Development of a stimulating mechanism for the coordinated management of agents’ resources in the implementations of joint projects

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Abstract. This article is devoted to the development of a mechanism that makes it possible to increase the efficiency of agent resource management by forming an optimal package of projects and a coordinated distribution of profits from its implementation. A feature of the proposed mechanism is its focus on stimulating agents to be active at the stages of initialization and implementation of merger projects. The proposed approach is based on mathematical models and methods. At the first stage of the mechanism, it is proposed to find the optimal package of projects on the basis of a discrete optimization model. To implement the second stage, associated with the distribution of the obtained profit, the concept of an agreed profit distribution is introduced and its connection with the solution of a cooperative game is described. The basis of the stage is the algorithm of the agreed profit distribution taking into account the activity of agents. The developed software product allows you to automate the practical calculations of the stages of the mechanism.

1. Introduction

One of the forms of interaction of elements (agents) of a socio-economic system of any level is unification or cooperation, formed on the basis of the principles of organization or self-organization. Economic examples can be various associations of economic entities — financial and industrial groups, holdings, associations, concerns, etc. [1–3].

By uniting, agents create a subsystem, which, as a rule, is of a temporary nature. The motive for cooperation is the receipt of additional benefits due to the achievement of a synergistic effect, and its necessary condition is the presence of common interests of the participants. These interests are transformed into system-wide interests of the association, common goals and joint projects.

One of the most important tasks of the management center of the association is the effective management of the aggregate resources of agents. On the one hand, the problem arises of choosing the optimal set of projects that ensure the merger receives the maximum benefit (profit). On the other hand, each agent pursues private interests and is interested in obtaining the largest possible share of the total profit. Therefore, the process of distribution of profits from the implementation of projects to unite agents is of a conflicting nature. The search for innovative
mechanisms that ensure effective management of agents’ resources in the implementation of projects, as well as the coordinated distribution of profits, taking into account the interests and contributions of each participant, is an urgent task. Its solution is impossible without the involvement of mathematical methods and models.

The theoretical basis for solving this problem was provided by advanced domestic and foreign research in the field of formation and functioning of integrated business structures and associations, resource management (including project management), harmonization of interests and incentives for agents.

A fairly large amount of scientific literature is devoted to the issues of studying integrated structures, in particular, integrated business entities. Researchers study the organization of structures, connections between elements, interaction in the economic and legal field [1–4].

The formation of mechanisms for the distribution of centralized resources between active agents in organizational systems is the subject of numerous works by V. N. Burkov, D. A. Novikov, A. V. Shchepkin and others [5, 6]. The issues of resource allocation in planning and implementing projects are studied in the works of S. A. Barkalov, P. N. Kurochka, P. Brucker, C. Artigues and many others [7–10]. The issues of harmonizing the interests of counterparties in the context of the theory of contracts are discussed in detail in the works of J. Tyrol, P. Bolton, E. Berlinger, A. Lovas and others [11–13].

Algorithms for reconciling interests between enterprises of a financial and industrial group when formning an innovation plan are presented in [14]. The paper considers the distribution of profits in proportion to the invested funds. Our analysis of the proposed algorithms showed that such a distribution of profits can lead to a conflict of interests and the exit of an agent (group of agents) from the association. In addition, one of the assumptions of the approach is the lack of priority in making a profit, which leads to insufficient motivation for the active implementation of projects.

The mathematical approach to reconciling conflicting participants (players) in a conflict situation (game) is investigated within the framework of the theory of cooperative games or games in the form of a characteristic function [15–17]. The substantiated theoretical provisions related to the construction of non-dominated divisions that form the C-core are taken as the basis for the approach to the coordinated distribution of the profit of a pooling proposed in this article. It is taken into account that the division of the C-cores has a number of disadvantages, including the multiplicity of elements and the impossibility of taking into account the activity of each participant in achieving the goals of the union.

The approach proposed in this article to the choice of the only distribution of the agents’ joint profit is based on motivating agents to actively participate in the initialization and implementation of projects. This is explained by the fact that the activity of agents significantly affects the size of the pool profit. The solution to this problem is based on modern mechanisms of motivation in organizational, hierarchical and socio-economic systems, presented in the works of Yu. V. Bondarenko, I. V. Goroshko, D. A. Novikov, O. I. Gorbaneva, G. A. Ougolnitsky and many others [5, 18–20].

The purpose of this study is to develop a stimulating mechanism for coordinated management of agents’ resources that allows:

– improve the efficiency of agent resource management by ensuring a synergistic effect from joint implementation of projects;
– stimulate agents to be actively involved in the initiation and implementation of profitable merger projects;
– coordinate the interests of agents in the distribution of profits from the implementation of projects, providing each agent with the benefits of cooperation from the standpoint of achieving their own goals.

A distinctive feature of the mechanism proposed in this work is that it not only ensures the
coordination of the interests of the agents and the stability of the association, but also stimulates the agents to actively participate in the projects of the association. The software implementation of the mechanism makes it convenient for practical use.

2. Materials and methods
We will consider an active system that includes the following elements:
- control center (CC);
- agents, the number of which we denote by \( n \).

The role of an agent can be an enterprise, an individual, an association of business entities, an organization, etc. As an important property of agents, we note their activity — the ability to formulate their own goals and a certain independence in making decisions to achieve goals.

We believe that each agent \( A_i \), where \( i = 1, \ldots, n \), has \( M \) types of resources that he is ready to invest in the implementation of projects. These resources include financial resources, material resources, fixed assets, labor resources, etc.

We represent the amount of resources available for investment of each agent as a set:

\[
R^i = (R^i_1, R^i_2, \ldots, R^i_M),
\]

where \( R^i_m \) — amount of agent \( A_i \) type resource \( m \), where \( R^i_m \geq 0 \), \( m = 1, \ldots, M \).

By being proactive in making investment decisions, each agent can:
- independently, with your own funds, form and implement a package of projects;
- uniting with other agents of the system, transfer resources to the control center ("centralized fund" of the system) for the implementation of joint projects.

We believe that the economic goals of decision-making by individual agents is to maximize their own profits from the implementation of projects. The goals of the control center are to improve the efficiency of the system as a whole and to preserve its systemic properties.

The incentive mechanism proposed in this work for the coordinated management of agents’ resources in the implementation of joint projects includes two enlarged stages:

**Stage 1.** Formation of an optimal package of projects that ensures the receipt of the maximum aggregate profit of combining agents.

**Stage 2.** Coordinated distribution of profits between agents, ensuring a compromise of interests and incentives for agents to actively participate in the initiation and implementation of projects.

At the first stage, each agent \( A_i \) sends to the management center his proposals for options for those projects in the implementation of which he is interested:

\[
P^i = \{P^i_1, P^i_2, \ldots, P^i_{Q_i}\},
\]

where \( Q_i \) — number of projects, \( P^i \) — many projects, \( P^i_1, \ldots, P^i_{Q_i} \) — list of agent \( A_i \) projects.

We believe that each project is designed for a certain period of time (for example, one year). The agent \( A_i \) for each of his projects \( P^i_q \) (\( i = 1, \ldots, n \), \( q = 1, \ldots, Q_i \)) calculates:
- \( c_{mq}^i \) — the amount of expenditure of resources of each type \( m \),
- the amount of benefit (profit) \( \Pi_{iq}^i \geq 0 \), that is expected to be obtained from the implementation of the project \( q \).

In addition, each agent offers its own resources in quantities of \( R^i_1, R^i_2, \ldots, R^i_M \).

At the same time, the agent’s own resources may be sufficient or insufficient for the independent implementation of projects of a set \( P^i \).

Thus, the control center receives information about a variety of merger projects:

\[
P = \bigcup_{i=1}^n P^i = \{P^1, P^2, \ldots, P^n\} = \{P^1_1, P^2_1, \ldots, P^1_{Q_1}, \ldots, P^n_1, \ldots, P^n_{Q_n}\},
\]
as well as the available quantities of each type of resource:

\[ R_m = \sum_{i=1}^{n} R_{iq}, \quad m = 1, M. \]

The practical implementation of the first stage of the mechanism (the formation of an optimal package of system projects) is proposed to be carried out on the basis of solving the optimization problem.

Let us introduce the following binary variables:

\[ y_{iq} = \begin{cases} 
1, & \text{if the project } P^i_q \text{ is included packed,} \\
0, & \text{otherwise}
\end{cases} \]

The mathematical problem of forming an optimal package of system projects has the following form:

\[ f(y) = \sum_{i=1}^{n} \sum_{q=1}^{Q_i} \Pi_{iq} \cdot y_{iq} \rightarrow \max, \]  

\[ \begin{align*} 
\sum_{i=1}^{n} \sum_{q=1}^{Q_i} c_{mq} \cdot y_{iq} & \leq R_m, \quad m = 1, \ldots, M, \\
y_{iq} & \in \{0, 1\}, \quad i = 1, \ldots, n; \quad q = 1, \ldots, Q_i.
\end{align*} \]  

Problem (1)–(2) is a multidimensional knapsack problem, for which the branch and bound method can be chosen. If the constraint system (2) contains one inequality, then (1)–(2) is a knapsack problem. The latter is possible when, for example, agents allocate only financial resources for the implementation of projects.

The solution to problem (1)–(2) is the optimal vector of values of the variables:

\[ y^* = (y_{11}^*, \ldots, y_{1Q_1}^*, \ldots, y_{n1}^*, \ldots, y_{nQ_n}^*). \]

Based on the obtained solution to the problem \( y^* \):

- an optimal package of projects for combining (system) agents is formed

\[ P^* = \{ P_q^i \in P \mid y_{iq}^* = 1 \}, \]

- the optimal profit of the merger is calculated

\[ f^* = f(y^*), \]

which is expected from the implementation of the optimal package of projects.

The second stage of the mechanism is the construction of a rule and an algorithm for the distribution of profits \( f^* \) between the agents of the system.

Let us denote by \( \tilde{f}_i \) the amount of profit that the agent \( A_i \) receives as a result of distribution \((i = 1, \ldots, n)\).

Then \( \tilde{f} = (\tilde{f}_1, \tilde{f}_2, \ldots, \tilde{f}_n) \) is the required set (vector) of profit distribution.

Moreover, it is obvious \( \tilde{f}_i \geq 0 \) that for all \( i = 1, \ldots, n \) and \( \sum_{i=1}^{n} \tilde{f}_i = f^* \).

We introduce the following definition.

We will say that the distribution \( \tilde{f} \) provides a compromise of interests of the agents of the system, or is consistent, if the following consistency condition is satisfied: it is not profitable
for any of the associations of agents to independently implement their own projects, separating from the other agents of the system.

For a formal description of the consistency condition, consider the set of indices of agents in the system: \( I = \{1, 2, \ldots, n\} \), as well as all possible nonempty subsets of this set (coalitions of agents), the number of which is the \( 2^n - 1 \). Subset including agents with numbers \( i_1, i_2, \ldots, i_k \) we denote as \( I_{i_1,i_2,\ldots,i_k} \).

Let \( f^*_i \) be the profit that a coalition of agents can independently obtain through the implementation of their own projects \( I_{i_1,i_2,\ldots,i_k} \).

Within the introduced notation, the consistency condition can be formalized as the following system of inequalities:

\[
\begin{align*}
\widetilde{f}_i & \geq f^*_i, \quad i = 1, \ldots, n; \\
\widetilde{f}_{i_1} + \widetilde{f}_{i_2} + \cdots + \widetilde{f}_{i_k} & > f^*_1 + f^*_2 + \cdots + f^*_k, \quad \forall I_{i_1,i_2,\ldots,i_k} \subseteq I; \\
\widetilde{f}_1 + \widetilde{f}_2 + \cdots + \widetilde{f}_n & = f^*.
\end{align*}
\]

Inequalities highlighted in the first line of conditions (3), in the theory of cooperative games, are called the conditions of individual rationality, and in the last line — the conditions of collective rationality [15, 16].

The value of the profit \( f^*_i \) of each individual agent in system (3) can be calculated by the control center as the maximum value of the agent’s profit \( A_i \), that he can receive as a result of the implementation of his own projects with his own resources. The model that allows you to make such calculations is as follows:

\[
f_i(x^i) = \sum_{q=1}^{Q_i} \Pi_{iq} \cdot x_{iq} \rightarrow \max,
\]

\[
\sum_{q=1}^{Q_i} c_{iq}^m \cdot x_{iq} \leq R^m_i, \quad m = 1, \ldots, M,
\]

\[
x_{iq} \in \{0, 1\}, \quad q = 1, \ldots, Q_i.
\]

Model variables (4)–(5) are binary. If at the optimal point \( x^*_iq = 1 \), then the project \( q \) is included in the agent’s optimal project package \( A_i \), and if \( x^*_iq = 0 \), that is not. Then \( f^*_i = f_i((x^i)^*) \) is the optimal value of the goal function.

Problem (4)–(5), like problem (1)–(2), belongs to the multidimensional knapsack problem and can be solved by the same methods.

A similar problem is formed to calculate the profit of each coalition of agents \( I_{i_1,i_2,\ldots,i_k} \):

\[
f_{i_1,i_2,\ldots,i_k}(z) = \sum_{i \in I_{i_1,i_2,\ldots,i_k}} \sum_{q=1}^{Q_i} \Pi_{iq} \cdot z_{iq} \rightarrow \max,
\]

\[
\sum_{i \in I_{i_1,i_2,\ldots,i_k}} \sum_{q=1}^{Q_i} c_{mq}^i \cdot z_{iq} \leq R^1_i + R^2_i + \cdots + R^h_i, \quad m = 1, \ldots, M,
\]

\[
z_{iq} \in \{0, 1\}, \quad i \in I_{i_1,i_2,\ldots,i_k}, \quad q = 1, \ldots, Q_i.
\]

The optimal values of the binary variables \( z^*_iq \) of the model (6)–(7), similarly to the variables of problems (1)–(2) and (4)–(5), determine the set of projects that provides the coalition of agents with the maximum profit in the amount:

\[
f^*_{i_1,i_2,\ldots,i_k} = f_{i_1,i_2,\ldots,i_k}(z^*)
\]
It can be shown that the optimal values of the goal functions of problems (1)–(2), (4)–(5), and (6)–(7) have the following properties:

1) the sum of the optimal values of the goal function $n$ of problems (4)–(5) for each individual agent does not exceed the optimal value of the goal function of the problem (1)–(2):

$$f_{i1}^* + f_{i2}^*$$

2) for any two disjoint coalitions of agents $I_1$ and $I_2$ the following inequality holds:

$$f_{i1}^* + f_{i2}^* > f_{i1}^* + f_{i2}^*$$

The noted properties guarantee the existence of a solution to system (3) and allow us to consider the problem of profit distribution as a game in the form of a characteristic function, and the solution of the system of inequalities (3) (agreed profit distribution) as an element of the C-core [15].

Note that the agreed profit $\tilde{f} = (\tilde{f}_1, \tilde{f}_2, \ldots, \tilde{f}_n)$, distribution, which is a solution to system (3), stimulates agents to actively search for projects that ensure high profits.

System (3) can have many solutions, each of which is a consistent profit distribution. It seems logical that the final distribution of profits should not only have the property of consistency, but also motivate agents to actively participate and initiate projects, both present and future. As a basis for the formation of such a distribution of profits, it is proposed to use quantitative indicators of the activity of each agent in the implementation of projects.

**Algorithm for the agreed distribution of profits taking into account the activity of agents**

**Step 1.** The control center for each agent $A_i$ forms the lower $\Delta_i$ and upper $\Delta_i$ boundaries of the incentive premium $\Delta_i$, where $\Delta_i \in [\Delta_i, \Delta_i]$.

**Step 2.** The experts of the management center determine $\alpha_i$ — a quantitative indicator of the agent’s activity $A_i$, $\alpha_i > 0$, $\sum_{i=1}^{n} \alpha_i = 1$.

**Step 3.** Solution of the problem of forming the optimal vector of the agreed distribution of agents’ profit taking into account the activity:

$$\sum_{i=1}^{n} \alpha_i \cdot \frac{\Delta_i - \Delta_i}{\Delta_i - \Delta_i} \rightarrow \max,$$

$$\begin{align*}
\tilde{f}_i & \geq f_i^* + \Delta_i, & i = 1, \ldots, n; \\
\tilde{f}_i + \tilde{f}_i + \ldots + \tilde{f}_i & \geq f_{i1, i2, \ldots, i_k}^* \quad \forall I_{i1, i2, \ldots, i_k} \subset I, \\
\tilde{f}_i + \tilde{f}_2 + \ldots + \tilde{f}_n &= f^*, \\
\Delta_i & \in [\Delta_i, \Delta_i].
\end{align*}$$

Since problem (8)–(9) with variables $\tilde{f}_i$, $\Delta_i$ (where $i = 1, \ldots, n$) is a linear programming problem, the simplex method can be chosen to solve it. The optimal solution to the problem $f^* = (f_1^*, f_2^*, \ldots, f_n^*)$ is a consistent profit distribution, taking into account the activity of agents.

### 3. Results and discussion

For the practical implementation of the incentive mechanism for coordinated resource management of agents, a software product has been developed. The program is written in the C# programming language in the Microsoft Visual Studio Enterprise 2015 development environment version 14.0.25431.01.

Let’s give an example of practical calculations.
Consider a union that includes three agents: $A_1$, $A_2$, $A_3$.
The agent $A_1$ offers 4 projects for implementation: P 11, P 12, P 13, P 14.
The agent $A_2$ offers the following projects: P 21, P 22, P 23, P 24.
The agent $A_3$ offers five projects: P 31, P 32, P 33, P 34, P 35.
We believe that only the financial resources of agents are involved in the implementation of projects. The projects of each agent, the costs of their implementation, the planned profit from the implementation of each project and the financial resources of each agent, expressed in conventional monetary units, are presented in table 1.

Table 1. Initial data.

| Agents | Projects | Project implementation costs, monetary units | Profit from project implementation, monetary units | Agent’s financial resources, monetary units |
|--------|----------|---------------------------------------------|-------------------------------------------------|-------------------------------------------|
| Agent 1 | P 11     | 200                                         | 70                                              | 600                                       |
|        | P 12     | 250                                         | 64                                              |                                           |
|        | P 13     | 120                                         | 18                                              |                                           |
|        | P 14     | 300                                         | 120                                             |                                           |
|        | P 15     | 150                                         | 18                                              |                                           |
| Agent 2 | P 21     | 180                                         | 57.6                                            | 300                                       |
|        | P 22     | 250                                         | 75                                              |                                           |
|        | P 23     | 100                                         | 25                                              |                                           |
|        | P 24     | 200                                         | 36                                              |                                           |
| Agent 3 | P 31     | 400                                         | 72                                              | 1000                                      |
|        | P 32     | 300                                         | 36                                              |                                           |
|        | P 33     | 200                                         | 10                                              |                                           |
|        | P 34     | 300                                         | 80                                              |                                           |
|        | P 35     | 500                                         | 100                                             |                                           |

The results of solving optimization problems of forming an optimal package of unification projects (1)–(3), each agent separately (4)–(5) and coalitions of agents (6)–(7) are presented in table 2.

Table 2. Results of solving problems of forming optimal project packages.

| Agents           | Optimal package of projects | Optimal profit |
|------------------|-----------------------------|----------------|
| Agent 1          | P 11, P 14                 | 190            |
| Agent 2          | P 21, P 23                 | 82.6           |
| Agent 3          | P 33, P 34, P 35           | 190            |
| Agent 1, Agent 2 | P 11, P 13, P 14, P 21, P 23 | 290.6         |
| Agent 1, Agent 3 | P 11, P 12, P 14, P 34, P 35 | 434            |
| Agent 2, Agent 3 | P 21, P 22, P 34, P 35     | 312.6          |
| Union            | P 11, P 12, P 13, P 14, P 21, P 22, P 23, P 24, P 34 | 545.6          |
As the calculation results showed, the optimal package of projects for combining agents included four agent $A_1$, projects, four agent $A_2$ projects and only one project $A_3$.

The agreed distribution of profit is a vector $\tilde{f} = (\tilde{f}_1, \tilde{f}_2, \tilde{f}_3)$ whose coordinates satisfy the conditions of individual and collective rationality:

$$\tilde{f}_1 \geq 190, \quad \tilde{f}_2 \geq 82.6, \quad \tilde{f}_3 \geq 190, \quad \tilde{f}_1 + \tilde{f}_2 + \tilde{f}_3 = 545.6.$$ 

Let us choose the following values of agents’ activity indicators:

$$\alpha_1 = 0.4, \quad \alpha_2 = 0.5, \quad \alpha_3 = 0.1.$$ 

Selected intervals for changing the incentive allowance:

$$40 \leq \Delta_1 \leq 50, \quad 5 \leq \Delta_2 \leq 40, \quad 2 \leq \Delta_3 \leq 10.$$ 

Model (8)–(9) takes the following form:

$$\begin{align*}
0.4 \left( \frac{\Delta_1 - 40}{10} \right) + 0.5 \left( \frac{\Delta_2 - 5}{35} \right) + 0.1 \left( \frac{\Delta_3 - 2}{8} \right) \to \max, \\
\begin{cases}
\tilde{f}_1 - \Delta_1 \geq 190, \\
\tilde{f}_2 - \Delta_2 \geq 82.6, \\
\tilde{f}_3 - \Delta_3 \geq 190, \\
\tilde{f}_1 + \tilde{f}_2 \geq 290.6, \\
\tilde{f}_1 + \tilde{f}_3 \geq 434, \\
\tilde{f}_2 + \tilde{f}_3 \geq 312.6, \\
\tilde{f}_1 + \tilde{f}_2 + \tilde{f}_3 = 545.6, \\
40 \leq \Delta_1 \leq 50, \quad 5 \leq \Delta_2 \leq 40, \quad 2 \leq \Delta_3 \leq 8.
\end{cases}
\end{align*}$$

The solution to the problem is the following agreed distribution of profit, taking into account the activity of agents:

$$\tilde{f}_1 = 233, \quad \tilde{f}_2 = 111.6, \quad \tilde{f}_3 = 201.$$ 

The resulting profit distribution vector belongs to the C-core, i.e. is undominated. With such a distribution, it is beneficial for all agents and coalitions to unite for joint implementation of projects. Taking into account the coefficients of significance and intervals of a stimulating additive motivates agents to actively search for and implement effective projects for combining.

Let’s compare the obtained calculations with the distribution of profits in proportion to the invested funds and the distribution of profits according to the principle in proportion to the residual funds [14].

If we are guided by the principle of distribution of profits in proportion to the funds invested in projects, then the agents will receive, respectively, 216.2, 95.7 and 233.68 monetary units. At the same time, we note that according to this distribution $A_3$, the one who submitted less profitable projects, but a larger amount of finance, is in a more advantageous position than the first agent.

If the funds are distributed according to the residual value principle, then each agent will receive 259.17, 96.43 and 190. In this case, Agent 3 does not receive additional funds, which makes it unprofitable for him to combine. Moreover, it is beneficial for Agent 2 and Agent 3 to pool their resources and implement projects on their own.

The above comparative analysis confirms the advisability of applying the approach presented in this article.
4. Conclusion
This article has developed a stimulating mechanism for coordinated resource management of agents in the implementation of joint projects, which is based on mathematical models and methods. At the first stage of the mechanism, an optimal package of union tests is formed based on the proposals of agents and their resource capabilities. It is proposed to form the optimal test package that ensures the highest merger profit is based on the solution of the discrete optimization problem. At the second stage of the mechanism, an agreed distribution of profits between agents is carried out. The paper introduces the concept of a consistent distribution of profits, provides a condition for consistency and substantiates that such a distribution of profit is the C-core of the game in the form of a characteristic function. It is proposed to select the only consistent distribution vector from the set of possible ones based on the indicators of agents’ activity in the initialization and implementation of projects based on the developed algorithm. This distribution ensures not only the coordination of the interests of the members of the association, but also motivates them to be active, aimed at obtaining the greatest profit from the association. The developed software product made it possible to carry out practical calculations, and the discussion of the results with the heads of the companies of Voronezh confirmed the practical significance of the mechanism and allowed to outline the ways of its further development.

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