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CONTROL MECHANISMS FOR ORGANIZATIONAL-TECHNICAL SYSTEMS: PROBLEMS OF INTEGRATION AND DECOMPOSITION

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Abstract: This paper discusses theoretical problems connected with analysis of integrated control mechanisms for the organizational- technical systems (OTS). The existing classification of these systems is extended using transition from separate control mechanisms to integrated ones. A detailed consideration is given to a key problem, i.e., efficiency assessment for an integrated mechanism and its decomposition into assessments for separate elementary mechanisms.

Keywords: multiagent systems, game theory, strategy proofness, integrated mechanism, strategic reflexion, project planning and scheduling, mechanism design

1. INTRODUCTION

Game theory has always motivated and supplied operational research and combinatorial optimization with new challenging problems [Fudenberg, Tirole (1995), Myerson (1991)], be it the complexity of Nash equilibrium calculation [Nisan and etc. (2006), Mansour (2003)], or a hierarchical programming problem [Germeier (1986)] originated from the Stackelberg game. Some of these problems are not solved yet. *Mechanism design* (MD) and *theory of active systems* (TAS) [Bolton, Dewatripont (2005), Burkov (1977), Burkov et al. (2015), Novikov (2001), Novikov et al. (2013),] are research directions that systematically study the mathematical models of conflict among several rational agents under asymmetric information and a nontrivial sequence of moves; using the MD/TAS framework, efficient management mechanisms (decision rules for a manager–the so-called Principal) were developed for a wide range of problems in management and social choice. For modern state of art see [Burkov et al. (2013)].

The revelation principle, as the cornerstone of MD which allows reducing the hierarchical programming problem of MD to the tractable programming problem with equality constraints, was established in parallel in Western countries by R. Myerson et al. [Myerson (1979), Myerson (1982)] and in the USSR by V. Burkov and his scientific school [Burkov (1977)]. During recent decades, a toolkit of basic optimal mechanisms for all stages of a management cycle [Novikov et al. (2013)] was developed by the members of Burkov's school. Each mechanism in the toolkit is optimal (i.e., maximizes the Principal's profit) and strategy-proof (i.e., the agents cannot gain by reporting wrong information to the Principal).

To solve complex real-life management problems, basic mechanisms are often combined and a current open issue of the theory is how to preserve good properties of basic mechanisms being *combined* into an *integrated one*. Therefore, a topical problem concerns the development of general conditions to-be-imposed on basic mechanisms for their robustness with respect to their combination in integrated mechanisms. If a basic mechanism satisfies these conditions, then it can be used as a simple brick during integrated mechanism construction. This new level of the theory would dramatically simplify the process of integrated mechanisms implementation. That is especially actual in scope of development of «Smart» systems with high involvement of humans' interests (cities, infrastructure, grids etc.), where complex control solutions may be implemented with necessity to take into account possibility of being affected by controlled rational subjects , see for example [Korgin, Korepanov (2016)].

Here a "dual" problem is *decomposition of control mechanisms*, the representability of a given mechanism in the form of an aggregate of several interconnected simple mechanisms. As the bases of such decomposition, one can use the hierarchical levels of a system, time periods, etc. Decomposition poses the same issues of inheritance of characteristics as integration does. In the sequel, integration is considered par excellence.

2. ELEMENTARY AND INTEGRATED CONTROL MECHANISMS

Consider the *basic model* of an organizational or organizational-technical system (OTS) composed of a control subject (*Principal*) and a controlled subject (*agent*) [Burkov (1977), Novikov (2013), Novikov et al. (2013)]. Here the

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input is a *control action*, while the output is an *action* of the controlled subject (also termed the *state* of the controlled system). Feedback provides Principal with information on the state of the controlled system. In this case, *control mechanism* coincides with control action (in the general case, a control mechanism is a mapping of the agent's action set into the Principal's action set, see below and [Novikov (2013)]).

Let the agent's state be characterized by his *action* $y \in A$ chosen from a set A of admissible actions. Suppose that the control $u \in U$ belongs to a set U of admissible controls. Consider an efficiency criterion $\Phi(u, y)$: $A \times U \to R^1$ describing operation of the whole system; it depends on the system variables, namely, the control and the system state.

Suppose that the response of the controlled subject to an applied control is known. The elementary response is defined by a given function of control, i.e., $y = G(u)$, where $G(y)$ specifies a model of an active controlled subject (or a controlled object in case of a passive technical object) describing the response to the control action y. Substitution of $G(\cdot)$ into the efficiency criterion yields the functional $K(u) = \Phi(u, G(u))$ incorporating only the control u as its argument. This functional is said to be *control efficiency*.

Then the *control problem* is to find an *optimal control*, i.e., a admissible control $u \in U$ ensuring the maximal efficiency: $K(u) \to \max_{u \in U}$. And the maximal efficiency is calculated as $K^* = \max_{u \in U} \Phi(u, G(u))$.

Note that this statement is elementary. In the general case, a control mechanism includes the stages of information revelation (inducing the problems of *strategy-proofness* when the agents gain by truth-telling), planning (inducing the problems of *incentive compatibility* when the agents gain by plans fulfillment) and implementation [Burkov (1977), Burkov et al. (2015), Novikov et al. (2013)].

An elementary mechanism is a mechanism containing no other mechanisms, i.e., admits no decomposition under a given level of detail. *An integrated mechanism* is a mechanism containing one or several elementary or other integrated mechanisms. Accordingly, *integration* is construction of an integrated mechanism, whereas *decomposition* is extraction of simpler mechanisms (components) for a given integrated mechanism. In the context of integration/decomposition, key issues include the *completeness* of a set of elementary mechanisms (is it possible to construct any integrated mechanism from some set using a given aggregate of elementary mechanisms?) and their *minimality* (what is the minimum complete set of elementary mechanisms?).

The elementary (*basic*) model of an OS consists of a single controlled subject (*agent*) and a single control subject (*Principal*), both making decisions one-time under complete information.

Extensions of the basic model are the following, see [Novikov (2013)]]:

1. *dynamic OS* (repeated decision-making by the participants; an extension with respect to the sequence of moves);
2. *multiagent OS* (simultaneous decision-making by several agents; an extension with respect to staff control);
3. *multilevel OS* (three or even more levels of hierarchy; an extension with respect to structure control);
4. *OS with distributed control* (the same agents controlled by several Principals; an extension with respect to structure control);
5. *OS with uncertainty* (the participants having incomplete or imperfect information on essential parameters; an extension with respect to information control);
6. *OS with joint activity constraints* (global constraints imposed on the joint choice of agents' actions; an extension with respect to institutional control);
7. *OS with information revelation* (reporting private information to other agents and/or Principal; an extension with respect to informational control).

Therefore, if the basic model uses a certain elementary mechanism, then transition to one of the first four extensions of the basic model (each treated as a set of interconnected basic models) induces *the integration problem* of elementary mechanisms in the following statement: construct a new integrated mechanism representable as an aggregate of interconnected elementary mechanisms.

Another reasonable extension of the model is consideration of an integrated mechanism decomposed into a set of elementary ones, i.e., *OS with an integrated mechanism*. However, in contrast to the above-mentioned extensions, such an extension appears inapplicable to the basic model of an OS; it should be considered with one of the first four extensions of the basic model (each treated as an aggregate of interconnected basic models). The next classification seems rational in the context of increasing the number of agents and the number of mechanisms for results systematization in theory of control in organizational systems.

OS consisting of a single Principal and a single agent:

1.1. dynamic OS with a single agent and an integrated mechanism: principal implements complex interaction with a single agent, which can be considered as a dynamic OS where the former and latter interact within different control mechanisms at different steps.

OS consisting of a single Principal and several agents:

2.1. multiagent OS with an integrated mechanism decomposable with respect to agents: Principal interacts within each elementary mechanism or a “subcomplex” of control mechanisms forming a complex with a single agent (or nonintersecting subsets of agents); and so, the OS includes a “chain” of smaller subsystems.

2.2. multiagent OS with an integrated mechanism decomposed with respect to mechanisms: Principal implements the same complex interaction with each agent. The classical “fan” structure of the OS is preserved.

2.3. multiagent OS with an integrated mechanism. Here we have a complex structure of intersections for the subsets of agents for each elementary mechanism.

OS consisting of a single Principal and several agents, more than two levels of hierarchy:

3.1. multilevel OS with an integrated mechanism. Consideration of elementary mechanisms entering an integrated mechanism involves "delegation" of authority: within some elementary mechanisms, separate agents act as intermediate-level Principals being assigned their subordinates from a subset of agents. Moreover, different situations described in the current classification are possible at different levels of hierarchy.

OS consisting of several Principals and a single agent:

4.1. OS with distributed control and an integrated mechanism decomposable with respect to Principal. A single Principal or a nonintersecting subset of Principals interacts with the agent within each elementary mechanism.

4.2. OS with distributed control and an integrated mechanism decomposable with respect to mechanisms. All Principals implement the same complex interaction with the agent. The classical "fan" structure of the OS is preserved.

4.3. OS with distributed control and an integrated mechanism. Here we have a complex structure of intersections for the subsets of Principals for each elementary mechanism.

For the multiagent OS with simultaneous decision-making of the agents, it makes sense to consider *parallel integration*. In the case of dynamic OS, multilevel OS or OS with distributed control, *series integration* arises naturally, where the "sequence" of elementary mechanisms is defined by time/causality and the decision-making procedures of the participants. Some formal models of parallel and series integration are considered below. In the general case, *networked integration* can be also studied when a network describes the causal sequence of mechanisms "interaction" and time steps match the network *front*. Under the hypothesis that a single Principal and a single agent do not interact within several mechanisms simultaneously, note that Extensions 1.1, 2.2 and 3.2 admit only series integration, whereas Extensions 2.1 and 3.1 only parallel integration. Networked integration is possible in Extensions 2.1., 2.3., 3.1 and 3.3.

In addition, an important attribute of classification is the interconnection of elementary mechanisms entering an integrated mechanism. By analogy with the classification of the incentive problem (a basic control problem) given in [Burkov et al. (2015)], introduce the notions of strongly and weakly related elementary mechanisms, as well as the notion of unrelated elementary mechanisms:

Two control mechanisms are said to be *weakly related* if the decision made within one mechanism affects only the constraints imposed on the actions of agents within the other mechanism, and conversely. For instance, the decision within the resource allotment mechanism [Novikov et al. (2013)] affects only the reward of a separate agent available to the Principal while solving the incentive problem [Novikov et al. (2013)].

Two mechanisms are said to be *strongly related* if the decision made within one mechanism affects directly the parameters and efficiency criterion of the other mechanism. For instance, the decision within the active expertise mechanism [Novikov et al. (2013)] of project assessment affects the weight of a given project during resource allocation among several projects using the priority-based resource allotment mechanism [Novikov et al. (2013)].

Accordingly, *unrelated* mechanisms are the mechanisms whose decision-making processes do not affect each other.

For integrated mechanisms, the main problem is efficiency assessment (particularly, against the efficiency of corresponding elementary mechanisms) and choice of integration methods for designing a most efficient integrated mechanism.

Also, the following general problems are open for integrated mechanisms:

1) admissibility (satisfaction of a given system of constraints);

2) consistency (sufficiency of information, "adjacenty" of sequential inputs and outputs, acyclicity of decision-making procedures);

3) completeness and minimality (see above);

4) operationability and applicability (integrated mechanism synthesis, ideally, analytical synthesis);

5) inheritance (stability) of properties of elementary mechanisms (such as efficiency, strategy-proofness, incentive compatibility, etc.) against integration and decomposition.

The forthcoming section deals with the problems of parallel and series integration.

3. PARALLEL INTEGRATION

Consider the parallel integration problem arising in integrated mechanism design from two elementary mechanisms using transition from two basic OS structures with the same Principal to the two-agent structure. The efficiencies of the first and second elementary mechanisms are

(1) $K_1^* = \max_{u_1 \in U_1} \Phi_1(u_1, G_1(u_1))$ and $K_2^* = \max_{u_2 \in U_2} \Phi_2(u_2, G_2(u_2))$.

Denote $(y_1, y_2) = \hat{G}(u_1, u_2)$; then the efficiency of the integrated mechanism is defined by analogy, i.e.,

(2) $K^* = \max_{(u_1, u_2) \in U} \Phi(u_1, u_2, \hat{G}(u_1, u_2))$.

In the context of integration, a key question concerns the relationship of the efficiencies K^* and (K_1^*, K_2^*). To answer this question, one should consider the relationship of the following elements:

1) the efficiency criteria $\Phi(\cdot)$ and $(\Phi_1(\cdot), \Phi_2(\cdot))$. As possible situations, the criterion $\Phi(\cdot)$ is monotonic, or additive, etc. with respect to the criteria $\Phi_1(\cdot)$ and $\Phi_2(\cdot)$, or coincides with the latter criterion;

2) the admissible control sets U and (U_1, U_2). As possible situations, the control actions are independent ($U = U_1 \times U_2$), or there exist resource constraints ($0 \le u_1 \le C_1$, $0 \le u_2 \le C_2 \to 0 \le u \le C_1 + C_2$), or the control actions in the integrated mechanism are unified, i.e., identical for all agents ($u_1 \equiv u_2$), and so on;

3) the agents' behavioral models $\hat{G}(\cdot)$ and ($G_1(\cdot)$, $G_2(\cdot)$). As possible situations, the agents are independent ($\hat{G}(u_1, u_2) = (G_1(u_1), G_2(u_2))$, or dependent.

If the efficiency criterion is additive, resource constraints are imposed on the control actions and the agents are independent, then clearly

(3) $K^* \ge K_1^* + K_2^*$.

The quantity $\Delta = K^* - (K_1^* + K_2^*)$ can be called *the price of integration*.

Example 1. Consider the incentive model in an OS with weakly related agents, see [Novikov (2013)]. Let $N = \{1, 2, ..., n\}$ be the set of agents, $y_i \ge 0$ the action of agent i and $c_i(y_i)$ the costs of agent i, representing a monotonically increasing convex function, $i \in N$. If $u_i(y_i)$ specifies an incentive scheme applied by the Principal, then the agent's goal function has the form $f_i(u_i, y_i) = u_i(y_i) - c_i(y_i)$ and the agent's behavioral model is described by

$$G_i(u_i, y_i) = \arg \max_{y_i \ge 0} f_i(u_i, y_i).$$

Assume that the individual rewards of the agents have given upper bounds $\{C_i\}_{i \in N}$, i.e., $\forall\, y_i \ge 0$: $u_i(y_i) \le C_i$, $i \in N$. The optimal incentive scheme of agent i is defined by [Novikov (2013)]

$$(4)\ u_i(x_i, y_i) = \begin{cases} c_i(x_i), & y_i \ge x_i \\ 0, & y_i < x_i \end{cases},$$

where $x_i \in [0; c_i^{-1}(C_i)]$ denotes the plan of agent i and $G_i(u_i(x_i, y_i)) = x_i$, $i \in N$.

The Principal earns an income from the activity of agent i, representing a monotonically increasing linear or concave function $H_i(y_i)$. In other words, the Principal's goal function has the form $\Phi_i(u_i(x_i, y_i), y_i) = H_i(y_i) - u_i(x_i, y_i)$. Substituting $G_i(u_i(x_i, y_i)) = x_i$ into this formula yields $\Phi_i(u_i(x_i, y_i), y_i) = H_i(x_i) - c_i(x_i)$. And hence,

$$(5)\ K_i^*(C_i) = \max_{x_i \in [0;\, c_i^{-1}(C_i)]} [H_i(x_i) - c_i(x_i)],\ i \in N.$$

Now, consider an integrated mechanism where the Principal controls n agents by applying the incentive scheme (4) to each of them. Suppose that the *wage fund* (WF) is bounded by R, i.e.,

$$(6)\ \sum_{i \in N} C_i \le R,$$

and the Principal's goal function is additive with respect to the criteria of the one-element problems: $\Phi(u, y) = \sum_{i \in N} [H_i(y_i) - u_i(x_i, y_i)]$; here $y = (y_1, y_2, ..., y_n)$ means the agents action vector, $y \in A' = \prod_{i \in N} A_i$, and $u = (u_1, u_2, \ldots, u_n)$ is the control vector. In this case,

$$(7)\ K^*(R) = \max_{\{x_i \in [0;\, c_i^{-1}(C_i)]\},\ \{C_i \ge 0 | \sum_{i \in N} C_i \le R\}} \sum_{i \in N} H_i(x_i) - R.$$

Obviously, (5) and (7) satisfy (3), that is, $K^* \ge \sum_{i \in N} K_i^*(C_i)$ holds for any $\{\{C_i \ge 0\}_{i \in N} \mid \sum_{i \in N} C_i \le R\}$. Therefore, the price of integration is nonnegative.

If the WF forms a variable, then its optimal value R^* can be found by solving the problem $R^* = \arg \max_{R \ge 0} K^*(R)$. Interestingly, optimal WF calculation can be treated as the series integration problem.

Concluding this example, note that the relationships between the efficiencies are defined in a somewhat simpler fashion in case of mechanisms decomposition. For instance, consider an integrated mechanism with the efficiency (2). For parallel decomposition, it is possible to determine the efficiency criteria of the first and second partial mechanisms using that of the integrated mechanism:

$$K_1^*(u_2) = \max_{u_1 \in U_1} \Phi(u_1, u_2, \mathrm{Proj}_1(\hat{G}(u_1, u_2)))$$

and

$$K_2^*(u_1) = \max_{u_2 \in U_2} \Phi(u_1, u_2, \mathrm{Proj}_2(\hat{G}(u_1, u_2))),$$

e.g., assuming that $U_1 = \mathrm{Proj}_1(U)$, $U_2 = \mathrm{Proj}_2(U)$. However, one should keep in mind that coordinate-wise optimization may give an inadmissible solution, both in the state and control action (if $\hat{G}(u_1, u_2) \ne (G_1(u_1), G_2(u_2))$ and/or $U \ne \mathrm{Proj}_1(U) \times \mathrm{Proj}_2(U)$).

In addition, an efficient parallel decomposition tool involves the *theorems on agents' game decomposition* in multi-element systems [Novikov (2013)]. Really, imagine that an optimal control mechanism is constructed where each agent possesses a dominant strategy. Then it is possible to believe that agents have independent decision-making, analyzing control mechanisms for each of them.

4. SERIES INTEGRATION

Consider the series integration problem arising in integrated mechanism design from two elementary mechanisms. For series integration, the efficiency of the first mechanism is defined by (5), i.e., $K_1^* = \max_{u_1 \in U_1} \Phi_1(u_1, G_1(u_1))$, while the efficiency of the second mechanism, as well as the admissible control set and the behavioral model of agent 2 generally depend on the control action used in the first mechanism. In other words, the efficiency of the second mechanism is

(8) $K_2^*(u_1) = \max_{u_2 \in U_2(u_1)} \Phi_2(u_2, G_2(u_1, u_2))$.

Define the efficiency of the integrated mechanism in the form

(9) $K^* = \max_{(u_1, u_2) \in U} \Phi(u_1, u_2, \hat{G}_1(u_1), \hat{G}_2(u_1, u_2))$.

Just like for parallel integration, the relationship between the efficiencies K^* and (K_1^*, $K_2^*(u_1)$) depends on the relationship of the corresponding efficiency criteria, admissible control sets and behavioral models of the agents, see above. Concerning efficiency analysis, both for series decomposition and series integration, a natural approach is consider the *terminal* value of the efficiency that corresponds to the last step ("time moment"), as illustrated by the expressions (8) and (9). In the context of "economic" applications, the efficiency criterion of an elementary control mechanism associated with some step of the sequence can be the "value added" at this step (in terms of the terminal criterion).

In the case of additive efficiency criteria that corresponds to transition from the static model of an OS to its dynamic counterpart, the expression (9) acquires the form

(10) $K^* = \max_{u_1 \in U_1} \max_{u_2 \in U_2(u_1)} \{\Phi_1(u_1, G_1(u_1)) + \Phi_2(u_2, G_2(u_1, u_2))\}$.

This yields the following analog of Bellman's optimality principle:

(11) $K^* = K_1^* + \max_{u_1 \in U_1} K_2^*(u_1)$.

Obviously, $\forall u_1 \in U_1 : K^* \geq K_1^* + K_2^*(u_1)$.

5. STRATEGY-PROOFNESS OF INTEGRATED MECHANISMS

In sections 3 and 4, the relationship between the efficiencies of elementary and resulting integrated mechanisms has been considered. Similar questions can be formulated regarding strategy-proofness, namely,

1) is an integrated mechanism constructed from a set of elementary strategy-proof mechanisms strategy-proof?

2) assume that, for elementary control problems, an efficient solution belongs to the class of strategy-proof mechanisms. If a complex control problem consists of such elementary problems, does its solution belong to the class of mechanisms "assembled" from the strategy-proof integrated mechanisms?

A clue to these questions is how far a complex control problem can be decomposed in terms of the following aspects. First, how deep are the relations between the elementary mechanisms within an integrated mechanism. Second, how strong are the mutual interests of the agents within elementary mechanisms, and how this is formalized in terms of the goal functions of the agents. The whole essence is that strategy-proofness of an integrated mechanism can be considered as strategy-proofness in a planning problem in a multidimensional space: for each mechanism, planning runs in an appropriate parameter subspace. As shown for this class of problems (e.g., see [Bondarik, Korgin (2013), Korgin, (2014)]), strategy-proof mechanisms exist if the interests of the agents are formalized by multidimensional single-peaked preference functions where the best value for any planned parameter [Barberá (2011)] is independent of the values of the other planned parameters. And strategy-proof mechanisms must not be strongly related. An efficient solution belongs to the class of strategy-proof mechanisms only in the situations where each agent is interested in at most one planned parameter [Korgin (2014), Moulin (2015)].

Therefore, a positive answer to the first question is expected for the weakly related elementary mechanisms forming an integrated mechanism, or for the integrated mechanisms decomposable with respect to agents (extension 2.1). And a positive answer to the second question is expected for the integrated mechanisms decomposable with respect to agents.

And finally, for control mechanisms, the issue of strategy-proofness is complementary to that of equivalence [Burkov et al. (2015)]. This issue admits the following statement in the case of integrated control mechanisms. Consider a two-level OTS with some planning mechanism; does there exist a three-level OTS with the same staff of the agents and an integrated planning mechanism in this system such that the equilibrium messages and the assigned plans in these OTS coincide? This problem is called *the ideal aggregation problem of planning mechanisms*, see [Novikov (2016b)].

CONCLUSION

There exist no general methods to design analytically an optimal complex of control mechanisms for organizational systems, making it necessary to systematize and separate corresponding special cases. Their possible classification has been given above.

A global challenge is to establish most general conditions for the control mechanisms stable against integration. Such conditions can be compared with the decomposition conditions in optimization for reducing solution of a complex problem to a set of simpler problems (these approaches were developed for a long time in optimization [Pervozvanskii, Gaitsgori (1979), Tsurkov (1981), Lasdon (1970), Nesterov (2014)], coordination of hierarchical decisions [Burkov 1977, Germeier (1986)], hierarchical modeling [Mesarovic, Mako, Takahara (1970), Novikov (2016b)], etc.; nowadays, most intensive investigations are in the field of distributed optimization [Boyd et al. (2011), Ren, Yongcan(2011)], see surveys in [Novikov (2016a, 2016b)]).

Indeed, revelation of the constraints induced by integration is akin to decomposition of the solution of an optimization problem (for paralleling) and to ideal aggregation; however, here the united "components" (control mechanisms) are essentially heterogeneous, while separate mechanisms are connected via a common optimality criterion and, moreover, via "technological" relations involving common variables fixed by one mechanism and adopted by the other mechanism, shared resource constraints, and so on.

Project management and network scheduling methods (particularly, network programming [Burkov, Burkova (2012)]) can be fruitful in integrated mechanism analysis. Really, system functioning with a given integrated mechanism can be represented as a network without loops, whose nodes answer information processing centers or production centers and arcs express informational or technological links. Such a representation resembles system description as a business process, except that in some (active) nodes decisions are made by an agent pursuing individual interests. As a rule, system functioning is decomposed in periods, and each period can be therefore treated as a project. For efficiency assessment of an integrated mechanism, one has to estimate system potential (the maximum value of the goal function under complete awareness and fulfillment of all plans). Under a given set of mechanisms and accepted behavioral models of the agents, comparing the efficiency assessment with this potential allows judging the efficiency of the integrated mechanism.

A promising research is to develop an analysis-synthesis theory for the integrated mechanisms of organizational control using the game-theoretic and optimization-based models and methods. The presence of a library of elementary mechanisms and their efficient integration rules would appreciably simplify integrated mechanism design for organizational control, bringing MD closer to the needs of modern management. In the context of practice, the corresponding theoretical results can be a foundation for applications-oriented integrated reengineering of control mechanisms for business, public administration, etc.

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