Rational Management of Energy Efficiency in a Power Complex

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Abstract. The problem of energy efficiency management in the energy complex under stochastic conditions and taking into account the human factor is analysed. Undesirable activities of the Executive of complex subdivision associated with the presence of his own goals have been identified. Such unwanted activity can lead to a decrease in the energy efficiency of the complex. To improve this efficiency, a control system is proposed that uses a digital learning procedure for the Manager of the complex with the help of the Counsellor, who, in turn, learns to evaluate actual energy efficiency. In addition, this system includes digital procedures for planning and classifying the Executive, depending on the energy efficiency of the subdivision he heads. The task is to determine a control system in which the actual energy efficiency of the subdivision will be equal to the maximum possible under stochastic conditions. This problem is solved by synthesizing a control system that includes a set of decision-making procedures by the Manager (planning and classification) together with a set of advisory procedures used by the Counsellor (evaluation and judgment). The problems of forming such an energy efficiency management system in the energy complex are discussed.

1 Introduction

To solve the problems of power complex, in the context of rising energy prices, the science and practice of increasing energy efficiency is used - the effective (rational) use of energy resources at the existing level of development of technology and technology. The scientific approach to increasing energy efficiency is based on system analysis, mathematical modeling, computer and information technology.

In practice, large-scale power complexes create energy management systems (EMS) aimed at improving energy efficiency. These systems, being located on the energy network, form a network structure similar to the structure of this network. Each subdivision has its own EMS service, the head of which (briefly – the Executive) must organize the allocation of financial and other resources for the implementation of new energy-efficient means and technologies.

In large-scale power complexes, standards have been developed that regulate the management of the implementation of innovative energy-efficient means and technologies. For this purpose, a special hierarchical management structure has been created, in which

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each subdivision complex must solve the problem of ensuring the allocation of financial resources for implementation through the management of a large-scale power complex (in short - Manager). In turn, management must distribute the budget so as to achieve maximum efficiency of energy resources in the subdivision and complex as a whole.

However, Managers of subdivision know own possibilities better than higher management. In such cases, they talk about asymmetric awareness of the management of the complex and the executives in the subdivision. Theoretical problems of interaction between fully informed and uninformed elements of such complex systems are considered in [1]. It has been shown that better informed elements have the ability to use the lack of information from other elements of complex system to achieve their own goals [2]. Therefore, the management of the complex must ensure that each division of the complex makes maximum use of its internal reserves for increasing energy efficiency. The complexity of this problem determines the relevance of modelling and assessing hierarchical energy efficiency management structures.

In this work, this problem is considered from the perspective of theory of organizational control [3]. In accordance with this theory, it is assumed that a scientifically based energy efficiency management system should include an appropriate structure and mechanism for its functioning. Moreover, each management structure has a specific functioning mechanism. Accordingly, in order to assess the effectiveness of the management structure, it is necessary to consider it together with this mechanism. After this, by comparing the energy efficiency of the management systems based on different structures, it is possible to draw a conclusion about the effectiveness of a particular control structure.

Let’s consider a model of a two-level energy efficiency management system for a large-scale power complex, including the corresponding organizational structure and the mechanism of its functioning. At the top level of this organizational structure is the Manager, who provides overall management of energy efficiency. To do this, it uses suitable planning and incentive procedures, integrated into an organizational energy efficiency management mechanism. At the bottom level of this organizational structure is the Executive, which ensures energy efficiency of production processes in the subdivision.

In conditions of uncertainty, the real mechanisms for the functioning of large-scale production and organizational systems are based, as a rule, on inherently adaptive planning procedures “from what has been achieved.” In the practice of power complex, this is manifested in the fact that energy efficiency plans grow with an increase in current energy efficiency indicators. Accordingly, the Executive may not be interested in increasing current energy efficiency indicators, since this will give more demanding plans that he may not meet.

Therefore, it is important that this mechanism of functioning of the EMS power complex takes into account the human factor and is progressive [4], i.e. interested the Executive in reducing risks, reducing time and costs for the implementation of innovative means and energy efficiency technologies. Without this, their effective implementation is impossible, and their development becomes meaningless. The progressive mechanism makes it possible to determine and predict the energy efficiency potential of the power complex, using effective adaptation and learning algorithms in technical systems.

The above determines the relevance of the study of adaptive and learning mechanisms for managing energy efficiency of the power complex, which would ensure the Executive’s desire to unlock the energy efficiency potential of the subdivision (and, accordingly, its effective identification and forecasting).

Along with the activation of the human factor, intelligent, informational, digital and automated technologies of Industry 4.0 are used to solve energy efficiency management problems of the power complex, including big data [5], intellectual analysis [6] and machine learning (ML) [7]. The usefulness of ML lies in the fact that ML allows one to
simplify models of the power complex, considering some subsystems of this complex as black boxes [8]. Otherwise, it would be necessary to build mathematical models of these subsystems, solve problems of their coordination with other models, carry out complex calculations, etc. [9]. However, the application of ML in control models must be theoretically justified [10]. And here we should rely on the results obtained in the three main directions of theory of organizational control [3].

The first direction is aimed at the construction of adaptive mechanisms for digital control of large-scale complex systems. For example, theoretical problems of constructing optimal mechanisms for such control are considered in [3]. The task is set to synthesize an adaptive control mechanism for a two-level active system that has progressive properties. Sufficient conditions have been found for the synthesis of adaptive mechanisms with identification, in which planning and stimulation of active elements are combined with the disclosure of their potential. These conditions make it possible to solve problems of assessing and predicting the potential of organizational systems using adaptive identification algorithms in technical systems. The results obtained in this direction create a theoretical basis for building management mechanisms that reduce risks and reduce the time and costs of complex systems.

Similarly, research is being conducted in the other two main directions of theory of organizational control. The second direction is associated with unsupervised learning in hierarchical management [4]. The third direction is aimed at supervised learning in large-scale the management systems and their applications [11]. Combinations of these basic models have been used to build more complex control models based on the concept of Model-Based Systems Engineering [12]. For example, this is how control mechanisms were built using ML [4].

Based on the results obtained in these areas of theory of organizational control, we consider the model of a digital control of energy efficiency in a hierarchical power complex under the leadership of the Manager. Its task is to increase the energy efficiency of the subdivision headed by the Executive. To achieve this in the face of uncertainty, the Manager uses the advice of the Counsellor.

2 The structure of the energy efficiency management system

The hierarchical structure of the energy efficiency management system is determined by the complexity of such management. The energy efficiency of power complex divisions is influenced by stochastic influences unknown to the top Manager. The Executive also cannot predict future energy efficiency due to stochastic impacts. However, he knows better the current energy efficiency. Taking advantage of this, The Executive can try to obtain additional benefits by underestimating the current energy efficiency.

To prevent this, the Manager uses the resources available to it, including advice from the Counsellor. However, by Machiavelli, the sovereign who is not wise himself will never receive good advice. Therefore, the Manager himself must, firstly, understand the behavioral features of the Executive under the existing practice of managing the energy efficiency in an power complex. Secondly, the Manager must learn to manage in a stochastic environment in order to make scientifically based decisions when dealing with stochastic impacts on a power complex subdivision.

In accordance with actual practice of managing the energy efficiency in an power complex, the Executive receives incentives if the energy efficiency is not smaller the plan. Two conclusions follow from this. First, the Executive’s current incentives are not zero only if the subdivision energy efficiency is not smaller than the current plan. Therefore, the higher this plan, the more difficult it is for the Executive to receive incentives.
Secondly, the plan for the next period usually increases by a certain percentage of the energy efficiency achieved today. This is the essence of the principle of energy efficiency planning “from the level that has been achieved”, which is often used in large-scale industrial systems [4]. Accordingly, the higher is energy efficiency today, the higher will be future plans. Consequently, the Executive may not be interested in reducing energy efficiency below the plan. Thus, the problem arises of the lack of interest of the Executive in enlarging energy efficiency. Thus, the Manager should motivate the Executive to enlarge subdivision energy efficiency.

To study this problem, consider the dynamics of a two-level organizational system, the structure of which includes the Manager at the top level and the Executive at the bottom. Let denote \( t \) the period of time, \( t = 0,1, \ldots \). Subdivision energy efficiency in the period \( t \) is characterized by the indicator \( e_t, e_t \epsilon E_t = [0, E_t] \), where \( E_t \) is the set of possible states of the Executive, \( E_t \epsilon E = [0, \epsilon] \). There \( E_t \) is the stochastic maximum subdivision energy efficiency (opportunity) known to the Executive in the period \( t \). But the Manager and the Counselor do not know \( E_t \). So, the Executive can manipulate \( e_t \), choosing \( e_t < E_t \).

For simplicity, we will now consider the subdivision’s energy efficiency management system using relative energy efficiency indexes:

\[
i_t = e_t / \epsilon, \quad i_t \in I = [0,1], \quad I_t = E_t / \epsilon, \quad E_t \epsilon I, \quad t = 0,1, \ldots .
\] (1)

### 3 Classification the Manager learning using the Counsellor

Let assume the Manager classifies the Executive work as acceptable (class 1) or non-acceptable (class 0) with the aid of index (1). Incorrect classification leads to damage. We denote:

- \( d_{10} \) - damage from incorrect assignment of class 0 (although the Executive deserves a class 1).
- \( d_{01} \) - damage from incorrect assignment of class 1 (although the Executive deserves a class 0).

For correct classification, the Manager can use supervised learning [11], using the Counsellor’s judgement \( j_t(i_t) \) on whether subdivision energy efficiency is acceptable. If the Counsellor considers this energy efficiency to be acceptable in period \( t \), then \( j_t(i_t) = 1 \), otherwise \( j_t(i_t) = 0 \).

If \( i_t \) is a stationary stochastic value, a supervised learning algorithm is suitable for minimizing of mean damage [11]. Then, plan used for classification (briefly – plan) \( p_t+1 \) in period \( t+1 \) is:

\[
p_{t+1} = P(p_t, i_t) = p_t - \alpha_t[p_t - 0.5 - d_{01} + (d_{01} + d_{10})j_t(i_t)], \quad p_0 = p^0
\] (2)

Where \( P(p_t, i_t) \) is the planning procedure, \( 0 < \alpha_{t+1} < \alpha_t, \sum_{t=0}^{\infty} \alpha_t < \infty \), \( t = 0,1, \ldots \). Then the Executive’s class is:

\[
c_t = C(p_t, i_t) = \begin{cases} 1 \text{ if } i_t \geq p_t \\ 0 \text{ if } i_t < p_t \end{cases}
\] (3)

Where \( C(p_t, i_t) \) is called classification procedure.
3 The Counsellor’s self-learning of classification

The Counsellor communicates to the Manager his own judgement \( j_t(i_t) \) on whether energy efficiency \( e_t \) is acceptable: if energy efficiency index \( i_t \) is acceptable, then \( j_t(i_t) = 1 \), else \( j_t(i_t) = 0 \).

To diminish the average loss of wrong judgement, the Counsellor is self-learning. Let introduce the functions of the Counsellor’s loss:

- \( l_0(a, i_t) = i_t \beta a \) - loss of the Counsellor in case of incorrect judgement \( j_t(i_t) = 0 \), while correct judgement \( j_t(i_t) = 1 \).
- \( l_1(a, i_t) = \gamma (a - i_t) \) - loss of the Counsellor in case of incorrect judgement \( j_t(i_t) = 1 \), while correct judgement \( j_t(i_t) = 0 \).

Here \( a \) is a the parameter that needs to be adjusted to minimize the average loss, \( 0 < \beta < 1, \gamma > 0 \). Using the self-learning algorithm [4], we can obtain an assessment \( a_{t+1} \) of parameter \( a \) in period \( t+1 \):

\[
a_{t+1} = A(a_t, i_t) = \begin{cases} a_t + \beta \delta_t & \text{if } i_t < n_t \\ a_t - \gamma \delta_t & \text{if } i_t \geq n_t' \end{cases}, \quad a_o = a^0, \quad t = 0, 1, ... \tag{4}
\]

Where \( A(a_t, i_t) \) is called assessment procedure, \( n_t = a_t (\beta + \gamma)/(\gamma + 1), \quad 0 < \delta_{t+1} < \delta_t, \sum_{t=1}^{\infty} \delta_t < \infty \).

The Counsellor judgement is:

\[
j_t(i_t) = J(a_t, i_t) = \begin{cases} 1 & \text{if } i_t \geq a_t \\ 0 & \text{if } i_t < a_t' \end{cases} \tag{5}
\]

Where \( J(a_t, i_t) \) is called judgement procedure. Then the Counsellor communicates to the Manager judgement \( j_t(i_t) \).

The set of decision-making procedures by the Manager (planning \( P(\bullet) \) and classification \( C(\bullet) \)), together with the set of decision-making procedures by the Advisor (assessment \( A(\bullet) \) and judgment \( J(\bullet) \)), is called the management system \( S = (A, J, P, C) \).

4 Solution of the game of the Executive with the Manager

Let’s consider the following order of operation of the energy efficiency management. First, the Manager sets the management system \( S = (A, J, P, C) \). The Executive then selects energy efficiency. In fact, the game of the Executive with the Manager is realized. Let’s consider its solution under the assumption that the Executive strives to increase in period \( t \) functional grows with the growth of its current and future classes dependent on energy efficiency:

\[
F_t = F[c_t, c_{t+1}, \ldots, c_{t+f}], \quad F_t \uparrow c_t, \quad \tau = t, t + \bar{t}, \quad t = 0, 1, ... \tag{6}
\]

Where \( f \) is the Executive’s foresight.

Assume that the Executive knows in period \( t \) only the future sets of possible states \( E_t \in E \) and \( e_t \in E_t, \quad \tau = t + 1, t + \bar{f} \). To make a decision about \( i_t \) in period \( t \), under conditions of uncertainty, the Executive focuses on maximal guaranteed value of the functional (6):

\[
V_t(S, i_t) = \min_{\tau = t+1, t+\bar{f}} \min_{e_t \in E_t} \min_{e_t \in E_t} F_t \tag{7}
\]
Then the set of solutions of the game the Executive with the Manager in period \( t \) is the set of states of the Executive that maximize value (6):

\[
V_t(S, i_t) \xrightarrow{i_t \in I} \text{max} \tag{8}
\]

In essence, \( V_t(S, i_t) \) plays the role of the objective function of the Executive in period \( t \) under conditions of uncertainty. By (8), the set of solutions to the game the Executive with the Manager is

\[
G_t(S) = \{ i_t^* | V_t(S, i_t) \geq V_t(S, i_t'), i_t \in I, i_t^* \in I \} \tag{9}
\]

We will assume the Executive’s amiability towards the Manager: if \( i_t \in G_t(S) \), then \( i_t^* = I_t, t = 0,1, \ldots \). In essence, this means that the Executive does not underestimate its indicator \( v_t \) if it is not profitable for it.

5 Rational system of energy efficiency management

The Manager should enlarge energy efficiency \( e_t \) to \( E_t \). By (3), the Executive’s class enlarges when index \( i_t \) enlarges to plan \( p_t \). This should interest the Executive in enlarging index \( i_t \) and indicator \( e_t \). Moreover, as stated above in the practice of power complexes, the future plan of energy efficiency usually enlarges when the actual energy efficiency enlarges to the actual plan. Other words, the plan \( p_{t+1} \) in the period \( t+1 \) enlarges when the index \( i_t \) enlarges.

However, by (3), the higher the plan \( p_{t+1} \), the higher energy efficiency index \( i_{t+1} \) will be needed in the period \( t+1 \) to enlarge the Executive’s class. Remember that the maximum energy efficiency index \( I_{t+1} \) is a stochastic value. And under strong negative impacts \( i_{t+1} < p_{t+1} \). Then the Executive can’t get a class \( c_{t+1} = 1 \). Thus, forward-looking Executive isn’t interested in enlarging index \( i_t \) above plan \( p_t \). This is the problem of “planning from the achieved level”[11]. Therefore, the Manager needs rational management system which stimulates the Executive to enlarge energy efficiency in every period: \( e_t = E_t, t = 0,1, \ldots \).

Theorem. The management system \( S = (A, J, P, C) \) is sufficient for use opportunity in every period: \( e_t = E_t, t = 0,1, \ldots \).

Proof. The management system \( S = (A, J, P, C) \) includes procedures (2)-(5). By (6), the objective function of the Executive (7) enlarges on future class \( c_t, \tau = t, t + f \). By (3), the actual class \( c_t = C(p_t, i_t) \) does not decline with enlarging of \( i_t \).

Consider the dependence of the future class \( c_t = C(p_t, i_t), \tau = t + 1, t + f \), on \( i_t \). By (5), the Counsellor’s judgement \( j_t \) is determined by \( n_t = a_t(\beta + \gamma)/(\gamma + 1) \). By (4), \( a_t \) and \( n_t \) does not enlarge with enlarging \( i_t, \tau = t + 1, t + f \). Thus, by (5), \( j_t(i_t) \) does not decline with enlarging \( i_t \). Therefore, by (2), plan \( p_t \) does not enlarge with enlarging \( i_t \). And by (3), class \( c_t = C(p_t, i_t) \) does not decline with declining \( p_t \).

So, the class \( c_t = C(p_t, i_t) \) does not decline with \( i_t \) enlarging at \( \tau = t + 1, t + f \). Consequently, by (6) and (7), we obtain that objective function \( V_t(S, i_t) \) does not decline with \( i_t \) enlarging. Since \( v_t \leq V_t \) by (3), then \( V_t(S, i_t) \geq V_t(S, i_t) \). Thus, by (9) \( I_t \in G_t(S) \), and by the Executive’s amiability towards the Manager, \( i_t^* = I_t \). Then by (3) \( e_t = E_t, t = 0,1, \ldots , \) Q.E.D.
6 Discussion

In essence, the theorem establishes the conditions under which the management system $S = (A, J, P, C)$ ensures the Executive’s desire to unlock energy efficiency opportunities.

Exactly, the plan $p_t$ corresponds to acceptable energy efficiency for the Manager, at which the Executive receives class $1$ ($c_t = 1$). If energy efficiency index $i_t$ is smaller than $p_t$ ($i_t < p_t$), then the class is zero ($c_t = 0$), which is bad for the Executive. Thus, the Executive’s functional should increase with its class. For this reason, the functional of forward-looking Executive (6) enlarges with both the actual and future classes.

To enlarge the functional (6) in period $t$, the Executive chooses energy efficiency $e_t$ that determine the index $i_t$ (1). Also, this choice depends on stochastic value $E_t$. In fact, choosing $e_t$ corresponds to the course of the game between the Executive and the Manager in the period $t$, with the help of which the Executive strives to enlarge functional (6).

If the conditions of theorem are met, the current class of the Executive (i.e. incentive) grows with increasing energy efficiency indicator. At the same time, the future plan decreases (does not increase) with increasing energy efficiency. Therefore, the Executive’s future incentives increase with the increase in energy efficiency. Thus, if the conditions of theorem are met, the Executive is certainly interested in increasing the energy efficiency indicator to the maximum achievable level. This makes it possible to unlock energy efficiency opportunity.

Conditions of theorem are constructive in nature, directly defining the procedures of Manager’s decision-making - planning $P(\bullet)$ and classification $C(\bullet)$, together with the procedures of Counsellor’s decision-making - assessment $A(\bullet)$ and judgement $J(\bullet)$. The results obtained provide a theoretical basis for the selection of effective structures and mechanisms for energy efficiency management.

7 Conclusions

We examined theoretical problems that arise when constructing energy efficiency management systems. The problem statement is given, and sufficient conditions for the synthesis of rational system for increasing energy efficiency are found. These conditions are constructive and allow us to determine decision-making procedures – planning and classification based on assessment and judgment, in which all (including stochastic) opportunities for increasing energy efficiency are used.

The results obtained create a theoretical basis for the selection of rational systems for managing energy efficiency in hierarchical power complex.

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