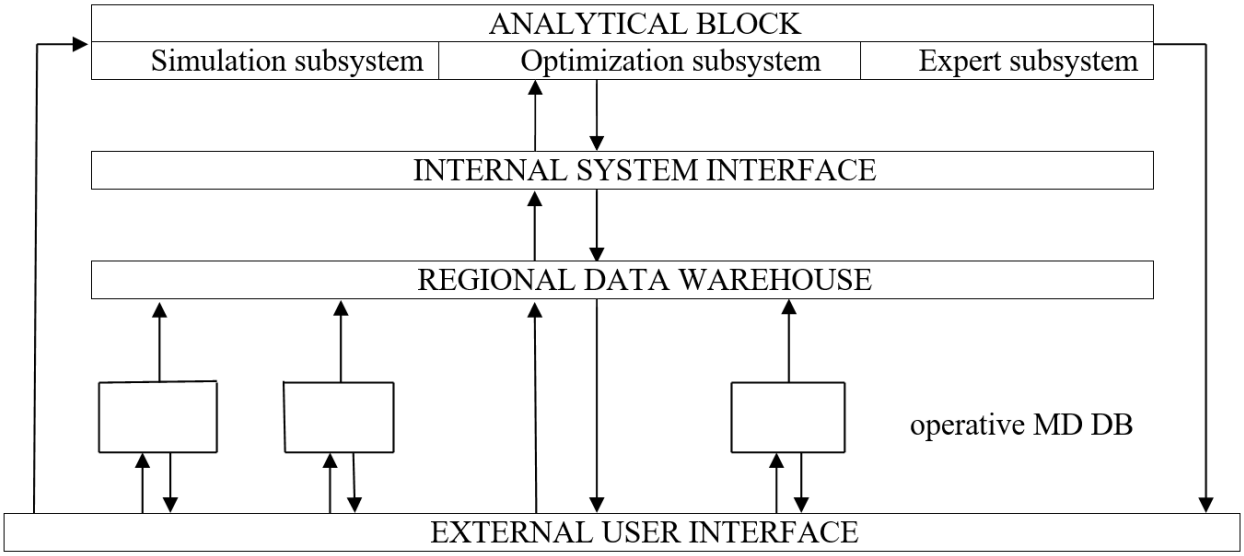

Fig. 4 Structure of the regional information-analytical sustainable management support system

Here the optimization subsystem includes mathematical models like the game (1)-(7) while the simulation subsystem allows for their solution. The expert subsystem additionally uses an expert knowledge.

6. CONCLUSION

The system approach plays an important methodological role in the solution of difficult complex interdisciplinary problems of the regional sustainable management. A specific character of the regional level of control consists in its intermediate, dual nature. From one side, a regional administration plays a role of the Center relating to the municipal formations within the region, from the other side it is itself an active agent in the interrelation of the regions with their federal center. In spite of it, RA can and must be an agent of the sustainable management. It follows from the hierarchical nature of sustainable development, the achievement of which on the global level is provided by the totality of efforts of all agents on the lower control levels. This fact determines a necessity of the delegation of an essential volume of administrative and economic powers on the RA level. It should be noticed that the need of solution of the problems of sustainable management is not always realized by the agent, and the mission of science and public opinion formed by the science is of great importance here.

A key role in the solution of the sustainable management problems is played by the coordination of interests of the Center as the subject of sustainable development and the active agents who implement it directly. The requirements of homeostasis will not be satisfied by themselves unless specific agents be interested in it. In the great majority of cases the interests of active agents contain only maximization of their economic payoff in short periods of time. That's why it is necessary to design and implement administrative and economic control mechanisms that incorporate the conditions of homeostasis in the agents' payoff functions and feasible sets of strategies.

Later it is planned to analyze horizontal connections in a regional active system that leads to the cooperative games as conflict control models and investigation of the time consistency of their solutions.

It is supposed particularly to apply the described methodology for decision support of the sustainable development of the Rostov region (Russian Federation).

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