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Incentive schemes in development of socio-economic systems

V V Grachev, K A Ivushkin and L P Myshlyaev

1 Siberian State Industrial University, 42 Kirova street, Novokuznetsk, 654007, Russia
2 Consolidated Company “Sibshakhtostroy” LLC, 9 Kuznetskoye highway, Novokuznetsk, 654034, Russia

E-mail: mail@nicsu.ru

Abstract. The paper is devoted to the study of incentive schemes when developing socio-economic systems. The article analyzes the existing incentive schemes. It is established that the traditional incentive mechanisms do not fully take into account the specifics of the creation of each socio-economic system and, as a rule, are difficult to implement. The incentive schemes based on the full-scale simulation approach, which allow the most complete information from the existing projects of creation of socio-economic systems to be extracted, are proposed. The statement of the problem is given, the method and algorithm of the full-scale simulation study of the efficiency of incentive functions is developed. The results of the study are presented. It is shown that the use of quadratic and piecewise linear functions of incentive allows the time and costs for creating social and economic systems to be reduced by 10%-15%.

1. Introduction

The need to stimulate the work executors when creating socio-economic systems is obvious. Timing for the implementation of specific project operations and, in general, the creation of the entire socio-economic system depend on the stimulation of performers quantitatively and sometimes qualitatively.

Until the 90’s of the last century, a great number research materials and studies were devoted to stimulation in the construction industry [1-7]. In the works both material and moral forms of stimulation were considered. Some of them [1, 2, 5] mentioned the necessity for stimulation as a means of improving and accelerating the construction industry without specific methodological recommendations. Others considered practical ways of stimulating [3, 4, 7], focusing, as a rule, on research methods of moral effect, for example, socialist competitions.

However, the transition to a market economy, a change in the participants in the construction industry and the demands placed on them required additional study of issues related to the stimulation of construction production as a factor of its acceleration. In the late twentieth century, within the framework of the science “Project Management” (a section of the theory in management of socio-economic systems), the study of incentive mechanisms was carried out in the theory of active systems, in the theory of hierarchical games, in contract theory [8-14].

2. Analysis of previous studies

The greatest results in the development of the theoretical foundations of incentive mechanisms in Russia were achieved by the researchers of the Institute of Problems of Management of the Russian Academy of Sciences (Moscow): Burkov V.N., Novikov D.A., Tsvetkov A.V., Kochiyeva T.B., Zalozhnev A.Yu. and others.
In [11, 15-16] four basic incentive schemes are distinguished: jump-like (C-type), compensatory (K-type), proportional (L-type), incentive schemes based on income redistribution (D-type).

Jump-like incentive schemes \( \delta_c(x, y) \) (C-type) [15] are characterized by the fact that the agent (performer of operations) receives a permanent reward (equal to the pre-set value of C), provided that the chosen action \( y \) is not less than the specified \( x \); and zero reward – if less actions are selected (figure 1):

\[
\delta_c(x, y) = \begin{cases} 
C, & y \geq x; \\
0, & y < x.
\end{cases}
\]  

(1)

\[\begin{array}{c}
\sigma_c(x, y) \\
\hline
C \\
\hline
0 \\
-\end{array}\]

\[\begin{array}{c}
x \\
\hline\end{array}\]

\[\begin{array}{c}
y \\
\hline\end{array}\]

Figure 1. Jump-like incentive scheme (C-type).

Compensatory incentive scheme \( \delta_k(x, y) \) (K-type) is characterized by the fact that the agent is compensated for costs, provided that his actions lie in a certain range, given, for example, by restrictions on the absolute amount of individual compensation:

\[
\delta_k(x, y) = \begin{cases} 
c(y), & y \leq x; \\
0, & y > x;
\end{cases}
\]  

(2)

where \( x \leq c^{-1}(C), c^{-1}(\cdot) \) is the function inverse to the cost function of the agent, that is, the center can compensate the agent for costs if \( y \leq x \) and not pay for the choice of large actions (figure 2).

\[\begin{array}{c}
\sigma_k(x, y) \\
\hline
c(x) \\
\hline
0 \\
-\end{array}\]

\[\begin{array}{c}
x \\
\hline\end{array}\]

\[\begin{array}{c}
c(y) \\
\hline\end{array}\]

\[\begin{array}{c}
y \\
\hline\end{array}\]

Figure 2. Compensatory incentive scheme (K-type).

Proportional incentive schemes \( \delta_l(y) \) (L-type). In practice, wage systems based on the use of constant rates of payment are widespread: time-based payment implies the existence of a rate of
payment for a unit of working time (usually an hour or a day), piece-rate payment – the existence of a rate of payment per unit of output, etc. These payment systems are combined by the fact that the remuneration of an agent is directly proportional to its effect (the number of hours worked, the volume of output, etc.), and the payment rate \( \alpha > 0 \) is the proportionality coefficient (figure 3):

\[
\delta_L(y) = \alpha \cdot y
\]

\( \sigma_L(y) \)

\( c(y) \)

\( \sigma_L(y) \)

\( y \)

\( 0 \)

Figure 3. Proportional incentive scheme (L-type).

Incentive schemes based on income redistribution \( \delta_D(y) \) (D-type) use the following idea. Since the center expresses the interests of the system as a whole, it is possible to conditionally identify its income and income from the activities of the entire organizational system. Therefore, it is possible to base the agent’s incentive on the amount of the center’s revenue – set the agent’s reward equal to a certain (for example, constant) share of the center’s income:

\[
\delta_D(y) = \xi \cdot H(y).
\]

where \( H(y) \) is the function of the center’s income, \( \xi \in [0; 1] \).

Based on the four basic incentive schemes considered above, the systems derived from them are formed, for example CL-type, QD-type.

“The task of stimulation is to choose the optimal incentive scheme that has the maximum efficiency” [15, p. 15]. However, considering various incentive schemes, the authors of the works do not describe methods, algorithms for determining the optimal stimulation system. In works [11, 15-16], the researchers take a priori some stimulation systems, “guess” them, resorting to heuristic procedures, without evaluating the formalized effectiveness of structures of stimulating functions. “One can guess the optimal stimulation system based on substantive considerations, and then correctly justify its optimality” [15, p. 21].

The considered basic incentive schemes – C, K, L, D-type, in our opinion, in practice will not give the proper result. For example, a C-type incentive approach does not encourage the agent – contractor to complete the operation in the shortest possible time. The agent, having received compensation for the achieved action – operation performed over period of time \( T > T^{\text{Min}} \), will not in the future strive to reduce the time of the operation. When stimulating the K-type, the cost function of the agent \( c(y) \) is usually unknown. Agents can distort it in various ways, seeking only to obtain the maximum amount of compensation without shortening the duration of the operation to \( T^{\text{Min}} \). Proportional incentive schemes – L-type do not ensure the implementation of the decreasing returns law [17]. The essence of this law is that each subsequent day of reduction in the operation duration requires more stimulation
than the previous one. With proportional incentive schemes, there is no such increase in funding with a reduction in duration of operations – for each day of duration reduction a fixed amount of stimulus is allocated.

Besides, D.A. Novikov, V.N. Burkov, V.A. Pogozhiya [8, 11, 14-15] in their research, when considering the structures of incentive functions, do not pay due attention to the objects, they are not described as such. Using the game approach, the authors analyze the stimulating functions purely analytically, in absolute terms, without using historical information from previous objects. This approach, based only on analytical methods, requires the construction and use of complex models, attracting a cumbersome mathematical apparatus. Analytical methods are very diverse and strongly depend on the model of the system under study. The variety of these methods is caused, on the one hand, by the desire to obtain a solution analytically, since such solution, as a rule, gives a broader idea of the dependence of the efficiency of stimulating functions on parameters and conditions, and, on the other hand, the mathematical difficulties in obtaining solutions that in different special cases are overcome in their own way. It is typical that, especially for complex systems the application of analytical methods is possible only with substantial simplifications. Thus, in the case of application of analytical methods, it is usually possible to obtain the characteristics of some simplified model of the system.

It is necessary to find new ways for solving the effectiveness evaluation of incentive functions with the most complete extraction of information from existing projects. That is possible with the use of the method of full-scale mathematical modeling [18-20].

From this standpoint, the statement of the problem in the general case can be represented in the following form.

3. Statement of the research task

**Given:** 1. A set of structures of stimulating functions \( S_{t,j}(T) \) for performing operations:

a) linear function

\[
S_{t,j} = a \cdot T_j + b,
\]  

b) piecewise linear function

\[
S_{t,j} = \begin{cases} 
        a_1 \cdot T_j + b_1, & \text{if } T_j^{\text{min}} \leq T_j \leq T_{1,j}; \\
        a_2 \cdot T_j + b_2, & \text{if } T_{1,j} \leq T_j \leq T_{2,j}; \\
        a_3 \cdot T_j + b_3, & \text{if } T_{2,j} \leq T_j \leq T_j^H, 
       \end{cases}
\]  

where

\[
T_{1,j} = \frac{1}{3}(T_j^H - T_j^{\text{min}}), \quad T_{2,j} = \frac{2}{3}(T_j^H - T_j^{\text{min}}),
\]

c) quadratic function

\[
S_{t,j} = a \cdot T_j^2 + b \cdot T_j + c,
\]

d) inverse function

\[
S_{t,j} = \frac{a}{T_j},
\]
where \( a, b, c \) – the function parameters, \( T_j \) – the duration of the \( j \)-th operation, \( T_j^{\min} \) – the minimum execution time of the \( j \)-th operation, \( T_j^H \) – the nominal (in particular, actual) execution time of the \( j \)-th operation.

2. Data on actually implemented projects, including
   - network schedule of design and construction;
   - nominal value \( C_j^N \) and nominal time of performance \( T_j^N \);
   - the basic structure of the stimulation function \( St_j^B(T) \), in particular the constant, C-type;
   - restrictions on the operations duration
     \[
     T_j^{\min} \leq T_j \leq T_j^N ;
     \]  
   - restrictions on the amount of incentives for performance of operations
     \[
     0 \leq St_j \leq St_j^\max ,
     \]  
where \( St_j^\max \) – the maximum possible stimulation of the project’s operation;
   - the function structure of income from the operation of the enterprise after its achievement of design performance \( V(t) \).

3. Recalculation modeling procedures, including
   - full-scale data on the characteristics of completed projects;
   - recalculation models that allow the variations of the input data to be recalculated into a change of output target variables;
   - operations of formation of initial model and calculated indicators.

4. Criterion of the project effectiveness \( Q(\Delta t) \), reflecting the costs and revenue from the creation of a technological complex

\[
Q(\Delta t) = V(\Delta t) - St(\Delta t),
\]  
where \( \Delta t \) – the time of change in the duration of the project performance, \( V(\Delta t) \) – the income of the enterprise over time \( \Delta t \), \( St(\Delta t) \) – the costs for incentives to reduce the project duration by \( \Delta t \).

**Required:**
1. To develop an algorithm for determining the effectiveness of stimulating functions.
2. To investigate the effectiveness of stimulating functions \( St_j^B(T) \) from a given set by the criterion \( Q(\Delta t) \).

4. Algorithm for solving the problem
To solve the problem on investigation of the effectiveness of stimulating functions an algorithm was developed, the block diagram of which is shown in figure 4.

This algorithm allows the optimal structure of stimulating functions from the point of view of the criterion \( Q(\Delta t) \) to be determined.

The algorithm for determining the effectiveness of stimulating functions consists of three aggregated functional blocks: the input block of input data, the block of simulation recalculation...
modeling and the block of criterion calculation and selection of the best structure of stimulating function.

Below there is a brief description of each of these three aggregated functional blocks of the algorithm.

**Block 1. Input of initial data.**

The input of data necessary for the operation of the algorithm is carried out.

1. Input of data on the implemented project.
   - network schedule of design and construction;
   - the nominal value \( C_j \), the nominal time of execution \( T_j \) of each operation;
   - restrictions on the implementation duration \( T_j^{\min} \leq T_j \leq T_j^{\max} \) and on the stimulation \( 0 \leq S_j \leq S_j^{\max} \) of each operation;
   - function structure of the income from the enterprise operation after its achievement of the design performance.

A set of structures of stimulating functions \( S_{t,j}(T) \) was formed from a set of elementary functions that satisfy the decreasing returns law and the simplest and most informative ones. As a result of the selection, the following functions were included in the set

- linear (5);
- piecewise-linear (6);
- quadratic (7);
- inverse proportionality (8).

**Block 2. Simulated recalculation modeling of the implemented project for each i-th option of the structure \( S_{t,j}(T) \).**

Consistently the structure of the incentive function from the given set is considered. For each project operation, the incentive costs are calculated to shorten the duration of each \( j \)-th operation for time \( \Delta T \)

\[
S_{t,j}(\Delta T) = S_j^B(\Delta T) + f[Str_j(\Delta T) - Str_i(\Delta T)],
\]

where \( f[·] \) – the operator for recalculating the variations of the parameters of the current \( i \)-th structure of stimulation function \( Str_i \) from the parameters of the basic structure of the stimulation function \( S_j^B \), \( S_j^B \) – the value of the basic stimulation of the \( j \)-th operation.

After the calculation \( S_{t,j}(\Delta T) \), the set \( \Theta' \) is formed

\[
\Theta' = \{S_{t,j}(\Delta T)\}, \ j = \overline{1,n}, \ \Delta T = \overline{T_j^{\max} - T_j^{\min}}
\]

Further, using the search procedure, the block diagram of which is shown in figure 5, the incentive costs for reduction of the project critical path by the value \( \Delta t \) for each \( i \)-th option of the structure \( S_{t,i}(\Delta t) \) are determined.
The essence of this procedure is to compare the many possible options to reduce the duration of the project critical path by reducing the duration of individual operations and choosing the best from them.

At the first stage, the necessary initial values of the variables are entered for the functioning of the procedure, a set of critical operations $\Theta$ and the initial length of the critical path $T_{0}^{CP}$ are determined.
Figure 5. Block diagram of the search procedure for determining the incentive costs on reduction in the project critical path.
Further, from the set of critical non-optimized operations $\Omega$, an operation $O_l$ with minimal incentive costs is found to shorten its duration by time $\Delta T$.

$$O_l = \min\{ St_j(\Delta T) \}, \ l = 1,|\Omega|, \Delta T = \min \{ \Delta T_j^{\text{min}}, T_j^H - T_j^{\text{min}} \}$$ \hspace{1cm} (14)

Then, by the value $St_j(\Delta T)$ we increase the incentive costs on reduction in the critical path by the current time $\Delta t$

$$St(\Delta t) = St(\Delta t) + St_j(\Delta T).$$ \hspace{1cm} (15)

After we remove $St_j(\Delta T)$ from the set $\Theta$ and shorten the duration of the $l$-th operation. After the reduction, the duration of the $l$-th operation will be $T^N - \Delta T$.

We check whether the critical path has changed.

If the critical path of the project has changed, then the described procedure is repeated, while the incentive costs on reduction in the critical path by the current time $\Delta t$ will constantly increase by the amount of costs on reduction of operations from $\Theta$ with the minimum $St_j(\Delta T)$.

If the critical path of the project has not changed, then the incentive costs for reducing the duration of the project critical path $St(\Delta t)$ by the current time $\Delta t$ are remembered, the current time is increased by one $\Delta t = \Delta t + 1$ and the described search procedure is repeated again. And so long as the possibilities for reduction in the duration of the operations of the set $\Theta$ will be exhausted, that is, for the time being, equality $T_j = T_j^{\text{min}}$ will not be fulfilled for all critical works.

As a result of performing the search procedure for each structure from the set of incentive functions, the dependence of the incentive costs on the reduction of the project critical path $St(\Delta t)$, $\Delta t = 1, T_0^C - T_0^F$ will be formed, where $T_0^C$, $T_0^F$ – the length of the initial and final critical path of the project, respectively.

**Block 3. Calculation of the optimality criterion and selection of the best structure of the stimulation function.**

For each of the structures of the incentive function $St_{i,j}(T)$, the criterion of effectiveness $Q_i$ is defined

$$Q_i = \max\{ Q_i(\Delta t) \} = \max\{ V(\Delta t) - St_i(\Delta t) \}. \hspace{1cm} (16)$$

In the final stage, the criterion with the maximum value is selected from the set $Q_i$

$$Q = \max\{ Q_i \}. \hspace{1cm} (17)$$

As a result, the $i$-th structure of the stimulating function will be considered the most efficient, for which condition is fulfilled

$$Q_i = Q. \hspace{1cm} (18)$$
Knowing the best structure of the stimulation function and the greatest value of the optimality criterion $Q$, to find the optimal time of reduction in the project critical path $\Delta t^{opt}$ is not a difficult task: at which $Q = \max\{Q(\Delta t^{opt})\}$.

The software realization of the algorithm is implemented in the Microsoft Project Professional and Microsoft Excel environments in the scripting language Visual Basic for Applications.

The full-scale data for the quantitative factors were taken from the realized project of the coal preparation plant.

5. Conclusions
The results of calculations for the selected set of stimulation functions are shown in figure 6, from which it follows that the best are the quadratic and piecewise linear stimulation functions.

![Figure 6](image)

**Figure 6.** Performance criterion for various structures of incentive function with a company’s daily income of 400 thousand rubles.

For the piecewise-linear stimulation function for a specific coal-processing plant, an optimal reduction in the duration of $\Delta t^{opt}$ was obtained for 57 days at a value of $Q$ equal to 12459.12 thousand rubles, and for a quadratic function $\Delta t^{opt} = 54$ days, $Q = 12134.47$ thousand rubles.

When the daily income of the enterprise changes, the quadratic and piecewise linear stimulation functions also remain preferable and outperform other stimulation functions by the efficiency criterion $Q$ by at least 50%.

Using the procedure of the recalculation full-scale mathematical modeling allows the incentive values for project operations to be recalculated, while their duration and duration of the whole project change. The network schedule is also dynamically adjusted.

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