Adv Syst Sci Appl 2019; **03**; 65-79
Published online at http://ijassa.ipu.ru/index.php/ijassa/article/view/705

Sustainable Management Of Universities

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Received February 2, 2019; Revised September 2, 2019; Published October 1, 2019

Abstract: This paper considers the problems of sustainable management of universities. A university as an active system is analyzed, and some sustainable development criteria are suggested and formally described using the integrated assessment approach. A series of sustainable management models at the levels of department, faculty, and university are presented as follows: a dynamic incentive model for the participants of a research project; a static reward distribution model as a game in the characteristic function form; a dynamic working time distribution model for department staff as a differential game in the normal or characteristic function form based on compulsion; dual discrete programming problems with sustainable development constraints for determining an optimal staff structure of a faculty, with assessing the efficiency of different paired unions of departments; dynamic coordination models for the social and private interests of university staff in the course of innovations promotion, as differential games in the normal and characteristic function form based on impulsion; finally, dynamic models of anti-corruption drive. Major emphasis is placed on problem statements and possible solution methods.

Keywords: active systems, dynamic games, integer programming problems, universities, sustainable management.

1. INTRODUCTION

The theory of sustainable management of active systems was introduced in [8–13, 18]. The main postulates of this theory can be applied to the sustainable management of higher education institutions (universities), which forms a topical problem. The approach suggested below has the following distinctive features.

First, we study management processes of universities as organizations [7], without considering, e.g., the interaction of lecturers and students in the course of learning. Second, we are mostly concerned with the sustainable management problem of universities as active systems. Third, our analysis employs mathematical models, predominantly the dynamic models of conflict and cooperative control (hierarchical differential games) [1, 15] and their solution methods (simulation modeling). And fourth, the ultimate goal of our research is to develop and test practical procedures for solving some sustainable management problems of universities based on the corresponding mathematical models and software.

A significant contribution to this field of investigations was made by the monograph [6], which specified the general methodology of organizational control to educational systems. In particular, the author [6] proposed the main principles of education improvement (in terms of quality, availability and efficiency), which leads to the corresponding control problems; concluded that the backbone element of the theory of control of educational systems is the category of an organization; identified six hierarchical levels of educational systems; specified a series of general concepts of organizational control (the types, principles and mechanisms of control) to educational systems and gave illustrative examples.

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The game-theoretic framework that will be developed below treats the sustainable development of universities as the simultaneous satisfaction of the homeostasis and motivation conditions. Homeostasis means that the key indicators of the university's operation (the characteristics of research, educational, and innovative and business activities) must take values within certain ranges. Motivation implies that the private interests of university staff are properly considered and coordinated with the social interests of the whole organization.

It seems reasonable to solve the sustainable management problems of universities by constructing and examining separate sustainable management models at the levels of department, faculty, and university. These models include the following: a dynamic incentive model for the participants of a research project; a static reward distribution model as a game in the characteristic function form; a dynamic working time distribution model for department staff as a differential game in the normal or characteristic function form based on compulsion; dual discrete programming problems with sustainable development constraints for determining an optimal staff structure of a faculty, with assessing the efficiency of different paired unions of departments; dynamic coordination models for the social and private interests of university staff in the course of innovations promotion, as differential games in the normal and characteristic function form based on impulsion; finally, dynamic models of anti-corruption drive. We suggest the method of qualitatively representative scenarios of simulation modeling as the main tool for solving dynamic games [13]. In addition, we adopt traditional methods such as Pontryagin's maximum principle, dynamic programming, and discrete optimization methods.

Therefore, this paper considers sustainable management models for universities, with major emphasis on problem statements and possible solution methods. The remainder of this paper is organized as follows. In Section 2, we introduce the definition of a university as an active system. In Section 3, we present sustainable development criteria for universities. In Section 4, we propose separate sustainable management models at the levels of department, faculty, and university. In Section 5, we describe the models of anti-corruption drive for universities. In the Conclusions, we summarize the outcomes of this paper and outline further research.

2. UNIVERSITY AS AN ACTIVE SYSTEM

Universities are complex multilevel dynamic systems with specific goals and interests of different agents at all levels and also with a complex system of relations with an environment. Consider a university as an active system in detail in accordance with the following scheme: elements; subsystems; functions; environment; problems.

Elements. The upper level of the organizational structure of a university is occupied by administrative staff. The university's rector, deans (directors of institutes) and heads of departments (laboratories) implement line management—general direction in all fields of activity. Vice-rectors, vice-deans, and the heads of support auxiliary units (education and science, accounting, human resources, maintenance, etc.) are responsible for functional management (separate fields of activity). Line managers often combine administrative load with research and/or teaching.

Lecturers and researchers are a controlled subsystem for administrative staff and a control subsystem for students (under- and postgraduates). In other words, each lecturer of a modern university has to be engaged in research in order to know the current state of affairs in his/her specialty area and be prepared for teaching.

Students, including postgraduates working for the degrees of Candidate or Doctor, have dual role. On the one hand, they form a controlled subsystem taught by lecturers and researchers; on the other, they are not passive at all. First, a commonly encountered idea in pedagogical science dictates that the subject–object impact on a student must be replaced by the subject–subject interaction with proper consideration of the student's interests and his/her active involvement in educational process. Second, the active system concept implies that a controlled subsystem is intensively affecting the control process. Students play major role in the university's life, including management and decision-making. This is done through student bodies and unions, in particular, by integrating students into the Academic councils of different institutes and departments, by collecting students' assessments of different lecturers (feedback), by analyzing the students' choice of different courses, etc.

Subsystems. As natural subsystems the structure of a university consists of faculties and institutes as well as functional units. This determines the traditional line-functional management structure. A series of universities, however, use project management (e.g., the management of educational programs and research projects); in this case, project groups can be treated as temporal subsystems, in addition to the permanent (line-functional) ones.

Functions. Historically, universities were mostly in charge of education although university lecturers always included prominent scientists. At the junction of the 18th and 19th centuries, brothers Alexander and Wilhelm von Humboldt suggested the concept of a new university: education must rest on firm foundation of research, and research must play key role. In the second half of the 20th century, the classical "research+education" formula pioneered by the von Humboldts was supplemented with the third component, which is difficult to characterize by a single term. The matter concerns innovations, entrepreneurship (business activities), and the contribution of universities into regional development. In the recent two decades the terms "entrepreneurial university" and "academic capitalism" have become firmly entrenched in the literature [2, 17]. Thus, a modern university has a triune function that can be described as "research+education+application." Note that the key role in this triad is played by research. Precisely research creates prerequisites for implementing educational programs of all levels (especially for Master programs) and also for developing regional and industry-oriented applications, including new products and technologies, additional education, consultation with regional authorities, etc.

Environment. The following elements make up the environment for universities: The Ministry of Education and Higher Education of the Russian Federation; regional authorities; state science foundations; other universities of a given and other regions; regional population; finally, regional enterprises and organizations.

As indicated by the above analysis, there exist the following basic *problems* that cause conflicts in universities as active systems.

1. the distribution of limited resources among different units and also among the participants of research projects;

2. the distribution of working time among the main activity at a university and external activities for higher gain (combining jobs at different universities, tutoring, consulting, etc.) by university staff;

3. the contradictions between the aspiration of separate departments (their staff and heads personally) for their preservation and the objective norms of controllability in combination with the interests of faculties;

4. the contradiction between the need for technological and managerial innovations and the aspiration of university staff for minimum effort and risk;

5. the contradiction between the well-established idea that the university's managers (from rector to the heads of departments) have to be researchers, the leaders of scientific schools and methodologists, and the modern trend to give these positions to "effective managers" often far from research and education;

6. the aspiration of auxiliary units for imposing their "rules of play" on lecturers and researchers;

7. corruption at universities.

These problems can be solved by coordinating the interests of all active agents for the sustainable development of a university using suitable mathematical models—in the first place, the dynamic game-theoretic models that describe the conflict and cooperation of players and guarantee a reasonable compromise between them. However, in a series of cases, (simpler) static optimization models seem a more appropriate choice.

3. SUSTAINABLE DEVELOPMENT CRITERIA FOR UNIVERSITIES

The sustainable development of a university as an active system consists in the homeostasis condition and the motivation condition of active agents, which must be satisfied simultaneously. The original theory of sustainable development defines homeostasis using the concept of "three pillars," meaning that ecological, economic, and social goals must be considered and balanced all together. In the course of modeling, the state vector must include variables associated with some economic, ecological, and social indexes. For universities, the three pillars are research activity (RA), teaching and methodological activity (TMA), and also innovative and entrepreneurial activity (IEA), which is of equal importance. Indexes by these three groups have to be defined and analyzed at the level of department, faculty, and university using some aggregation procedures.

Therefore, the university's homeostasis will be verified using an integrated assessment procedure that rests on the integrated assessment approach introduced in [6]. This procedure includes several steps as follows:

1) compile the list of indexes by groups RA, TMA and IEA at the level of department;

2) to each index assign numerical scores

$x_{ijk}, y_{ijk}, z_{ijk} \in \{2,3,4,5\}$,

with the following notations: 2, 3, 4, and 5 as "poor," "fair," "good," and "excellent," respectively; x as RA; y as TMA; z as IEA; i as faculty number; j as department number; finally, k as index number. Then $X = \| x_{ijk} \|, Y = \| y_{ijk} \|, Z = \| z_{ijk} \|$ are the numerical score matrices of the initial indexes of all departments;

3) calculate the indexes of RA, TMA and IEA at the level of department as

$x_{ij} = f_{ij}(X),\ y_{ij} = g_{ij}(Y),\ z_{ij} = h_{ij}(Z)$;

for the sake of simplicity, let $\forall i, j: f_{ij} = g_{ij} = h_{ij} = F$ (uniform aggregation);

4) calculate the indexes of RA, TMA and IEA at the level of faculties as $x_i = \frac{1}{n_i} \sum_{j=1}^{n_i} x_{ij}$, where n_i denotes the number of departments at faculty i; y_i, z_i are calculated by analogy, with standard rounding rules;

5) calculate the indexes of RA, TMA and IEA at the level of university as $x = \frac{1}{m} \sum_{i=1}^{m} x_i$, where m denotes the number of faculties at the university; y, z are calculated by analogy, with standard rounding rules;

6) rank the departments in the faculty's three-dimensional space, the faculties in the university's three-dimensional space, and the universities in the country's (or world's) three-dimensional space in the following way:

a) find the Pareto set in the index space;

b) calculate a single homeostasis index. Note that the same index for assessing the university's homeostasis at any of the three levels is an oversimplification: a more adequate approach is to consider the three-dimensional space of qualitatively different criteria of RA, TMA and IEA. Nevertheless, sometimes a single homeostasis index seems appropriate, and it can be calculated using a similar aggregation procedure as described above.

It should be emphasized that Steps 1–3 of this procedure inevitably have subjective character. One would hardly suggest any objective grounds for choosing indexes, their numerical scores (to say nothing of more complicated assessments!) and further aggregation into a single index. General principles of systems analysis, the experience and knowledge of experts and further testing of assessment procedures in practice are the only possible remedies here.

Thus, consider an integrated assessment procedure as an illustrative example. Its specifics consist in Steps 1–3, because the indexes at the levels of faculty and university are obtained by simple averaging of the corresponding values calculated at the lower level. Pareto set calculation is also a standard operation, although it can be implemented in different ways [5].

1. The list of initial homeostasis indexes at the level of department is given in Table 1. Basically, they correspond to standard reporting, with some supplements and modifications. For fixed numbers of department and faculty, it suffices to number indexes only.

Table 1. Homeostasis indexes by groups, level of department

RA	**TMA**	**IEA**
x_1—papers published by department staff per annum (regular journals indexed by Web of Science/Scopus), in total	y_1—textbooks and teaching aids with official stamp published by department staff per annum, in total	z_1—attracted funding
x_2—papers published by department staff per annum (regular journals listed by The State Commission for Academic Degrees and Titles of the Russian Federation), in total	y_2—electronic educational resources developed by department staff per annum, in total	z_2—contracts with third parties (basic departments at enterprises, joint projects, etc.)
x_3—papers at international conferences published by department staff per annum, in total	y_3—Master's dissertations supervised by department staff per annum, in total	
x_4—dissertations (Cand. Sci., Dr. Sci.) defended or supervised by department staff within three years, in total	y_4—average results of students' groups taught by department staff	
x_5—members of editorial boards of scientific journals, organizing committees of conferences, and dissertation councils among department staff, in total		
x_6—reviews of submitted draft papers, dissertations and abstracts of dissertations per annum, in total		

2. Of course, assigning numerical scores {2,3,4,5} to the chosen indexes has the highest complexity here. The rules suggested below are not unique and seem somewhat conditional; but they rest on experience and certain plausible arguments. The indexes of RA are as follows:

$$x_1 = \begin{cases} 5, & u_1 \geq 1; \\ 4, & 0.5 \leq u_1 < 1; \\ 3, & 0.25 \leq u_1 < 0.5; \\ 2, & u_1 < 0.25, \end{cases}$$

where u_1 denotes the papers of type 1 per one department's employee;

$$x_2 = \begin{cases} 5, & u_2 \geq 2; \\ 4, & 1 \leq u_2 < 2; \\ 3, & 0.5 \leq u_2 < 1; \\ 2, & u_2 < 0.5, \end{cases}$$

where u_2 denotes the papers of type 2 per one department's employee;

$$x_3 = \begin{cases} 5, & u_3 \geq 1; \\ 4, & 0.5 \leq u_3 < 1; \\ 3, & 0.25 \leq u_3 < 0.5; \\ 2, & u_3 < 0.25, \end{cases}$$

where u_3 denotes the papers of type 3 per one department's employee;

$$x_4 = \begin{cases} 5, & d \geq 1 \text{ and } c \geq 3; \\ 4, & c \geq 2; \\ 3, & c \geq 1; \\ 2, & c = d = 0, \end{cases}$$

where d and c denote Cand. Sci. and Dr. Sci. dissertations;

$$x_5 = \begin{cases} 5, & u_4 \geq 1; \\ 4, & 0.5 \leq u_4 < 1; \\ 3, & 0.25 \leq u_4 < 0.5; \\ 2, & u_4 < 0.25, \end{cases}$$

where u_4 denotes the members of the corresponding type per one department's employee;

$$x_6 = \begin{cases} 5, & u_5 \geq 2; \\ 4, & 1 \leq u_5 < 2; \\ 3, & 0.5 \leq u_5 < 1; \\ 2, & u_5 < 0.5, \end{cases}$$

where u_5 denotes reviews per one department's employee.

The indexes of TMA and IEA are assessed by analogy.

3. For fixed faculty and department, the numerical score matrices X, Y and Z turn into vectors. Hence, the indexes of RA, TMA and IEA of a department are constructed by specifying an aggregation function

$$F : P^{k_i} \to P,$$

where $P = \{2,3,4,5\}$ and k_i is the number of all indexes in group i=1,2,3 (Table 1). Denote by $p = (p_1,..., p_{k_i}) \in P^{k_i}$ the value set of all indexes in group i. Possible aggregation procedures are as follows.

1) $F_{\max} = \max_{1 \le j \le k_i} \{p_j\}$, determining the extremely soft assessment;

2) $F_{\min} = \min_{1 \le j \le k_i} \{p_j\}$, determining the extremely hard assessment;

3) $F_{maj} = p_{maj}$, where $|\{p_{maj}\}| > k_i / 2$ is the majority assessment;

4) $F_{med} = p_{med}$, where p_{med} is the median (the medium term of the sequence p in the ascending order), determining the median assessment;

5) $F_w = \sum_{j=1}^{k_i} w_j p_j$, determining the weighed assessment (with subjective weights w_j such that $w_j \ge 0, \sum_{j=1}^{k_i} w_j = 1$). Note that the third and fourth aggregation procedures generally require an odd number of initial indexes.

The choice of an aggregation procedure is a matter of principle because the initial indexes from Table 1 have different significance. Consider an illustrative numerical example (Table 2). Assume department staff consists of 10 employees.

Obviously, the first and second aggregation procedures are not completely adequate because of the extreme assessments that coincide with one or two components among the six ones. The other procedures yielding the same index value should be treated adequate (in the case of weighted assessment, after rounding up or down to the nearest integer).

Table 2. Indexes of RA

Initial value of index	Specific value (if applicable)	Assessment of index	Index of RA
6	$u_1 = 0.6$	$x_1 = 4$	$F_{max} = 5$
21	$u_2 = 2.1$	$x_2 = 5$	$F_{min} = 3$
7	$u_3 = 0.7$	$x_3 = 4$	$F_{maj} = 4$
c = 2, d = 0	c = 2, d = 0	$x_4 = 4$	F_{med} not defined due to even number of indexes
4	$u_4 = 0.4$	$x_5 = 3$	$F_w = [4.1] = 4$,
6	$u_5 = 0.6$	$x_6 = 3$	w=(0.3,0.3,0.1,0.1,0.1,0.1)

Now, consider the second component of sustainable development—the motivation of active agents (university's employees). As a quantitative measure of motivation choose the system concordance indexes

$$SCI = J_0^{\max} - J_0 , \tag{1}$$

where J_0 is the Principal's maximal guaranteed payoff for different informational rules of the games and $J_0^{\max}$ is the global maximum of this value. Then the system is concordant if $SCI = 0$. The condition $SCI \approx 0$ indicates that the system is almost concordant.

Assume a department, a faculty (an institute) and a university have a tree-like hierarchical structure in which the Principal's role is played by its head, dean (director) and rector, respectively and agents are their subordinates. In formula (1) the value J_0 is calculated using different pairs of classification attributes (open- and closed-loop strategies, strategies without/with agents' control feedback, compulsion/impulsion), which gives eight different system concordance indexes. The efficiency of different sustainable management methods is analyzed using the values of these indexes.

4. SUSTAINABLE MANAGEMENT PROBLEMS FOR UNIVERSITIES AND SOLUTION METHODS

Dynamic incentive model with homeostasis requirements. This model has the form

$$J_0 = \int_0^T e^{-\rho t}[H(u(t), x(t)) - \sum_{i\in N} s_i(u(t), x(t))]dt \to \max\ , \tag{2}$$

$$s_i(\cdot) \ge 0, i \in N; \tag{3}$$

$$J_i = \int_0^T e^{-\rho t}[s_i(u(t), x(t)) - h_i(u(t), x(t))]dt \to \max\ , \tag{4}$$

$$0 \le u_i(t) \le 1, i \in N; \tag{5}$$

$$\dot{x} = f(x(t), \sum_{i\in N} u_i(t)), x(0) = x_0\ . \tag{6}$$

The model describes relations in the “Principal–agent” tree-like control system. The Principal can be the manager of a research project while the agents the executors. The notations are the following: N as the agents set; H, $H(0,0) = 0$, as an increasing and convex function that characterizes the Principal’s income; h_i, $h_i(0,0) = 0$, as an increasing and convex function that characterizes the cost of agent *i*; u_i as the labor effort of agent *i* (e.g., his/her working time within the scope of the project); s_i as the compensation of the labor effort of agent *i* paid by the Principal (an incentive mechanism representing a nonnegative function); x as the state variable (e.g., the papers published within the scope of the project); $u = (u_1,..., u_n)$ as the labor effort vector of all agents (all these variables are considered as time-dependent functions); $\rho \in [0,1]$ as the discount factor; J_0, J_i as the payoff functionals of the Principal and agents, respectively; finally, T as a finite horizon.

The static theory of incentive mechanisms was introduced in [7]. Resting on the same considerations, for model (2)–(6) the optimal incentive mechanism is expected to have the form

$$s_i^*(u(t), x(t)) = \begin{cases} h_i(u_i^*(t), u_{-i}(t), x(t)) \text{ if } u_i(t) = u_i^*(t), \\ 0\ otherwise\ \ (i \in N), \end{cases} \tag{7}$$

where $u_{-i} = (u_1,..., u_{i-1}, u_{i+1},..., u_n)$, and

$$u^*(t) \in Arg \max_{u(t)} \int_0^T e^{-\rho t}[H(u(t), x(t)) - \sum_{i\in N} h_i(u(t), x(t))]dt\ . \tag{8}$$

The first result in this field of investigations was obtained in the paper [16]; more specifically, the above hypothesis was confirmed for the dynamic discrete-time infinite-horizon version of the

"Principal–agent" incentive problem with the Principal's and agent's payoff functionals defined in terms of expectations.

Now, supplement model (2)–(6) with the homeostasis requirement

$$\forall t\ x(t) \in X^* \tag{9}$$

and also introduce the sets

$$U^* = \{u(t) : \forall t\ x(t) \in X^*\} \text{ and } U^{SM} = U^* \cap NE,$$

where by assumption $U^* \neq \varnothing, U^{SM} \neq \varnothing$, and NE denotes the set of Nash equilibria in the differential normal-form game (4)–(6) of the agents.

Consider the incentive mechanism

$$s_i^{SM}(u(t), x(t)) = \begin{cases} h_i(u_i^{SM}(t), u_{-i}(t), x(t)) \text{ if } u_i(t) = u_i^{SM}(t), u^{SM}(t) \in U^{SM}, \\ 0 \textit{ otherwise } (i \in N). \end{cases} \tag{10}$$

Then the problem is to construct the set U^{SM} and compare the incentive mechanisms (7) and (10). Besides traditional methods, the set U^{SM} can be constructed (and the optimal control problem (8) can be solved) using the method of qualitatively representative scenarios from simulation modeling [13].

Dynamic working time control model with compulsion. This model has the form

$$J_0 = \int_0^T e^{-\rho t}[s_0(t)c(x(t)) - D(q(t))]dt \to \max, \tag{11}$$

$$0 \leq q_i(t) \leq 1,\ i \in N; \tag{12}$$

$$J_i = \int_0^T e^{-\rho t}[p_i(1 - u_i(t)) + s_i(t)c(x(t))]dt \to \max, \tag{13}$$

$$q_i(t) \leq u_i(t) \leq 1,\ i \in N; \tag{14}$$

$$\dot{x} = \sum_{i=1}^{n} k_i u_i(t) - \mu x(t),\ x(0) = x_0, \tag{15}$$

subject to the homeostasis requirement (9).

Like model (2)–(6), this model describes the relations in the tree-like "Principal–agent" control system. The agent's control variable u_i is, e.g., the share of working time spent on a research project. Similar to model (2)–(6), the state-space variable x can be interpreted as the papers published or another index of RA. The dynamic equation (15) is assumed to be linear for the sake of simplicity; in this equation, k_i denotes the agent's working time-to-paper conversion coefficient and μ the "depreciation" factor (less papers published without any labor efforts of the agents).

The specifics of model (11)–(15) are fully determined by the integrand of formula (13). By assumption each agent distributes his/her working time between a research project (the share u_i) and other types of activity (the share $(1 - u_i)$). Participating in other types of activity, each agent obtains additional income described by an increasing and concave function p_i. The aggregate participation of all agents in a research project produces an income $c(x)$ (an increasing and concave function), which is allocated among them by the Principal using given time-varying coefficients $s_i(t), i = 0,1,..., n$. Such models are called Social and Private Interests Coordination Engines models (SPICE-models) [4]. The Principal's control variable q_i restricts the agent's "selfishness" from below, which corresponds to compulsion [8]. In this case, the Principal's administrative control cost $D(q)$ (an increasing and convex function such that $D(0) = 0$) have to be considered for avoiding the trivial solution $q_i = 1$, i =1,...,n.

Model (9), (11)–(15) can be analyzed for different informational rules. Fixing the values $q_i(t)$ leads to the differential normal-form game (13)–(15) of the agents with the state-space constraints (9), with Nash equilibrium as a natural solution. In the hierarchical setup (11)–(15), (9), the solution is a Stackelberg equilibrium in which the Principal uses open-loop strategies $q_i(t)$, closed-loop strategies $q_i(t, x(t))$, without any control feedback or with the control feedback $q_i(t, u(t))$. The efficiency of these control methods can be compared using the system concordance indexes (1).

Moreover, from the differential normal-form game (13)–(15) it is possible to pass to the corresponding differential game in the characteristic function form, for further analysis of optimality principles to distribute the grand coalition's payoff among the players as well as their time consistency [15].

Dynamic innovations promotion model with impulsion. This model has the form

$$J_0 = \int_0^T e^{-\rho t} s_0(t) c(x(t)) dt \to \max , \tag{16}$$

$$\sum_{i=0}^{n} s_i(t) = 1,\ 0 \le s_i(t) \le 1,\ i = 0,1,..., n; \tag{17}$$

$$J_i = \int_0^T e^{-\rho t} [p_i (1 - u_i(t)) + s_i(t) c(x(t))] dt \to \max , \tag{18}$$

$$0 \le u_i(t) \le 1,\ i = 1,..., n; \tag{19}$$

$$\dot{x} = \sum_{i=1}^{n} k_i u_i(t) - \mu x(t),\ x(0) = x_0 , \tag{20}$$

subject to the homeostasis requirements (9).

Like model (11)–(15), this is a dynamic SPICE-model but with impulsion used instead of compulsion. The Principal chooses the control variables $s_i(t)$, i.e., the total income shares allocated to different agents, and report them to the latter. This model implies no compulsion; hence, the control cost is 0 and the agents' control variables $u_i(t)$ (the shares of working time or another resource spent on innovations promotion at a university) are not bounded from below. The informational rules are the same as in the previous model.

Dual discrete programming problems for faculty staff optimization. Let the staff structure of some faculty *j* be described by a collection

$$N = \{N_p, N_d, N_a\} = \left\{ \{N_{pj}\}_{j=1}^{m}, \{N_{dj}\}_{j=1}^{m}, \{N_{aj}\}_{j=1}^{m} \right\},$$

where N_p, N_d, N_a are the sets of professors, associate professors and senior lecturers (including assistants), respectively; m denotes the number of departments at faculty j.

Then the following dual discrete programming problems arise naturally:

$$\begin{cases} \sum_{j=1}^{m}\left[\sum_{i=1}^{k_1}\lambda_{ij}x_{ij}+\sum_{i=1}^{k_2}\mu_{ij}y_{ij}+\sum_{i=1}^{k_3}\nu_{ij}z_{ij}\right]\to \max_{n_p,n_d,n_a\in Z_+}, & (21)\\ s_p n_p + s_d n_d + s_a n_a = R; & (22) \end{cases}$$

$$\begin{cases} s_p n_p + s_d n_d + s_a n_a \to \min_{n_p,n_d,n_a\in Z_+}, & (23)\\ x_{ij}\ge x_i^*, i=1,\dots,6;\ y_{ij}\ge y_i^*, i=1,\dots,4;\ z_{ij}\ge z_i^*, i=1,2;\ j=1,\dots,m. & (24) \end{cases}$$

Here the additional condition is

$$w_{ij}=f_i(n_{pj},n_{dj},n_{aj})=\begin{cases} w_i^H \text{ if } (n_{pj},n_{dj},n_{aj})\in N_i^H,\\ w_i^L\ otherwise\,(i=1,\dots,k_l); \end{cases} \qquad w_{ij}\in\{x_{ij},y_{ij},z_{ij}\}, \quad (25)$$

which determines the pairs of problems (21)–(22) and (23)–(24) as dual. The other notations are the following: x_{ij}, y_{ij}, z_{ij} as the indexes of RA, TMA and IEA (Table 1); x_i^*, y_i^*, z_i^* as their homeostatic values; $\lambda_{ij}, \mu_{ij}, \nu_{ij}$ as the corresponding weight coefficients; i as index number; k_1, k_2, k_3 as the number of indexes in each group; s_p, s_d, s_a as the wages of the corresponding categories of lecturers; R as the total wage fund of the faculty; w_i^H, w_i^L $(w_i^H > w_i^L)$ as the high and low values of the indexes $\{x_{ij}, y_{ij}, z_{ij}\}$; N_i^H as the set of the values (n_p, n_d, n_a) under which w_i^H is reached; $k_l\in\{k_1,k_2,k_3\}$; finally, $n_z = |N_z|, z\in\{p,d,a\}$.

In particular, this setup can be used for assessing the efficiency of different paired unions of faculty's departments, a topical problem that arises in the conditions of teaching staff optimization. To this end, just consider C_m^2 potential unions of departments k and l, $k,l=1,\dots,m$, that lead to the teaching staffs $n_{pk}+n_{pl}, n_{dk}+n_{dl}, n_{ak}+n_{al}$, and solve problems (21)–(22), (23)–(24) subject to (25).

Note that the major difficulty consists in the identification of the function f_i in formula (25), which requires subjective considerations and expert appraisals. After that, the problems can be solved by standard dynamic programming methods [14] and computer simulations.

Reward distribution problem for participants of research project as static game in characteristic function form. The main task of the theory of cooperative games (games in the characteristic function form) is to distribute the grand coalition's payoff among separate players. Hence, this mathematical model seems natural for studying different reward distributions among the participants of a research project.

Denote by N the set of research project executors and write $N = N_p \cup N_d \cup N_a,\ N_i \cap N_j = \varnothing$, where N_p, N_d, N_a are its nonintersecting subsets of professors, associate professors, and senior lecturers (including assistants). Assume each executor $i \in N_m$ can independently publish $a_i = a_{im}$ papers in regular journals indexed by Web of Science/Scopus and also $b_i = b_{im}$ papers in regular journals listed by The State Commission for Academic Degrees and Titles of the Russian Federation, where $m \in \{p, d, a\}$. Then the executor's characteristic function can be defined as

$$v(i) = ca_i + b_i,\ c > 0,\ i \in N. \qquad (26)$$

This leads to the following analysis problems:

- completely define the superadditive characteristic function $v : 2^N \to R$ in different possible ways $v(K) = f(n_p^K, n_d^K, n_a^K), n^K = |N^K|, K \subseteq N$;

- for the resulting game in the characteristic function form, find the solutions using different optimality principles (the core, the Neumann–Morgenstern solution, the Shapley value, the nucleolus, etc. [15]);

- compare the results obtained for different values of the parameters $c, v(N), a_{im}, b_{im}$;

- verify the homeostasis requirements

$$\sum_{i \in N} a_i \geq a^*, \sum_{i \in N} b_i \geq b^*.$$

5. MODELS OF ANTI-CORRUPTION DRIVE IN UNIVERSITIES

The author's concept of corruption modeling was described in detail in the monograph [3]. As an illustrative example of struggling against *administrative corruption* consider a simple corruption model of an examination described an extensive-form game [15]. This game involves Lecturer and Student. In the course of an examination, Lecturer is finding out the Student's qualification: whether he/she deserves positive assessment (H—high qualification) or not (L—low qualification).

If Student has high qualification, then Lecturer chooses between two strategies: e—extortion (wringing money out of Student under threat of negative assessment) and h—honesty (giving the well-deserved positive assessment).

If Student has low qualification, then Lecturer also chooses between two strategies: c—capture (offering positive assessment for money) and h—honesty (sending to a resit).

If Lecturer chooses honesty, then the game ends; in this case, the Lecturer's payoff is 0 while the Student's payoff is either 5 (high qualification) or -2 (low qualification). If Lecturer suggests any of the corruption schemes, then Student chooses between two strategies: b—agreeing with a bribe and a—making an appeal.

Assume that, in case of appeal, Lecturer is fired out while Student receives the well-deserved assessment minus some cost. The resulting payoffs and the complete graph of this game are shown in Fig. 1.

This game will be solved by the backward induction method [15]. Obviously, with the above payoffs, Lecturer prefers honesty in the case of high qualification of Student and corruption scheme in the case of low qualification (and Student prefers to agree).

Instead of the extensive-form game, this conflict can be considered from the Lecturer's view under the assumption that he/she may assess the conditional probabilities of Student's choice (bribe or appeal) depending on qualification. For the same parameter values as before (see Fig. 1), this approach leads to the following Lecturer's payoffs:

under extortion,

$J^e = 10P_{b|H} - 100P_{a|H} = 10(P_{b|H} - 10P_{a|H})$;

under capture,

$J^c = 10P_{b|L} - 100P_{a|L} = 10(P_{b|L} - 10P_{a|L})$,

where P with appropriate subscripts denotes conditional probabilities.

In both cases, corruption is not beneficial for Lecturer (homeostasis) if
$P_b < 10P_a$.
In the general case, the homeostasis condition takes the form
$w_bP_b < w_aP_a$,
where w_a and w_b are the Lecturer's payoffs under appeal and bribe, respectively. The probability distributions can be estimated on the students set N using empirical data.

As an illustrative example of struggling against *economic corruption* consider a dynamic model of research funding. Introduce the following notations: $N = \{1,...,n\}$ as the set of competing participants (authors of research projects) who prefer bribery; $M = \{1,...,m\}$ as the set of grant competitions. Any project $i \in N$ can participate in any grant competition $j \in M$. The funding of each grant competition $j \in M$ can be used to support $k_j \in Z$ projects with a fixed grant G_j .

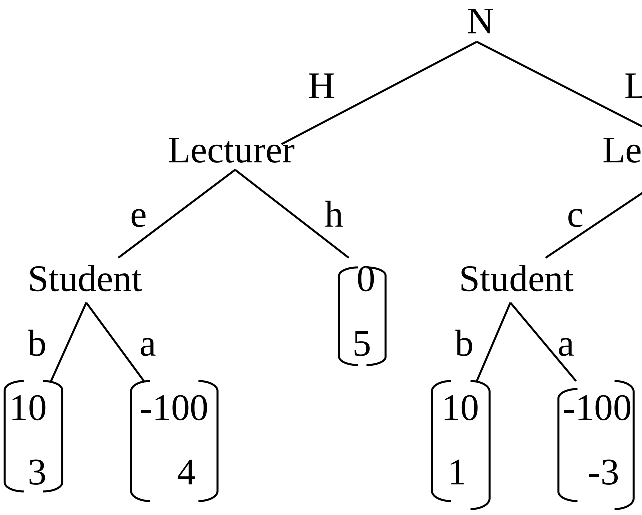

Fig. 1. Corruption model during examination as extensive-form game

At the beginning of each planning year $t = 1,...,T$,

1) the participants $i \in N$ choose their strategies b_{ij}^t (kickback shares)

$$0 \le \sum_{j=1}^{m} b_{ij}^t \le 1, b_{ij}^t \ge 0, i \in N, j \in M, t = 1,...,T; \tag{27}$$

let $b_{1j}^t > b_{2j}^t > ... > b_{nj}^t, \ j \in M$;

2) integers $\bar{k}_j^t \in [0, k_j^t], \ j \in M$, are chosen by a random uniform draw; the participants $1,2,...,\bar{k}_j^t$ receive their grants; the residue grants $k_j^t - \bar{k}_j^t$ are distributed among $i \notin N$ and are not considered at subsequent steps (years).

The payoff functionals of the participants have the form

$$J_i = \sum_{t=1}^{T} e^{-\rho t} \sum_{j=1}^{m} (1 - b_{ij}^t) r_{ij}^t \to \max , \tag{28}$$

where $r_{ij}^t = \begin{cases} G_j \ \textit{if participant i receives grant in competition } j, \\ 0 \ \textit{otherwise.} \end{cases}$

The values of the RA indexes $x_1 - x_4$ (see Table 1) are calculated from the dynamic difference equation

$$x_{ki}^{t+1} = x_{ki}^{t} + f_k\left(\sum_{j=1}^{m}(1-b_{ij}^{t})r_{ij}^{t}\right), x_{ki}^{0} = x_{ki0}, k = 1,2,3,4; i \in N; t = 0,1,...,T-1. \quad (29)$$

The homeostasis conditions have the form

$$x_{ki}^{t} \geq x_{k}^{*}, k = 1,2,3,4; i \in N; t = 0,1,...T. \quad (30)$$

In the basic setup, model (27)–(29) can be studied by the method of qualitatively representative scenarios $\{b_{ij}^t\}_{i=1}^{n}{}_{j=1}^{m}{}_{t=1}^{T}, \{\bar{k}_j^t\}_{j=1}^{m}{}_{t=1}^{T}$, with a proper verification of conditions (30). In addition, a game-theoretic setup with a simultaneous choice of a strategy b_{ij}^t by each agent, or a hierarchical setup with a strategy $\bar{k}_j^t$ chosen by the Principal are also possible.

6. CONCLUSIONS

In this paper, a systems approach to the sustainable management of universities has been introduced. Several setups of sustainable management problems for universities have been considered in which the sustainable development of universities is treated as the simultaneous satisfaction of the homeostasis and motivation conditions. A university as an active system has been analyzed, and some sustainable development criteria have been suggested and formally described. A series of game-theoretic sustainable management models at the levels of department, faculty, and university have been presented as follows: a dynamic incentive model for the participants of a research project; a static reward distribution model; a dynamic working time distribution model for department staff; an optimal staff structure model of a faculty; an innovations promotion model considering the social and private interests of university staff; finally, dynamic models of anti-corruption drive. As a basic tool for solving the dynamic game-theoretic models the method of qualitatively representative scenarios of simulation modeling [13] has been suggested. Further research will be focused on a detailed study of these models and their testing for real universities.

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