Control mechanism of electricity consumption in a transport company

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Abstract. To reduce electricity consumption in hierarchical management of fabrication, it is necessary to take into account the activity of managers associated with the presence of their own targets. A three-level model of managing electricity consumption in production is considered. At its top level is the superior who evaluates the executive who is at the middle level. At the bottom of the system is the director of fabrication. The superior must to manage the consumption of the executive in such a way as to save electricity. But the executive knows own electricity-saving opportunities better than the superior. In turn, the director knows his own electricity-saving capabilities better than the executive. So, both the executive and the director can manipulate their electricity consumption to gain more incentives. To avoid this, a control system for electricity consumption management in fabrication is proposed. This system includes procedure for machine learning of the superior and procedure for grading of the executive. Sufficient conditions of the optimality of this system are found, in which random opportunities of decreasing electricity consumption are used. With such a system, the executive is interested in minimizing electricity consumption. The Theorem is proved that for this it is sufficient to use linear procedures of adaptive standardization and stimulation of the director. The proposed approach to control of electricity consumption is illustrated by the example of railcars repairing in the Russian Railways company. Keywords: Transport, Energy, Systems Engineering, IT Technologies.

1 Introduction

The use of Artificial Intelligence methods can reduce energy consumption in transport systems. For example, smart meters are able to measure energy consumption [1] and use the capabilities of household energy storage units [2]. Machine learning (ML) is used to control energy consumption in a large company [3].

In addition, to reduce electricity consumption, it is necessary to take into account the human factor. To achieve their own goals, people can manipulate the consumption of electricity in order to influence the results of ML and the decisions of stakeholders in their favor. Accordingly, an important area of energy saving is associated with the disclosure of internal reserves and resources through the activation of employees. To solve such problems, the mathematical theory of organizational management is used [4]. This made it possible to

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obtain mechanisms for reducing energy consumption in a transport company through training [5]. Supervised energy cost management was studied in [6].

This paper is devoted to the study, using rigorous mathematical reasoning and evidence, a three-level energy saving management model with two-level ML. This model includes the top manager (the superior), the subordinated manager (the executive), and the director of fabrication. The superior does not know the random minimum possible consumption of electricity by the executive and the director. For this reason, the superior must learn. The executive knows about this consumption better than the superior. Thus, the executive can manipulate the consumption of electricity in order to influence the results of superior's learning and management in his favor. But the executive himself does not know the random minimum consumption of electricity in fabrication. This can be used by the director to achieve his own goal. So, the executive also needs to learn how to manage electricity consumption in fabrication. Due to the complexity of the model under consideration, the Model Based Systems Engineering approach [7] is used.

2 Grading of Electricity Consumption

Let denote t the period of time, E_t - electricity consumption, for which the executive is responsible in the period t, t=0,1,... There E_t is equal to the sum of fabrication electricity consumption F_t and the own executive electricity consumption $O_t : E_t = F_t + O_t$, where $O_t \in \Psi_t = [o_t, \psi]$, $F_t \in \Xi_t = [f_t, \zeta]$, $f_t \in \sigma = [\omega, \upsilon]$, $\omega > 0$, $\upsilon \le \zeta$, $o_t \in \phi = [\varsigma, \xi]$, $\varsigma > 0$, $\xi \le \psi$. Thus, the minimum electricity consumption for which the executive is responsible is equal to:

$$e_t = f_t + o_t. \tag{1}$$

Thus $E_t \in \Omega_t = [e_t, \zeta + \psi]$, $\Omega_t \subset \Omega = [\omega + \varsigma, \zeta + \psi]$. The superior does not know f_t, o_t, and e_t. On the other hand, these values become known to the executive at the beginning of the period t, i.e. before choosing E_t. Thus, the superior must reduce electricity consumption E_t to minimum e_t in the face of unawareness [8].

The superior does not know the minimum possible electricity consumption by the executive (and, moreover, of the director). But the superior can monitor deviations of actual consumption from some rate. Based on this, the superior can conclude whether the executive is using the electricity effectively. In the framework of grading concept, this means that the superior assigns the executive one of two grades - 1 (effective use of electricity) and 0 (ineffective use of electricity). Such grading is often used in fabrication [3,5,6].

The grade in period t is determined based on the executive consumption E_t. To determined this grade, the superior must assign E_t to one of the two sets Δ_1 and Δ_2 which make up the set Δ, $\Delta_1 \cup \Delta_2 = \Delta$. An incorrect assignment leads to damages. The problem is to determine Δ_1 and Δ_2 which minimizes average damages.

Let us first consider the case of complete awareness of the superior about the minimum the executive electricity consumption e_t as well as the density of its distribution $d(e_t)$. In this case, for each unknown set Δ_1 and Δ_2 the superior introduces 2 damage functions:

- $D_1(e_t,b)$ are damages in case if the superior believes that $e_t \in \Delta_2$, and gives the executive 1st grade (that is, the executive copes with his duties), while in fact it is not: $e_t \in \Delta_1$ (that is, the executive does not cope with his duties);
- $D_2(e_t,b)$ are damages in case if the superior believes that $e_t \in \Delta_1$, and gives the executive 0th grade (that is, the executive does not cope with his duties), while $e_t \in \Delta_2$ (that is, the executive copes with his duties).

There b is an unknown parameter of the decision rule separating set Δ_1 and set Δ_2. The optimal value of this parameter *(b*)* can be determined by solving the task of average damages minimization [5]:

$$\hat{D}(b) = \sum_{k=1}^{2} \int_{\Omega_k} D_k(e,b)\, d(c)\, de \xrightarrow[b]{} min \tag{2}$$

Usually, the superior does not know *d(c)*. So, it is impossible to solve task (2). Consider solution of task (2) in case when damage functions are linear:

$$D_1(e_t,b) = e_t - k_1 b,\ D_2(e_t,b) = k_2(b - e_t), \tag{3}$$

where k_i – coefficients, $0 < k_i < 1,\ i = \overline{1,2}.$ Then the condition of minimum average risk (2) is:

$$M_e\left\{\sum_{k=1}^{2} Z_k(e,b)\frac{dD_k(e,b)}{db}\right\} = 0,\ Z_k(e,b) = \begin{cases}1 \text{ if } e \in \Delta_k \\ 2 \text{ if } e \notin \Delta_k\end{cases}, \tag{4}$$

where M_e is the expectation operator. Using (4), one can use stochastic approximation to obtain a sequence of evaluations b_t, t=0,1,..., of an unknown parameter b^*. Namely, substituting (3) into (4), we obtain learning algorithm to obtain evaluations b_t, t=0,1,..., which solve (4), in the form:

$$b_{t+1} = B(e_t,b_t) = \begin{cases} b_t + \beta_t k_1 & \text{if } e_t \le (k_1+k_2)b_t/(k_2+1) \\ b_t - \beta_t k_2 & \text{if } e_t > (k_1+k_2)b_t/(k_2+1) \end{cases}, \tag{5}$$

where $\beta_t > 0,\ \sum_{t=0}^{\infty}\beta_t < \infty;\ b_0 = b^0,\ t = 0,1,...,$ In this case, evaluations b_t, t=0,1,..., converge to unknown parameter b^*:

$$b_{t+1} = B(e_t,b_t) \xrightarrow[t \to \infty]{} b^* = arg\,min\ \hat{D}(b) \tag{6}$$

Using (5), the superior determines the executive's grade:

$$g_t = G(e_t, b_t) = \begin{cases} 1 & if \quad e_t \le (k_1 + k_2)b_t / (k_2 + 1) \\ 0 & if \quad e_t > (k_1 + k_2)b_t / (k_2 + 1) \end{cases}, \tag{7}$$

If the superior does not know e_t, it can receive an appraisal a_t of evaluation b_t by replacing in (5) unknown e_t with the observed E_t :

$$a_{t+1} = A(a_t, E_t) = \begin{cases} a_t + \beta_t k_1 & if \quad E_t \le (k_1 + k_2)a_t / (k_2 + 1) \\ a_t - \beta_t k_2 & if \quad E_t > (k_1 + k_2)a_t / (k_2 + 1) \end{cases}, \tag{8}$$

where $A(a_t, E_t)$ is the learning procedure of the superior, $a_0 = b^0$, $t = 0,1,...$ In determining executive's grade, the superior is based on observation E_t and the appraisal a_t . In general, the sequence of appraisals a_t, t=0,1,..., does not converge to unknown parameter $b*$. Replacing in (7) unknown e_t with the observed E_t and evaluation b_t with appraisal a_t , we get executive's grade:

$$g_t = G(a_t, E_t) = \begin{cases} 1 & if \quad E_t \le (k_1 + k_2)a_t / (k_2 + 1) \\ 0 & if \quad E_t > (k_1 + k_2)a_t / (k_2 + 1) \end{cases}, \tag{9}$$

where $G(a_t, E_t)$ is the grading procedure. Denote $r_t = (k_1 + k_2)a_t / (k_2 + 1)$. In fact, r_t is the rate of electricity consumption in period t. If consumption is higher than this rate $(E_t > r_t)$ then the executive gets a low grade $(g_t = 0)$, otherwise – a high grade $(g_t = 1)$. It is assumed that the reward of the executive grows with the increase in the grade of electricity saving [3,5,6].

3 Electricity Consumption Management with Grading

A set of procedures of learning (8) and grading (9) constitute the grading control of electricity consumption denoted $C = (A, G)$.

3.1 Target of the Executive

Let us now consider the target of the executive in case of control $C = (A, G)$. Assume that at low grade $(g_t = 0)$ the executive being punished by the superior. Therefore, the executive is interested in increasing grade g_t (9). As stated above, the superior does not know e_t. Therefore, the superior assigns the grade (9) based on the observation E_t. The executive is more aware of possibilities of electricity savings than the superior. Suppose the realization of random value of minimal electricity consumption e_t becomes known to the executive before selecting E_t in period t. After that the executive selects E_t in period t, $E_t \ge e_t$. So the executive can choose E_t to maximize own target function:

$$H_t = H[g_t, g_{t+1}, \dots, g_{t+T}],\ G_t \uparrow g_i,\ i = \overline{t, t+T}, \qquad (10)$$

where $H[\bullet]$ is a monotonically increasing function of its arguments, T is the executive foresight. To make a decision about E_t on the conditions of uncertainty, the executive focuses on a guaranteed value of target function (10):

$$h_t(E_t) = \min_{\tau=\overline{t+1,t+T}} \min_{\Omega_\tau \subset \Omega} \min_{E_\tau \in \Omega_\tau} H_t \qquad (11)$$

Then the set of the executive possible decisions is the set of E_t^* that maximize $h_t(E_t)$:

$$P_t(C, e_t) = \{ E_t^* \in \Omega_t | h_t(E_t^*) \ge h_t(E_t),\ E_t \in \Omega_t \} \qquad (12)$$

Below the benevolence of the executive in relation to the superior is supposed: if $e_t \in P_t(C, e_t)$ then $E_t^* = e_t$.

3.2 Effective Grading Control

The target of the superior is to minimize the executive electricity consumption E_t. By (9), executive's grade increases when E_t decreases to e_t. This should make the executive interested in lowering E_t. On the other hand, in the practice of fabrication, the future appraisal of electricity consumption often decreases with the decrease of actual consumption. Formally, this means that appraisal a_{t+1} in the next period (t+1) decreases when consumption E_t decreases. However, according to (9), the lower the appraisal a_{t+1}, the lower consumption E_{t+1} will be needed in the period t+1 in order to increase the executive's grade. And since $E_{t+1} \ge e_{t+1}$, where the minimum consumption e_{t+1} is a random variable, then under unfavorable circumstances the executive can actually get a grade $g_{t+1} = 0$. For these reasons, forward-looking executive may not be interested in decreasing consumption E_t below appraisal a_t. This problem is similar to the problem of rationing carried out «from the achieved level» [6]. So it is necessary to develop an effective control system that motivates the executive to save electricity in every period: $E_t^* = e_t$, t=0,1,…

Statement 1. Grading control $C = (A, G)$ is sufficient for minimum electricity consumption of the executive: $E_t^* = e_t$, t=0,1,… In this case, the sequence of appraisals a_t, t=0,1,..., converges to unknown parameter b^*.

Proof. Control $C = (A, G)$ includes procedures of learning (8) and grading (9). According to (10), the target function of the executive (11) increases on both current and future grades g_τ, $\tau = \overline{t, t+T}$. According to (9), the current grade $g_t = G(a_t, E_t)$ does not decrease with decreasing of E_t.

Consider the dependence of the future grade $g_\tau = G(a_\tau, E_\tau)$, $\tau = \overline{t+1, t+T}$, on E_t. According to (9), the grade $g_\tau = G(a_\tau, E_\tau)$ does not increase with decreasing a_τ,

$\tau = \overline{t+1, t+T}$. Further, using recurrent equations (8), it is easy to show that a_τ does not decrease with decreasing of E_t, $\tau = \overline{t+1, t+T}$. Consequently, the grade $g_\tau = G(a_\tau, E_\tau)$ in the period τ does not decrease with E_t decreasing. Thus, from (10) and (11), target function $h_t(E_t)$ does not decrease with E_t decreasing: if $E_{t+1} \geq e_{t+1}$, then $h_t(e_t) \geq h_t(E_t)$. So by (12) $e_t \in P_t(C, e_t)$, and from the benevolence of the executive in relation to the superior we obtain $E_t^* = e_t$, t=0,1,... Then, according to (5), (6), and (8), the sequence of appraisals a_t, t=0,1,..., converges to unknown parameter b^* , Q.E.D.

Statement 1 defines an easily interpretable control method of motivation the executive in saving electricity when using an unsupervised learning model. Namely, Statement 1 means that to motivate the executive in saving electricity, the superior needs to use control $C = (A, G)$.

4 Fabrication Electricity Consumption

4.1 Decision Making of the Executive

According to Statement 1, if the superior uses control $C = (A, G)$ then the executive's decision is to save electricity: $E_t^* = e_t$, $t = 0,1,...$ Let us now consider decision making of the executive to save the electricity used for fabrication. Given (1), in order to achieve $E_t^* = e_t$, the executive is sufficient to provide $F_t = f_t$, $O_t = o_t$. The executive decision about O_t depends on the random variable o_t, $O_t \geq o_t$. Also his decision about F_t depends on the random value f_t.

According to above, o_t and f_t become known to the executive before the beginning of the period t, i.e. before choosing O_t and F_t. The executive obtains f_t from the director. There $f_t \geq x_t$, where x_t is the minimum electricity consumption of fabrication known to the director. But x_t is not known to the executive. This is the example of asymmetric awareness of the parties [9]. Consequently, the executive must take into account the activities of the director: to achieve own target, the director can manipulate electricity consumption in fabrication. This is typical for repairing [5]. Thus, the executive must motivate the director to minimize electricity consumption: $f_t = x_t$, t=0,1,… For this the executive needs special control to minimize fabrication electricity consumption.

4.2 Management of Fabrication Electricity Consumption

Suppose that the executive has sufficient statistics on minimum electricity consumption x_t . To evaluate x_t , he can use big data analytics for time series of electricity consumption [1]. If such statistics is insufficient, the adaptive methods for short-term electricity load in real time can be used [10].

Consider model of real-time management of electricity consumption in fabrication. Formally, assume x_t becomes known the director prior to period t. After that, the director makes a decision about electricity consumption f_t, $f_t \geq x_t$. t=0,1,… Then the executive knows f_t, and adaptive models can be used for real-time management of electricity consumption in fabrication with forecasting and standardization [11]. Namely, suppose the executive calculates the standard s_{t+1} of plant electricity consumption in period t+1 by adaptive Brown's model [12]:

$$s_{t+1} = S(s_t, f_t) = (1 - \varepsilon)s_t + \varepsilon f_t,\ 0 < \varepsilon < 1,\ \ s_0 = s^0, \tag{13}$$

We will call $S(s_t, f_t)$ standardization procedure, and ε its elasticity. The introduction of such a procedure is typical for data standardization in intelligent electricity management [11].

Consider the practical aspects of the director motivation to save electricity consumption in fabrication. Usually, in the practice of adaptive management in fabrication, both impetuses and standards for the future grow with saving of electricity consumption, compared to the current standard [5]. Then the future adaptive standards for electricity consumption will be the lower, the smaller their consumption today. In fact, this standardization is carried out “from the achieved level” [6]. Usually, such adaptive standards will be decreased by a certain percentage, compared to the current standard. But the lower future standards for electricity consumption, the more difficult it is to get the impetus in the future. As a result, subordinated employee may not be interested in saving electricity. For example, such undesirable activity is typical for the operation of energy storage units [2]. To avoid this, the executive can assign to the director’s impetus:

$$i_t = I(s_t, f_t) = \eta(s_t - f_t) + const,\quad \eta > 0,\ t = 0,1..., \tag{14}$$

where $I(\bullet)$ is linear impetus procedure.

4.3 Minimizing Fabrication Electricity Consumption

The procedures for standardization (13) and impetus (14) constitute adaptive control of electricity consumption management of fabrication $M = (I, S)$. Let's consider how to choose this control to motivate the director to save electricity for fabrication in each period: $f_t = x_t$, t=0,1,…. Suppose the director seeks to increase the own target function - discounted sum of impetuses (14) in the current and N future periods:

$$R_t(M) = \sum_{\tau=t}^{t+N} \rho^{\tau-t} I(s_\tau, f_\tau),\ \ 0 < \rho < 1, \tag{15}$$

where ρ is discount factor. Then the director’s decision is $f_t^* = \arg\max_{f_t \geq x_t} R_t(M)$.

Statement 2. For minimizing fabrication electricity consumption in every period: $f_t^* = x_t$, t=0,1,…, it is sufficient to use adaptive control $M = (I, S)$.

Proof. According to the condition of Statement 2, adaptive control $M = (I, S)$ includes procedures (13) and (14). Let us substitute (14) into (15). After that, let substitute the expressions for s_τ, $\tau = \overline{t+1, t+N}$, from (13) into (15). Then, using (13) as a recurrent equation, it is easy to obtain the following expression for $R_t(M)$ as a function of f_t:

$$R_t(M) = \{1 - \rho + \varepsilon\rho[\varepsilon(1 - \varepsilon)]^N\} f_t + const.$$

Therefore $\partial R_t(M)/\partial f_t = 1 - \rho + \varepsilon\rho[\varepsilon(1 - \varepsilon)]^N$. Considering that $0 < \varepsilon < 1$ according to (13), as well as $0 < \eta < 1$ according to (15), we obtain $\partial R_t(M)/\partial f_t > 0$. Thus, $f_t^* = \arg\max_{f_t \geq x_t} R_t(M) = x_t$, $t = 0,1,...,$ Q.E.D.

Statement 2 defines an easily interpretable control method of motivation the director in saving electricity. Namely, Statement 2 means that in order to motivate the director in saving electricity, the executive can use adaptive control $M = (I, S)$. Thus, the executive decision in the period t is choosing adaptive control $M = (I, S)$ and minimal own electricity consumption: $O_t = o_t$.

4.4 Control System of Electricity Consumption in Fabrication

Combining Statements 1 and 2, we obtain

Theorem. To minimize the electricity consumption of fabrication, the superior sufficient to use the grading control $C = (A, G)$. In this case, the sequence of appraisals a_t, t=0,1,..., converges to unknown parameter b^*.

Proof. According to Statement 1, grading control $C = (A, G)$ is sufficient for motivation of the executive to minimize electricity consumption: $E_t^* = e_t$, t=0,1,… In this case, the sequence of appraisals a_t, t=0,1,..., converges to unknown parameter b^*. According to Statement 2, to guarantee this, the executive is sufficient to choose both adaptive control $M = (I, S)$ and $O_t = o_t$ in the period t, Q.E.D.

The Theorem defines an easily interpretable control method to minimize the electricity consumption of fabrication: combining the executive control $C = (A, G)$ and adaptive control $M = (I, S)$, we obtain control system of electricity consumption in fabrication.

5 Example: Control System of Electricity Consumption During Railcar Repairing

Let us illustrate the results obtained on the example of control system of electricity consumption during the repairing of railcars in Carriage Repair Company which is the part of the Russian Railways company [13]. The model of electricity consumption management in this company includes top manager (as the superior), regional manager (as the executive), and the director of depot (as the director of fabrication). The superior must learn and grade the executive to minimize electricity consumption in company.

According to Statement 2, to save electricity, for the executive it is enough to use adaptive control $M = (I, S)$ with standards (13) and impetuses (14) of the director. According to theorem, in order to motivate the executive to minimize electricity consumption, the superior only needs to use the grading control $C = (A, G)$.

Thus, control system of electricity consumption during the repairing of railcars includes grading control $C = (A, G)$ and adaptive control $M = (I, S)$. The results of this control system functioning are illustrated in Figure 1. There E_t (black line in Figure 1a) is average electricity consumption during the repairing of one railcar, in thousands of kilowatt-hours in month t, $t = \overline{1,12}$. Appraisal a_t (red line in Figure 1a) is recalculated with the aid of (8). Using a_t, the superior determines monthly grade g_t of the executive responsible for electricity consumption (9). For his part, the executive monitors average monthly electricity consumption f_t for one railcar, $t = \overline{1,12}$. This example illustrates the simplicity and transparency of developed control system of electricity consumption of fabrication in a company, and the applicability of proved Theorem.

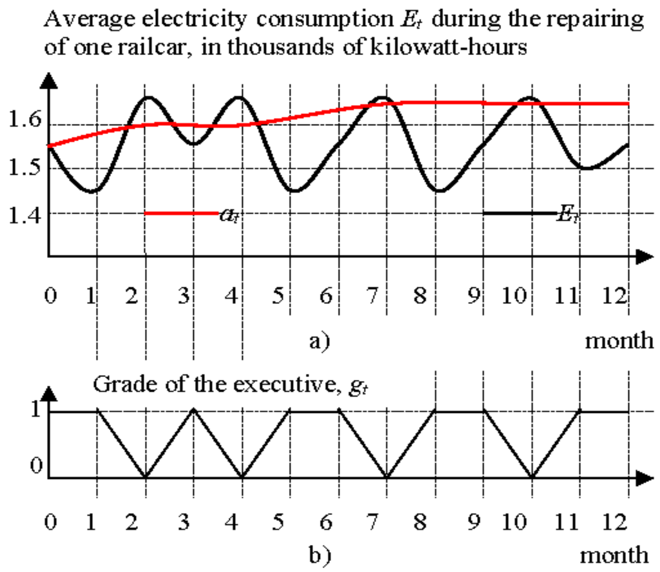

Fig. 1. a) average electricity consumption during the repairing of one railcar E_t (black line) and its appraisal a_t (red line), in thousands of kilowatt-hours in month t; b) grade of the executive g_t in month t.

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