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Systems Methodology And Model Tools For Territorial Sustainable Management

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Abstract: No doubt, this research is topical in the context of new challenges arising for different Russian territories due to intensive globalization processes and jumping trends of world economy. These challenges are stressing the need for an innovation-oriented improvement of territorial management systems in accordance with the realities of cyclicity and the conditions of fundamental resources to stimulate positive social and economic dynamics. The goal of the present paper is to justify a methodology and real ways of territorial sustainable development management system design based on efficient model tools and information technologies. For achieving this goal, several problems have been solved such as the dynamic modeling of a territorial social-ecological-economic system and coordination of public (social) and private interests, the elaboration of reasonable management approaches to territorial development risks, as well as the design of an appropriate methodology to integrate the suggested models and approaches within an information-analytical sustainable management support system. The novelty of an original scientific outlook introduced by the authors consists in the elaboration of a well-grounded systems methodology and model tools for territorial sustainable management and also in the justification and verification of qualitative and quantitative approaches to the analysis of development risks and their integration into a unified territorial sustainable management system.The methodology and model tools presented below can be used for enhancing the scientific and practical components of a territorial sustainable management system under dynamic and conflicting external conditions.

Keywords: homeostasis, simulation, econometric methods, territorial sustainable development, system compatibility, welfare capital reproduction, risk management, sustainable development management.

1. INTRODUCTION

This paper extends the results of the earlier publication [22], in which a systems approach to regional sustainable management was described. The methodology suggested below integrates territorial social-ecological-economic system simulation, econometric assessment of its innovative sustainable development potential and coordination of social and private interests into a unified territorial sustainable management system.

A conceptual platform of the original modeling approach is the evolutionary-cyclic paradigm of subject-object relations in the “welfare capital reproduction — territorial innovative sustainable development” system. In accordance with this paradigm, the network reality makes it necessary to elaborate a collectively compatible management strategy relying on the coordination and balancing of personalized interests for different subjects of innovative sustainable development, mutual benefit, trust, and public-private partnership (Fig. 1.1). As shown in [12], an alternative way to implement the coordination principle is to identify an ideal hierarchical chain of interests of economic subjects, associating it with an adequate incentive policy.

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The models that produce analysis tools for analyzing the object in strategic management systems – the trajectories of territorial sustainable development must have the following major features [14]:

- nonlinearity of the model and orientation for a long time interval;
- taking into account the impact of economic activity on natural processes and the state of the social sphere;
- •inclusion of feedback flows between the ecological, social and economic subsystems of the territorial system;
- not only material or monetary valued services of social and natural systems should be included, but also the rest, "intangible", such as favorable conditions for production and residence;
- taking into account the concern for future generations, which can be expressed in restrictions on natural capital, social and economic capital to ensure an even distribution of social, natural and economic potential between successive generations;
- the possibility of describing qualitative structural changes;
- reflection of the limited availability of resources, including the assimilation potential of the environment.

There are two methods to add the sustainable development conditions of dynamic trajectories in the model as follows:

– establishing temporal constraints for welfare level (at any time, welfare level must exceed a given threshold or welfare dynamics must have a uniform nondecreasing character);

– establishing physical constraints for resources (stocks and flows).

An important class of dynamic models of territorial economic development is formed by the so-called Computable General Equilibrium (CGE) models, see [6, 23]. These models have good microeconomic grounds and also provide a complete description for the sectoral structure of economy and mutual effects of different economic sectors. However, the CGE models suffer from a major drawback: in fact, they are mostly economic-mathematical models with a superficial treatment of ecological and social aspects and all the phenomena connected with dynamics and uncertainty. Besides, their identification is also a complex procedure.

The modeling framework of regional social-ecological-economic development using optimal control methods was suggested by Gurman et al. [19]. Regional development problems are studied by analytical methods in combination with simulation modeling.

In the monograph [8], the well-known Solow growth model [17] was modified taking into account the spatial aspect and environmental pollution. A detailed survey of the models and decision support systems for sustainable management was given in [21]; various economic growth models were described in [5].

The concept of homeostasis plays a key role for sustainable management. It can be formalized using Aubin's viability theory [4]. In particular, the so-called capture-viability kernels are of assistance here. The capture-viability kernel of a closed set K with closed target X under a set-valued dynamic F is the set of all initial states from which there exists at least one solution, remaining in K and reaching X at a given finite time horizon [7].

In the earlier works, the authors of this paper introduced an original complex approach to model the processes of accumulation and productive use of tangible and intangible assets – resources for territorial sustainable development as well as to model the coordination processes of social and private interests for resource allocation in hierarchical control systems. An implementation of this approach allowed to establish the system compatibility conditions for different control problem setups; to justify a control strategy design methodology for balancing the social and economic interests of national, regional (local) and global economic agents in the reproduction and utilization of welfare resources for the sustainable development of a regional system; to propose system coordination mechanisms and study their properties; to initiate application of the coordination models of social and private interests to real regional management problems, more specifically, to the design of administrative and economic coordination mechanisms (engines) for the interests of territorial subjects [3, 9, 10, 12].

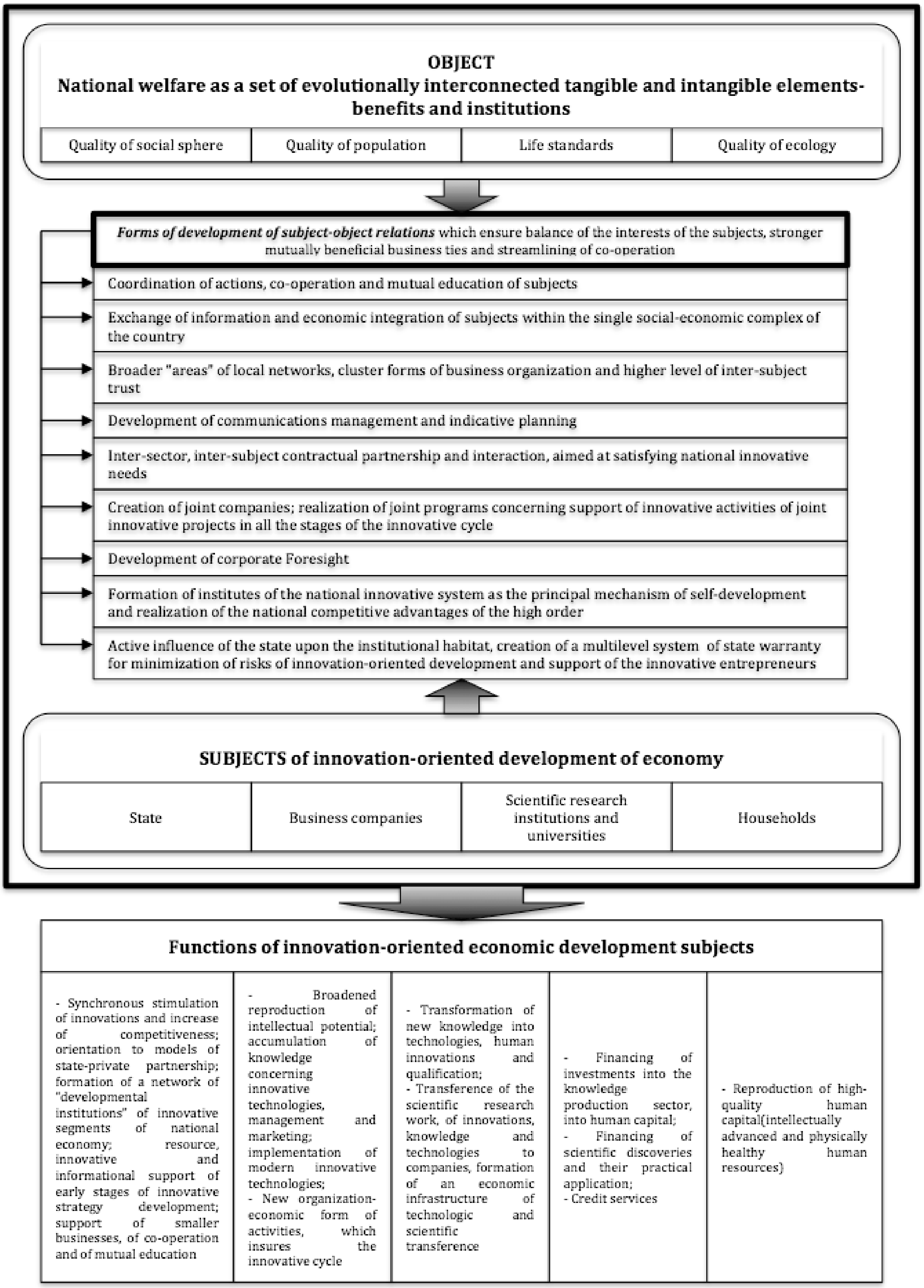

Fig. 1.1 The conceptual model of subject-object relations [12]

The problems of rationalizing the mutual influence of the subjects of environmental and economic relations within certain territorial boundaries have been repeatedly considered by the authors [1, 2, 16, 20]. In accordance with the concept of sustainable development, which emphasizes the vital importance of current needs satisfaction taking into account the interests of future generations, risk is a significant quantitative indicator of balanced decisions. For these purposes, a control algorithm for the ecological and economic risks of urbanized territories development was suggested in [20]. For managing the social and economic risks of territorial development, earlier the authors introduced the economic and mathematical models based on specification of the latent mutual influences of welfare capital accumulation and the pace of innovative sustainable development of a territory [15] and also on the use of an econometrically identified relationship between population health and the variations of environmental parameters as a primary functional characteristic of social and economic damage [2].

An implementation of the sustainable management methodology at the regional level requires a regional information-analytical support system [22] as a basic technological tool of management. This system has a hierarchical structure, and the subsystems at the lower levels of management can be used independently.

The remainder of this paper is organized as follows. In Section 2, the structure of the dynamic model of a regional social-ecological-economic system, its main variables and processes as well as operation of this model are presented. Section 3 is dedicated to the coordination mechanisms (engines) of interests in the public-private partnership and their use in the model. Next, in Section 4, risk management methods at territorial level are characterized. Section 5 is to synthesize the above-mentioned methods and models for territorial sustainable management system design. Finally, in Section 6, some concluding remarks are given.

2. DYNAMIC MODEL OF REGIONAL SOCIAL-ECOLOGICAL-ECONOMIC SYSTEM

The model of a regional social-ecological-economic system has the form

$$Y_i(t) = A_i(t)K_i^{\alpha_i}(t)(R_iL_i)^{1-\alpha_i}(t)\,; \tag{2.1}$$

$$I_i(t) = s_i(t)Y_i(t)\,; \tag{2.2}$$

$$C_i(t) = [1 - s_i(t)]Y_i(t)\,; \tag{2.3}$$

$$R_i(t+1) = (1+\eta_i)R_i(t)\,; \tag{2.4}$$

$$K_i(t+1) = (1-\mu_i)K_i(t) + \sum_{j=0}^{n} \kappa_{ji}(t)I_j(t)\,; \tag{2.5}$$

$$L_i(t+1) = (1+b_i - m_i)L_i(t)\,; \tag{2.6}$$

$$P_i^a(t) = [1 - c_i^a v_i^a(t)][B_{Ki}^a K_i(t) + B_{Li}^a L_i(t)]\,; \tag{2.7}$$

$$P_i^w(t) = [1 - c_i^w v_i^w(t)][B_{Ki}^w K_i(t) + B_{Li}^w L_i(t)]\,; \tag{2.8}$$

$$K_i(0) = K_i^0; \quad L_i(0) = L_i^0; \quad R_i(0) = R_i^0; \tag{2.9}$$

$$\sum_{j=0}^{n} \kappa_{ij}(t) + v_i^a(t) + v_i^w(t) = 1;\ 0 \le s_i(t) \le 1;\ \kappa_{ij} \ge 0;\ v_i^a(t) \ge 0;\ v_i^w(t) \ge 0; \quad (2.10)$$

$$i, j = 0,1,...,n;\ t = 0,1,2,...$$

As a rule, index i denotes a municipal unit within a region (e.g., within a federal subject). It can be associated with an enterprise but, in this case, productive and economic activity should be described by the firm model. In the sequel, it will be referred to as the agent's index. The model has discrete times t = 0, 1, 2, ... with a step of 1 year. The model also includes other variables and parameters as follows.

$Y_i(t)$ as the final output of agent i in year t (in financial terms); $K_i(t)$ as the agent's basic production assets (capital) in year t; $L_i(t)$ as the agent's labor resources in year t; $R_i(t)$ as the efficiency of the agent's labor resources in year t; $A_i(t)$ as the influence function of the agent's innovative activity on the final output in year t; α_i as the parameter of the agent's Cobb-Douglas production function; $I_i(t)$ as the agent's production investments in year t; $C_i(t)$ as the agent's nonproduction consumption in year t; $s_i(t)$ as the share of the agent's production investments in its final output in year t; η_i as the efficiency growth parameter of the agent's labor resources; μ_i as the depreciation factor of the agent's basic assets; $\kappa_{ij}(t)$ as the share of the investments of agent i in the activity of agent j (the cooperation coefficient of these agents); here index j=0 describes an external agent for the whole system; b_i and m_i as the reproduction and retirement coefficients of the agent's labor resources, respectively; $P_i^a(t)$ and $P_i^w(t)$ as the agent's pollutant emissions into air and water in year t, respectively; $v_i^a(t)$ and $v_i^w(t)$ as the agent's allocations to prevent air and water pollution in year t, respectively; c_i^a and c_i^w as the efficiency coefficients of these allocations; B_{Ki}^a and B_{Ki}^w as the specific rates of industrial pollution into air and water, respectively; B_{Li}^a and B_{Li}^w as the specific rates of human pollution (labor resources) into air and water, respectively; finally, K_i^0, L_i^0, and R_i^0 as given initial values of the model variables.

Therefore, the agent's state vector is

$$X_i(t) = (Y_i(t), I_i(t), C_i(t), K_i(t), L_i(t), R_i(t), P_i^a(t), P_i^w(t));$$

the control vector is

$$U_i(t) = (s_i(t), v_i^a(t), v_i^w(t), \{\kappa_{ij}(t)\}_{j=0}^{n});$$

and the parameter vector is

$$Z_i = (\alpha_i, \eta_i, b_i, m_i, \mu_i, c_i^a, c_i^w, B_{Ki}^a, B_{Ki}^w, B_{Li}^a, B_{Li}^w).$$

The whole system can be written as

$$X(t) = (X_1(t),..., X_n(t)), U(t) = (U_1(t),..., U_n(t)), Z = (Z_1,..., Z_n). \quad (2.11)$$

The innovative activity function $A_i(t)$ is considered separately [17].

With these notations, model (2.1)-(2.10) takes the form

$$X_i(t+1) = X_i(t) + f_i(X(t), U(t), Z); \quad (2.12)$$

$$U_i(t) \in \Xi_i \,; \tag{2.13}$$

$$X_i(0) = X_i^0,\ i = 1,...,n,\ t = 0,1,2,... \tag{2.14}$$

The structure of model (2.1)-(2.10) has three blocks, namely, economy (2.1)-(2.5), demography (2.6), and ecology (2.7)-(2.8). The transboundary interaction of municipal units is described using the control variables $\kappa_{ij}(t)$. Also note that innovative activity can be modeled by through model parameters instead of the function $A_i(t)$. More specifically, the parameter η_i characterizes labor productivity; the parameter μ_i - resource-saving technologies; the parameters c_i^a, c_i^w, B_{Ki}^a, and B_{Ki}^w - nature protection technologies; the parameter b_i - demographic policy; the parameter m_i - innovations in public health; the parameters B_{Li}^a and B_{Li}^w - the ecological consciousness of population.

To identify the parameters of model (2.1)-(2.10), it is necessary to define the numerical values of all elements of the vector Z. In a rough approximation, consider just two values of each parameter $z_i \in \{z_i^l, z_i^h\}$, where the second value corresponds to higher technological level. For further refinement, the parameter values can be taken from a discrete set $z_i \in \{z_i^1,...,z_i^{k_i}\}$.

The sustainable development conditions (homeostasis) of a regional social-ecological-economic system in model (2.1)-(2.10) can be defined by

$$Y_i(t) \ge Y_i^{\min};\ P_i^a(t) \le P_i^{a\max};\ P_i^w(t) \le P_i^{w\max};\quad i = 1,...,n;\quad t = 1,2,... \tag{2.15}$$

The first condition in (2.15) states the requirements to the agent's economic growth; the other, the maximum permissible emissions of pollutants into the environment. These conditions can be interpreted as the goal of control.

The agent's objective function in model (2.1)-(2.10) takes the natural form

$$J_i = \int_0^\infty e^{-\rho t} c_i(t)\,dt \to \max\,, \tag{2.16}$$

where $c_i(t) = C_i(t)/L_i(t)$ is the current specific consumption of agent i; ρ denotes the discount factor. Since the model has discrete time and will be studied using simulation, the objective function (2.16) should be replaced by its discrete analog

$$\bar{J}_i = \sum_{t=0}^{T} e^{-\rho t} c_i(t) \to \max\,. \tag{2.17}$$

Simulation scenarios for model (2.1)-(2.10) include some trajectories of control variables of vector (2.13). Here it seems reasonable to perform optimization by solving a certain control problem. A classification of such problems is given in Table 2.1.

Table 2.1. Control problem setups within the model

	Decentralized	Centralized
Optimal control	Optimization performed by each agent independently (optimal control problem)	Global optimization performed by an external agent (optimal control problem)
Conflict control	Conflict resolution with interaction of agents (differential normal form game)	Conflict resolution with the optimal response of agents (hierarchical differential normal form game)

The decentralized control problem setups treat all agents equally. If the situation is considered from the viewpoint of a single agent, then the optimal control problem with the objective function (2.16) or (2.17) subject to constraints (2.1)-(2.10) arises accordingly. Attempts to study the interaction of several or all agents lead to differential normal form games, with Nash equilibrium as a standard solution concept.

On the other hand, the centralized setups interpret one of the agents as a Principal responsible for the system goals. In practice, the Principal's role can be played by federal government, regional administration or even a special coordination body for the activity of several agents or the whole set of agents established on voluntary basis (e.g., coordinating committee, project directorate, etc.). As before, the Principal may perform global optimization or take into account the agents' response to its actions. In the latter case, hierarchical differential games are immediate, with Stackelberg equilibrium or the Germeier principle of guaranteed result as possible solution concepts, see [22].

3. COORDINATION MODELS FOR SOCIAL AND PRIVATE INTERESTS

In [9] and other publications, the authors constructed and analyzed coordination models for social and private interests (SPICE-models). The suggested approach consists in the following.

1. Consider *n* agents, each distributing his/her/its resource between private activity and the production of some social good.

2. In turn, the produced social good is allocated among the agents in given or controlled shares. This defines the distinction between social good and pure public good.

3. The payoff function of each agent includes two terms, the first reflecting his/her/its income from private activity while the second his/her/its share in social good.

4. The concept of system compatibility is defined to characterize in quantitative terms the degree of concordance of social and private interests in a corresponding organizational and technical system. Perfect system compatibility is achieved if the aggregate of the individually optimal strategies of all agents (dominant strategies or Nash equilibria) maximizes the social welfare function of the system.

5. In real economic organizations, perfect system compatibility is a rare thing due to the individualism of agents. Therefore, a special agent (Principal) should be assigned to represent the social interests (social welfare maximization) and ensure system compatibility.

6. The Principal controls the agents in two ways. First, he/she/it may restrict the share of resource allocated by the agents to their private activity (administrative mechanisms, compulsion). Second, the Principal may determine the shares of all agents in social good depending on their actions (economic mechanisms, impulsion). Speaking mathematically, these control mechanisms are formalized as the Germeier games Γ_1 and Γ_2 (the Stackelberg and inverse Stackelberg games, respectively).

An implementation of this approach yielded the following.

– system compatibility conditions were obtained for different control problem setups. The major result is that, without external control, perfect system compatibility can be achieved only by partitioning the set of all agents into pure individualists (distributing all their resources to private activity) and pure collectivists (distributing all their resources to social good production). In addition, the SPICE-models were compared in the cases of independent equal agents (Nash equilibrium), hierarchically organized agents (Stackelberg equilibrium), and full cooperation of agents (the Pareto maximal value of the total payoff function). It was demonstrated that equality is preferable to hierarchy in the sense of social welfare maximization;

– system coordination mechanisms were suggested and their properties were studied. A mechanism is system compatible if it ensures perfect system compatibility. Here empirical and theoretical approaches are possible as follows. In accordance with the former, it is necessary to analyze the mechanisms widely used in practice (e.g., proportional allocation). For instance, it was shown that the proportional allocation mechanism is system compatible only under the linear social income function. The theoretical approach suggests to construct the control mechanism as the ε-optimal solution of the Germeier game Γ_2 (the inverse Stackelberg game). The economic mechanism based on the Germeier game Γ_2 is system compatible if social and private incomes represent power functions with an exponential less than 1;

– an application of the SPICE-models to real regional management problems was also initiated; more specifically, the administrative and economic coordination mechanisms for the interests of regional subjects were explored. A control problem was studied in which two or more neighbor subjects distribute their funds between the development of their own and common (transboundary) territory or between private activity and a joint project. A special control authority (Principal) was introduced for activity coordination. The economic mechanism was considered in two modifications (financial participation in the development of a transboundary territory via income share control, and resource allocation). A detailed analysis of these mechanisms was carried out and their organizational and economic interpretation for specific regional management problems was given (public-private partnership, Euroregions), see [3,10].

The static SPICE-model has the form

$$g_i(u_1,...,u_n) = p_i(r_i - u_i) + s_i c(u_1,...,u_n) \to \max \tag{3.1}$$

$$0 \le u_i \le r_i,\ r_i \ge 0,\ s_i \ge 0,\ \sum_{j=1}^{n} s_j = \begin{cases} 1, \exists i : s_i > 0, \\ 0, \forall i\ s_i = 0, \end{cases} \quad i = 1,...,n. \tag{3.2}$$

The notations are as follows: $N = \{1,...,n\}$ as a finite set of active agents; $U_i = [0, r_i]$ as the set of admissible strategies of agent i; r_i as an amount of resource available to agent i; $g_i(u_1,...,u_n)$ as the payoff function of agent i; $g_i : U \to R, U = U_1 \times ... \times U_n$; $p_i(r_i - u_i)$ as the private interest function of agent i; $c(u_1,...,u_n)$ as a social income function; s_i as the share of social income allocated to agent i; $s_i c(u_1,...,u_n)$ as the social component of the payoff function of agent i. The following assumptions are applied to this model: c is a monotonically increasing function in all u_i such that $c(0,...,0) = 0$; p_i are monotonically increasing functions in $(r_i - u_i)$ and monotonically decreasing in u_i such that $p_i(0) = 0$ (for $u_i = r_i$); $s_i > 0$ if $u_i > 0$.

Construct the social welfare function

$$g(u_1,...,u_n) = \sum_{j=1}^{n} g_j(u_1,...,u_n) = \sum_{j=1}^{n} p_j(r_j - u_j) + c(u_1,...,u_n). \tag{3.3}$$

Denote by $NE = \{u_{(1)}^{NE},...,u_{(k)}^{NE}\}$ the set of Nash equilibria in game (3.1)–(3.2). Also let $g_{\min}^{NE} = \min\{ g(u_{(1)}^{NE}),...,g(u_{(k)}^{NE})\}$ and $g_{\max} = \max_{u \in U} g(u) = g(u^{\max})$. Then the price of anarchy in model (3.1)–(3.2) (an indicator of system compatibility) is

$$PA = \frac{g_{\min}^{NE}}{g_{\max}}. \tag{3.4}$$

Obviously, $PA \le 1$. If PA is close to 1, then the equilibria have high efficiency and there is little need for system coordination in model (3.1)–(3.2) (for $PA = 1$, even no need at all). The need for system coordination grows as PA is decreased.

As a matter of fact, in itself the condition of system compatibility ($PA = 1$) holds merely in some cases. To ensure this condition, it seems reasonable to use control mechanisms [18].

Suppose that maximization of the social welfare function (3.3) is the goal of a certain subject (Principal, Leader, or Mechanism Designer) that may influence the sets of admissible controls and/or payoff functions of agents to achieve it. Denote by $U_i = U_i(q_i)$ the first possibility and by $g_i = g_i(s_i, u_i)$ the second. Then the following control mechanisms are immediate, see Table 3.1.

The Principal may influence the sets of admissible controls of agents (administrative mechanism) or their payoff functions (economic mechanism). Both types of influence are based on the Germeier games Γ_1 and Γ_2 (the Stackelberg and inverse Stackelberg games, respectively). Therefore, there are four types of control mechanisms illustrated in Table 3.1.

Table 3.1. Control mechanisms

Principal influences:	based on Germeier games Γ_1 (Stackelberg games)	based on Germeier games Γ_2 (inverse Stackelberg games)
the sets of admissible controls of agents	compulsion, or administrative mechanism, without feedback $q_i = const$	compulsion, or administrative mechanism, with feedback $q_i = q_i(u)$
the payoff functions of agents	impulsion, or economic mechanism, without feedback $s_i = const$	impulsion, or economic mechanism, with feedback $s_i = s_i(u)$

The economic control mechanisms in the SPICE-model (3.1)-(3.2) are implemented as the result of choosing values s_i by the Principal. For the administrative mechanisms, an additional assumption is that the Principal may restrict the admissible controls of agents, i.e.

$$\tilde{q}_i \le u_i \le \bar{q}_i, \quad i \in N . \tag{3.5}$$

In the continuous-time setup with finite horizon, the agent's objective function (2.16) takes the form

$$J_i = \int_0^T e^{-\rho t}[c_i(t) + \sigma_i(t) F\left(\sum_{i=1}^{n}\sum_{j\neq i}\kappa_{ij} I_i(t)\right)]dt \to \max ; \tag{3.6}$$

in the discrete-time setup with the same horizon,

$$\bar{J}_i = \sum_{t=0}^{T} e^{-\rho t}[c_i(t) + \sigma_i(t) F\left(\sum_{i=1}^{n}\sum_{j\neq i}\kappa_{ij} I_i(t)\right)] \to \max . \tag{3.7}$$

In both cases, F denotes the social welfare function while ρ is the discount factor.

Note that, by choosing a control trajectory, the agent defines the logical chain

$$\kappa_{ii} \to K_i \to Y_i \to C_i \to c_i$$

in model (2.1)–(2.10), which corresponds to the choice of allocations to private activity in the static SPICE-model. Therefore, the first term in the integrand (summand) describes the agent's income from private activity; the second, his/her/its consumption of social good depending on the variable $\sigma_i(t)$.

The administrative and economic mechanisms can be described for the dynamic SPICE-model with a Principal. Using administrative mechanisms, the Principal explicitly restricts the "egoism" of agents by imposing the conditions

$$\kappa_{ii}(t) \le \kappa_{ii}^{\max}(t)\,. \tag{3.8}$$

Note that conditions (3.8) can be the result of a voluntary agreement of the agents. If they are established by the Principal, then his/her/its objective function also includes administrative control cost.

Economic mechanisms may have a share-based motivation of the agents, i.e.

$$\sigma_i(t) = \sigma_i(\kappa_{ii}(t))\,, \tag{3.9}$$

or a resource allocation among them performed by the Principal.

4. APPROACHES TO RISK FACTORS MANAGEMENT IN TERRITORIAL DEVELOPMENT

Sustainable development is impossible without proper consideration of risks, which have to be identified first. A detailed identification of territorial risks facilitates the objective formalization and modeling of territorial development, yielding adequate assessments for possible consequences of decisions using the integral risk indicator of a territory.

Territorial risk assessment methods are mostly reduced to score calculation in some rating scales for comparing the development levels of different regions. Speaking formally, the existing approaches to territorial risk analysis can be divided into several groups, namely, qualitative analysis, quantitative analysis, combined analysis, and structural analysis.

Qualitative analysis considers the weights of different factors affecting risks. Note that the list and significance of such factors are defined via expertise. Major disadvantages of this approach consist in the subjectivism and qualification of experts. Therefore, qualitative analysis makes sense only in the case of well-defined goals of study and available highly qualified experts, who have rich experience and sufficient familiarity with regional situation.

Quantitative analysis is often performed for most important risk indicators: consideration of all risk factors would dramatically increase the complexity of calculations and further examination. This approach allows constructing a multifactor function for explicit quantitative assessments. There are two standard methods to define regional risk functions as follows.

In accordance with the first method, it is necessary to consider only those factors that yield an objective quantitative characterization for the current state of economical, ecological, and social spheres. Then the territorial risk function takes the form

$$R = f(x_1, x_2, \ldots, x_n) = R(x_i),\ i = 1,...,n. \tag{4.1}$$

The second approach involves a set of numerical qualitative assessments, i.e.

$$R = f(r_1, r_2, \ldots, r_m) = R(r_i),\ i = 1,...,m. \tag{4.2}$$

Econometric modeling is intended for statistical data processing and prediction based on quantitative data arrays of key indicators. However, in real conditions, some significant factors and criteria (e.g., social and ecological situation in a region, or the synergetic effect of several environmental conditions) cannot be assessed in quantitative terms.

In this context, a reasonable solution is to integrate quantitative and qualitative assessment methods, which makes the essence of combined approaches. In this case, the integral risk indicator includes heterogeneous parameters of different risks in numerical form obtained by objective calculations and also by subjective qualitative assessments, which are considered in some scales or criteria.

The identified factors are used for assessing the risks of comparable level. The integral risk indicator R (4.1), (4.2) can be expressed as a linear relationship of the corresponding indicators calculated for the risk of smaller level, i.e.

$$R = f(x_1, x_2, x_3, x_4, x_5) = a_0 + a_1x_1 + a_2x_2 + a_3x_3 + a_4x_4 + a_5x_5. \quad (4.3)$$

Here the notations are as follows: $x_1 = y\,(b_1,\ldots,b_n)$ as the function of environmental and ecological factors; $x_2 = y(c_1,\ldots,c_m)$ as the function of social and demographic factors; $x_3 = y\,(t_1,\ldots,t_k)$ as the function of anthropogenic and production factors; $x_4 = y\,(s_1,\ldots,s_j)$ as the function of financial and economic factors; finally, $x_5 = y\,(h_1,\ldots,h_g)$ as the function of organizational and managerial factors.

These variables characterize the specific levels of corresponding risks; their weights $a_1, \ldots, a_5$ can be defined using qualitative methods in order to consider a basic level of risk formed by the associated factors.

The described approach to territorial risk assessment is rather flexible and convenient for practical implementation. Moreover, it takes into account any changes in structural parameters through the coefficients of the corresponding variables, which gives an objective description for the dynamics of external and internal territorial environment.

The sustainable development programs of different territories can be elaborated using the scenario approach. The number of scenarios under study (alternatives) may vary depending on regional capabilities and resources. As a rule, developmental prospects are considered in view of three alternatives.

The first regional development scenario is the preservation of current social and economic dynamics at the same level. This scenario implies that territorial authorities have no significant interference into social and economic development. Their major concern and funding are focused on maintaining the current volumes of regional gross domestic product (GDP) and the existing sectors of regional industry; economy is developing with orientation towards export of resources and raw materials.

The second territorial development scenario is based on the implementation of continuous investment projects and programs, not only in the sphere of raw materials and semi-products but also in financial and industrial groups, resource processing and resource supply. For this scenario, of crucial importance are the industries and productions oriented towards import substitution, high technologies, finished products and services.

The third territorial development scenario is a logical continuation of the second; it can be implemented in several fields simultaneously through initiation of long-term projects (clusters and growth drivers in industries, high technologies, science and education). In contrast to the productions oriented towards export of resources and raw materials, these projects can be implemented in form of medium and even small enterprises, hence with smaller capital investments and higher rates of return. In the long run, this scenario yields the multiplicative effect owing to the creation of new jobs, the development of adjacent, auxiliary and supporting industries, and natural clustering.

The structural method of territorial risk assessment is based on the expertise of given quantitative parameters—the probability and amount of losses. For the identified risks, this approach involves probabilistic weighting of each development scenario to distribute the final result. The territories with similar level and initial conditions of development can be compared using the integral risk indicator that includes several structural components, namely, (a) the ratio of regional GPD and average GDP for a corresponding group of regions; (b) the ratio of the deviation of regional GDP from average GDP for a corresponding group of regions; (c) the ratio of regional GPD increase rate and average GDP increase rate for a corresponding group of regions. Also this approach is a snap analysis tool for territorial risks in a given group of regions.

Note that the identification of possible risks and the assessment of average territorial risk must agree with the goals of development. For strategic development programming, such procedures allow to find territorial fields and spheres in which risk management is applicable and also reasonable. Consequently, the resulting assessments can be used to refine territorial development programs taking into account risk management methods and tools, territorial risk management system optimization and the prediction of possible consequences of different risk events. In this regard, there exists an obvious need for integrating the risk management subsystem directly into the territorial sustainable management system: otherwise, the whole complex of well-known approaches to risks identification, assessment and management would be fruitless, not gaining an expected effect. Integration must cover all levels of the management system, relying on available administrative resources and the support of all structural elements. This is the only way towards the required efficiency of risks monitoring and optimization with territorial sustainable development. The territorial risk management subsystem is deployed in the following way.

The functions and authorities are divided by management levels, industries, and spheres of development.

Necessary management information is exchanged by the structural units of the system in the online mode.

All necessary resources of each management level and any sphere of activity are immediately mobilized.

The goals of risk management must agree with the goals of territorial development for achieving strategic stability based on the prediction of possible threats and negative factors in the long run. Modern science has produced numerous methods to affect risks. Almost any territorial risk can be managed properly. One may control the probability of risks and also the amount of incurred losses by preventive and protective measures.

Evidence suggests that purely preventive methods do not completely eliminate the negative factors of risk in form of damage and loss conditions. Therefore, it is crucial to plan complex measures towards the abolition and/or absorption of territorial risks at the level of territorial administration, particularly with the engagement of large territorial taxpayers.

The external and global risks that are uncontrollable at the territorial level must be transferred to other management levels or secured using efficient financial mechanisms and tools (e.g., insurance). In this case, possible damage is compensated at necessary level (in terms of time and amount), which makes the territory independent of environmental disasters and anthropogenic accidents. So the strategic goals of territorial development can be achieved.

5. TERRITORIAL SUSTAINABLE DEVELOPMENT MANAGEMENT SYSTEM DESIGN BASED ON MATHEMATICAL MODELS AND INFORMATION TECHNOLOGIES

The territorial sustainable management system covers organizational and political as well as technical aspects. The former concerns the existence of well-defined sustainable development regulations and procedures for territorial (legislative and executive) authorities. In particular, of crucial importance is territorial monitoring that implements feedback in the management system through the acquisition of necessary information about the dynamics of the territorial social-ecological-economic system.

The technical part of the system is represented by the regional information-analytical sustainable development management support system, see Fig. 5.1.

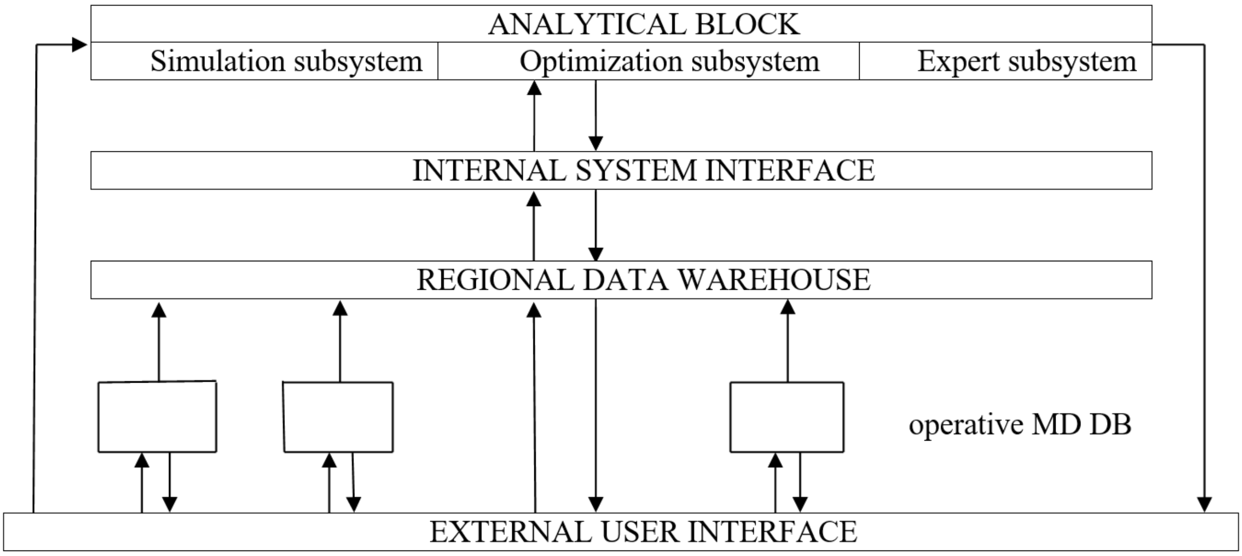

Fig. 5.1 Structure of regional information-analytical sustainable development management support system [22]

This information-analytical system has the client-server architecture. The client part includes the interfaces of models and data; the other blocks belong to the server part.

Operative databases contain information about separate municipalities and large enterprises, which is provided by the monitoring system. For regional management, it is necessary to integrate these (often heterogeneous) data. This problem is solved by importing all available data to the regional data warehouse. The latter also implements other functions such as data refinement, aggregation and security, processing of large data arrays, creation of multilevel metadata directories, execution of user requests, and generation of different reports.

The analytical block consists of three subsystems—simulation, optimization and expert ones. The simulation subsystem implements model (2.1)–(2.10) using data from the regional data warehouse. The optimization subsystem solves the control problems described in Table 3.1 using the dynamic optimality criteria (3.7) subject to constraints (2.1)–(2.10). The expert subsystem is optional: this subsystem allows to consider the control rules used in practice.

The internal system interface is responsible for the interaction of models and data as well as for the implementation of different calculation schemes. A major role is played by the external user interface, which provides a user-friendly environment for common users of the regional information-analytical sustainable management support system.

6. CONCLUSIONS

The intrinsic character of a territorial system as a multilayer polystructural complex of heterogeneous subsystems (economic, social, and ecological) suggests the idea to consider such systems as the subjects of sustainable economic growth and to review the methodological approaches to territorial management. These approaches must be focused on the territorial reproduction of qualitative resources (first of all, human capital) based on proper coordination of interests of different subjects and public-private partnership [11].

Overcoming the shortcomings of modern territorial management and emerging risks in its system is inextricably linked with the enhancement of the effectiveness of the mechanism for managing sustainable development of the territory on the basis of the current model tools and information technologies

No doubt, the methodology and model tools suggested in this paper will accelerate the positive processes of the innovation-oriented transformation of territorial sustainable development management systems. For the new strategic policy and its efficiency, a significant methodological aspect of dynamic systems analysis is the gradual transition to the management processes of functional-spatial territorial development, with highest priority assigned to the formation of innovative clusters and behavioral rules (economic, social, ecological, etc.) for the elements of social environment, see [13].

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REFERENCES

[1] Anopchenko, T.Yu. & Murzin, A.D. (2012). Upravlenie riskami razvitiya urbanizirovannykh territorii [Risk Management in Development of Urbanized Territories]. Rostov-on-Don: Rostov State University of Civil Engineering [in Russian].

[2] Anopchenko, T.Yu. & Murzin, A.D. (2014). Economic-mathematical modeling of social and environmental risks management of projects of urbanized territories development, *Asian Social Science*, 10(15), 249–254.

[3] Anopchenko, T.Yu., Murzin, A.D. & Ougolnitsky, G.A. (2017). Modelirovanie soglasovaniya interesov v zadachakh upravleniya ustoichivym razvitiem territorii [Modeling of interests coordination in regional sustainable management problems], *Ekonomika Prirodopol'zovaniya*, 6, 35-47.

[4] Aubin, J.-P. (1991). *Viability Theory*. Birkhauser: Springer-Verlag.

[5] Barro, R.J. & Sala-i-Martin, X. (2004). *Economic Growth*. Massachusetts: MIT Press.

[6] Bohringer, C. & Loschel, A. (2006). Computable general equilibrium models sustainability impact assessment: Status quo and prospects, *Ecological Economics*, 60 (1), 49-64.

[7] Bonneuil, N. & Boucekkine, R. (2017). Viable Nash equilibria in the problem of common pollution, *Pure and Applied Functional Analysis*, 2(3), 427-440.

[8] Druzhinin, A.G. & Ougolnitsky, G.A. (2013). Ustoichivoe razvitie territorial'nykh sotsial'no-ekonomicheskikh sistem: teoriya i praktika modelirovaniya [Sustainable Development of Regional Social and Economic Systems: Theory and Practice of Modeling]. Moscow, Russia: Vuzovskaya Kniga [in Russian].

[9] Gorbaneva, O.I. & Ougolnitsky, G.A. (2015). System compatibility: Price of anarchy and control mechanisms in the models of concordance of private and public interests, *Advances in Systems Science and Applications*, 15(1), 45-59.

[10] Gorbaneva, O.I., Murzin, A.D. & Ougolnitsky, G.A. (2018). Mekhanizmy soglasovaniya interesov pri upravlenii proektami razvitiya territorii [Mechanisms of interests' coordination in project management of regional development], *Upravlenie Bol'shimi Sistemami*, 71, 61-97.

[11] Lazareva, E. & Karaycheva, O. (2017). Human oriented reframing of the territories of innovative sustainable development system management model, *SGEM 2017 Proceedings*, book 4, vol. 2, 672-670.

[12] Lazareva, E.I. (2013). Features of national welfare innovative potential parametric indication information-analytical tools system in the globalization trends' context, *CEUR Workshop Proceedings 9, Integration, Harmonization and Knowledge Transfer*, 339-351.

[13] Lazareva, E., Anopchenko, T. & Lozovitskaya, D. (2016). Identification of the city welfare economics strategic management innovative model in the global challenges conditions, *SGEM 2016 Proceedings,* book 2, vol. 4, 3–11.

[14] Lazareva, E.I. (2011). Metody modelirovaniya innovatsionno-orientirovannykh ekonomicheskikh strategii ekologoustoychivogo razvitiya [Modeling Methods of Innovation-Oriented Economic Strategies of Ecological Sustainable Development]. Rostov-on-Don: Southern Federal University [in Russian].

[15] Lazareva, E.I. (2013). Osobennosti modelirovaniya traektorii prirashcheniya kapitala natsional'nogo blagosostoyaniya v perspektive ustoichivogo innovatsionno-orientirovannogo razvitiya [Modeling specifics for capital increment trajectories of national welfare capital subject to sustainable innovation-oriented development], *Partnerstvo Tsivilizatsii*, 4, 234-244.

[16] Lazareva, E.I. et al. (2012). Modeli ekologicheskoi orientatsii gosudarstvenno-chastnykh strategii investirovaniya chelovecheskogo kapitala v innovatsionnoi ekonomike [Models of Ecological Orientation of Public-Private Strategies of Human Capital Investment in Innovative Economy]. Rostov-on-Don: Southern Federal University [in Russian].

[17] Lotov, A.V. (1984). Vvedenie v ekonomiko-matematicheskoe modelirovanie [Introduction to Economic-Mathematical Modeling]. Moscow, Russia: Nauka [in Russian].

[18] *Mechanism Design and Management: Mathematical Methods for Smart Organizations*, Ed. by Prof. D. Novikov. New York: Nova Science Publishers, 2013.

[19] Modelirovanie sotsio-ekologo-ekonomicheskoi sistemy regiona [Modeling of Social-Ecological-Economic System of Region], Ed. by Gurman, V.I. & Ryumina, E.V. Moscow, Russia: Nauka (2001).

[20] Murzin, A.D. (2015). Algorithmization of ecologo-economic risk-management in urban areas, *Asian Social Science*, 11(9), 312-319.

[21] Ougolnitsky, G.A. (2015). Sustainable management as a key to sustainable development, in *Sustainable Development: Processes, Challenges and Prospects*, Ed. by D. Reyes. New York: Nova Science Publishers, 87-128.

[22] Ougolnitsky, G.A. (2017). A system approach to the regional sustainable management, *Advances in Systems Science and Applications*, 17(2), 52-62.

[23] Partridge, M.D. & Rickman, D.S. (2010). CGE modeling for regional economic development analysis, *Regional Studies*, 44(10), 1311-1328.