Coaching in energy efficiency control of manufacturing

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Abstract. New trends in the management of manufacturing efficiency are associated with the development of such areas of Data Science as Big Data and Data Analytics, taking into account the human factor. With asymmetric awareness of management and personnel about the potential for efficiency, undesirable activity of personnel is possible. In this case, personnel as the active element selects its state in such a way as to maximize its own objective function. For this reason the energy efficiency of manufacturing can be not equal to the potential. Therefore, traditional methods and algorithms of Data Science may be ineffective. To solve this problem in the face of uncertainty, adaptive decision support system with coacher's instructions is proposed. In this system, the manager is considered a disciple of the coach, even if both of them are not aware of the potential of the energy efficiency. In order to ensure the effectiveness of traditional learning algorithm of Data Science, that system includes rating and stimulation procedures. Sufficient conditions have been found for the synthesis of the decision support system which is learning with coacher's instructions, in which the active element uses the potential of energy efficiency. The use of such system is illustrated by the example of energy efficiency of a wagon repair company.

1. Introduction

The concept of the new INDUSTRIE 4.0 industrial revolution is based on the widespread use of elements of artificial intelligence, cognitive management and Data Science [1]. New trends in controlling manufacturing efficiency are associated with the development of areas of Data Science such as Big Data and Data Analytics. Appropriate tools and methods are widely used in the processing and disclosure of useful information from a huge amount of data generated in various areas of production. To adapt these tools and methods to changes, such areas of artificial intelligence as machine learning and other intelligent system techniques are developing. The modelling of cognitive functions creates the prerequisites for smart manufacturing management in according to Industry 4.0 concept [2].

Another important prerequisite for the synthesis of smart manufacturing management is related to the need to take into account the human factor - the activity of production elements whose goals do not always coincide with the goal of the organization as a whole. The analysis and synthesis of the mechanisms of smart management of organizational systems are aimed at harmonizing the interests of such an active elements [3]. Such mechanisms include forecasting, planning, resource allocation and stimulation procedures. At the initial stage of their synthesis, the main attention was paid to the adaptive mechanisms of sustainable development of organizations [4]. A review of the early stages of
theoretical analysis and synthesis of the mechanisms of intelligent control of the development of active systems was performed in [5].

In recent years, the main emphasis has been placed on the development and practical application of a variety of adaptive and learning mechanisms. For example, mechanisms proposed for digital control of industrial systems using machine learning [6]. Useful data analysis tools are adaptive information models used to manage production based on self-learning [7]. With their help, for example, adaptive identification of an innovative production function of a corporation can be carried out [8]. Another type of tool for processing Big Data, taking into account human activity, is a business management mechanism based on learning with a tutor [9]. The results obtained were illustrated by the example of mechanism for improving energy efficiency of a large-scale Russian Railways corporation. Based on these results, we will consider a decision support system with the instructions of a coach, which calculates estimates and incentives for energy efficiency of production.

2. Algorithm of learning with coacher

Consider manufacturing management task link to the classification of observed situations and events. The result of this classification affects on decisions such as rating and stimulus of manufacturing personnel. With sufficient a priori information, its manager can use the rules of theory of statistical solutions. However, in a practice, a priori information is often not enough. There is a need to learning with the aid of coacher. Such coaching can be modelled using an adaptive procedure, for example, based on recurrent probabilistic algorithms of a stochastic approximation.

Let \( p_t \) be a random variable characterizing energy efficiency potential in period \( t \), \( t = 0, 1, ..., \). \( p_t \in D \subset R_+ \). There \( D \) is compact set which consists of 2 domains \( D^0_1 \) and \( D^0_2 \). \( D^0_1 \cup D^0_2 = D \). Suppose that manager do not know domains \( D^0_1 \) and \( D^0_2 \). But he can observe \( p_t \). Task of manager is to classify the energy efficiency situation by assigning the random value \( p_t \) to one of 2 domains \( D_1 \) and \( D_2 \), that also make up the set \( D: D_1 \cup D_2 = D \). Incorrect classification (i.e. \( D_1 \neq D^0_1 \)) leads to losses.

Consider this problem using the approach to learning such an inexperienced manager (Disciple), developed by Tsyganov (2019c). For classification the Disciple uses Coacher's instruction:

\[
S(p_t) = \begin{cases} 
0 & \text{if } p_t \in D^0_1 \\
1 & \text{if } p_t \in D^0_2 
\end{cases}
\]  

(1)

To classify the energy efficiency situation \( p_t \), Disciple uses two-step decision rule:

Step 1. The Disciple uses the decision function:

\[
x(p_t, c_t) = p_t - c_t
\]  

(2)

Step 2. The Disciple uses the decision rule:

\[
p_t \in \begin{cases} 
D_1 & \text{if } x(p_t, c_t) < 0 \\
D_2 & \text{if } x(p_t, c_t) \geq 0
\end{cases}
\]  

(3)

Here \( c_t \) is a parameter minimizing the learning quality criterion \( J(c) \) [9]:

\[
c_{t+1} = F(c_t, p_t) \rightarrow c^* = \arg \min_c J(c), \; c_0 = c^0, \; t = 0, 1, ...
\]  

(4)

\[
F(c_t, p_t) = c_t - \gamma_t (c_t - 0.5 \cdot l_{12} + (l_{12} + l_{21}) S(p_t)),
\]  

(5)

2
where \( l_{km} \) - losses arising when the Disciple erroneously ascribes \( p_t \) rating \( m \) (which corresponds to the domain \( D^0_m \)), while in fact \( p_t \) really has a rating of \( k \) (which corresponds to the domain \( D^0_k \)), \( k \neq m, k = 1, 2, \ldots \), \( \gamma_t > 0, \sum_{t=0}^{\infty} \gamma_t < \infty \).

3. Decision support system with coacher

In practice personnel is often more informed about potential of energy efficiency than its manager. In such cases, we talk about the asymmetric awareness of the parties [3]. Then management is interested in maximal energy efficiency \( p_t \) unknown to it. However the personnel, knowing true potential \( p_t \), can choose its output \( y_t \), \( \leq p_t \), in such a way to provide the best stimuli today and in the future.

In order to investigate this problem of asymmetric awareness of the parties, we accept the following assumptions.

1. The potential \( p_t \) is unknown both to Disciple and to Coacher.
2. The potential \( p_t \) becomes known to the personnel at the beginning of the period \( t \), i.e. until the choice of output \( y_t \). Then the personnel, considered as an active element (AE), select the output \( y_t^* \), which is not necessarily equal to the potential: \( y_t^* \neq p_t \).
3. The Coacher observes AE output \( y_t^* \) and gives instruction to Disciple:

\[
S(y_t^*) = \begin{cases} 
0 & \text{if } y_t^* \in D^0_1 \\
1 & \text{if } y_t^* \in D^0_2
\end{cases}
\]

(6)

4. The Disciple should make decisions about both classification and stimulus knowing the output \( y_t^* \) and Coacher instruction (6). For this the Disciple forms assessment \( a_{t+1} \) of the decision rule parameter \( c_{t+1} \) according to (5):

\[
a_{t+1} = F(a_t, y_t^*) = a_t \cdot \frac{0.5 \cdot l_{12}}{l_{21} l_{12} + l_{12} l_{21}} S(y_t^*), \quad a_0 = c^0.
\]

(7)

Then the Disciple considers the approximation of the decision function (2): \( x(y_t^*, a_t) = y_t^* - a_t \). Thus the decision rule (3) transforms in classification procedure:

\[
y_t^* \in \begin{cases} 
D_1 & \text{if } y_t^* < a_t \\
D_2 & \text{if } y_t^* \geq a_t
\end{cases}
\]

(8)

Denote classification procedure (8) as \( C \). Based on it, Disciple determines the rating \( r_t \) of \( y_t^* \):

\[
r_t = R(y_t^*, a_t) = \begin{cases} 
2 & \text{if } y_t^* \geq a_t \\
1 & \text{if } y < a_t
\end{cases}
\]

(9)

4. Data disclosure terms

The problem of data extracting about potential \( p_t \) and parameter \( c^* \) arises because Coacher and Disciple are not able to take into account factors that become known to personnel only during the manufacturing process. This not only increases risks, costs and time of process, but also makes algorithm (7) ineffective. Note that (7) matches with (5) at \( y_t^* = p_t, t = 1, 2, \ldots \). In this case, (4) takes
place and the problem of identification of $c^*$ is solved. Conceptually, for such identification, it is enough to motivate the personnel to disclose data on potential in each period: $y_t^* = p_t$, $t = 1, 2, \ldots$.

Consider the following order of operations in the period $t$, $t = 0, 1, \ldots$. The AE (personnel) becomes known parameter $p_t$, $p_t \in D$. Based on this, the AE chooses the output $y_t^*$, $y_t^* \leq p_t$. The Coacher observes AE output $y_t^*$ and gives instruction (6) to Disciple. After this Disciple classifies $y_t^*$ using the procedure (8) with the assessment $a_t$ determined in the previous period $(t-I)$ by (7). In addition Disciple generates assessment $a_{t+1}$ for the next period $t+1$ using the recurrent procedure (7).

In practice, stimuli to personnel increase with increasing its effectiveness [10]. In our model energy effectiveness characterizes the output $y_t^*$, and rating $r_t$ grows (not decreases) with the output $y_t^*$ in accordance with (9). Thus we shall suppose that the stimulus for the AE:

$$i_t = I (r_t) \in R^1, \quad I (r_t) \uparrow r_t,$$

(10)

where $I (r_t)$ is the stimulation procedure grows with the rating $r_t$. This is consistent with the traditional practice of stimulating manufacturing: the higher the rating, the higher the personnel rewards [11].

A set of procedures of assessment $F$ (7), classification $C$ (8), rating (R) and stimulation $I$ (10) is called the decision support system with coaching (briefly, DSSC) and denoted $\Sigma_C = (F, C, R, I)$.

Suppose that to support decisions in conditions of uncertainty, Disciple uses the DSSC $\Sigma_C$. There an assessment $a_{t+1}$ of the decision rule parameter is formed, by using the algorithm (7) with Coacher’s instructions (6). In addition, based on $y_t$ and $a_t$ Disciple classify $y_t$ using the decision rule (8). Based on results of this classification, Disciple determines rating (9) and stimulus (10).

Suppose that the goal function of AE depends of present and future stimuli calculated by (10):

$$V_t = \sum_{\tau=t}^{T} \rho^{\tau-t} i_t,$$

(11)

where $\rho$ is the discount factor, $0 < \rho < 1$, $T$ is the AE foresight. The AE can choose $y_t$ to maximize goal function (12). Also the hypothesis of benevolence of AE in relation to the Disciple is supposed: if $p_t \in \text{Argmax} V_t$, then $y_t^* = p_t$, $t = 0, 1, \ldots$

The goal of management is the maximum of energy efficiency, which is achieved with using potential $p_t$. Thus the Disciple needs to synthesis DSSC $\Sigma_C$ where personnel as AE is interested in using potential that is, fulfilling equalities $y_t^* = p_t$, $t = 0, 1, \ldots$.

**Theorem.** In order for the AE to use the potential (i.e., for $y_t^* = p_t$, $t = 0, 1, \ldots$), it is enough DSSC $\Sigma_C = (F, C, R, I)$.

**Proof.** The goal function (11) depends on stimuli $i_t$, $\tau = t, t+T$. By (9) and (10), as $y_t$ grows, $i_t$ in (11) do not decrease. Also by (6) $S(y_t)$ do not decrease with $y_t$ at $p_t \in D$, $0 \leq y_t \leq p_t$, $\tau = t+1, t+T$. So it is obvious from (7) that $a_t$ do not increase with $y_t$. Also according to (9) $r_t$ do not increase with $a_t$. Then $r_t$ do not decrease with $y_t$. So $i_t$ do not decrease with $y_t$ at $p_t \in D$, $0 \leq y_t \leq p_t$, $\tau = t+1, t+T$. Thus the goal function (11) do not decrease with $y_t$. 


Taking into account that \( y_t \leq p_t \) we obtain \( p_t \in \text{Argmax } V_t \). Consequently by the goodwill hypothesis, \( y_t^* = p_t \), \( t=0,1,\ldots \), Q.E.D.

Theorem admits a transparent interpretation in case when \( y_t \) characterizing the energy efficiency in period \( t \), \( y_t \leq p_t \), where \( p_t \) is the unknown maximal energy efficiency. Disciple obtains from Coacher the instruction \( S(y_t) \) and, with the aid of (7), adapts the assessment using in decision rule for classification (8) and rating (9).

Further, in accordance with (9) and (10), Disciple makes rating and stimulating personnel according to its energy efficiency. If \( y_t < a_t \) then the personnel is considered as ineffective (rating \( r_t = 1 \)) and punished. If \( y_t \geq a_t \) then the personnel is considered as effective (rating \( r_t = 2 \)) and encouraged.

Any of these decisions is associated with a certain risk for the Disciple. In the first case, losses \( l_{21} \) arising when Disciple wrongly punishes the energy effective personnel. In the second case, losses \( l_{12} \) arising when Disciple wrongly encourages the ineffective personnel. So the classification assessment \( a_t \) is the lower limit of energy efficiency \( y_t \) corresponding to good work of the personnel.

Note that, according to (7) and (6), the higher the index \( y_t \), the lower the classification assessment \( a_t \) for the future period \( \tau \), \( \tau = t+1, t+\theta \). But according to (9) this assessment \( a_t \) plays the role of the threshold value of the index \( y_t \) at which the personnel receives a stimulus (10) in the period \( \tau \), \( \tau = t+1, t+\theta \). Consequently, it becomes easier for personnel to get a promotion from the Disciple in the future period \( \tau \), even with a smaller value of the random potential \( p_t \), \( \tau = t+1, t+\theta \).

In other words, with an increase of energy efficiency \( y_t \), personnel receives not only a higher stimulus. Also the threshold values for stimuli in the future are decreased. This further interest the personnel in the disclosure of its potential of energy efficiency, i.e. in the selection \( y_t^* = p_t \).

5. Coaching for energy efficiency of manufacturing
Consider the application of DSSC developed above to obtain data and use the energy efficiency potential in the wagon repair company which is the part of large-scale corporation Russian Railways.

5.1. Index of energy efficiency
The management of the car repair company (briefly the management) monitors the actual energy consumption in kind (in particular, the consumption of fuel, electricity, gas, etc.) for a week. The management then compares this real energy expenditure with its standard weekly value. For a weekly assessment of energy efficiency of production, the management uses the index

\[ y_t = (s_t - e_t)/s_t \]  

where \( e_t \) is the actual energy consumption in kind in week \( t \), \( s_t \) is the standard value of energy consumption per week \( t \), \( t = 0, 53 \). In fact management considered index (12) as the output of personnel characterizing energy efficiency.

Index \( y_t \) is calculated weekly. Based on index \( y_t \), classification is made, and manufacturing rating is determined. In order to make the results of this classification more visual for management, it is necessary to determine four ratings of this energy efficiency - excellent (rating 4), good (rating 3), satisfactory (rating 2), and bad (rating 1).
5.2. Recurrent assessments with coaching

To determine those four ratings, an inexperienced manager (Disciple) obtains instructions from an expert on energy efficiency in manufacturing (Coach). Then the Disciple uses the following two procedures of determining the assessments of the parameters of the decision rule, designed from the procedure (7).

1. If the current energy efficiency index is non-negative ($y_t \geq 0$), then the corresponding recurrent assessment $a_{t+1}^+$ used to assign the energy efficiency rating 3 or 4 is recalculated by formula:

$$a_{t+1}^+ = F^+(a_t^+, y_t) = a_t^+ - \gamma_t[^0 - 0.5 \gamma_0 + (1 - 1_2^2 + 1_2^2) S^+(y_t)],$$

where $a_t^+$ - the upper classification assessment, $S^+(y_t)$ - Coach's instruction determined according to (6):

$$S^+(y_t^*) = \begin{cases} 0 & \text{if } y_t^* \in D^0_3 \\ 1 & \text{if } y_t^* \in D^0_4 \end{cases}$$

2. If the current energy efficiency index is negative ($y_t < 0$), then the corresponding recurrent assessment $a_{t+1}$ used to assign the energy efficiency rating 1 or 2 is recalculated by formula:

$$a_{t+1} = F(a_t^-, y_t) = a_t^- - \gamma_t[^0 - 0.5 \gamma_0 + (1 - 1_2^2 + 1_2^2) S^-(y_t)],$$

where $a_t^-$ is the lower classification assessment, $S^-(y_t)$ - Coach's instruction determined according to (6):

$$S^-(y_t^*) = \begin{cases} 0 & \text{if } y_t^* \in D^0_1 \\ 1 & \text{if } y_t^* \in D^0_2 \end{cases}$$

Figure 1 shows the graphs of weekly indexes of energy efficiency $y_t$, as well as the upper assessment $a_t^+$ and lower assessment $a_t^-$ during the year, $t = 0.53$.

As can be seen from figure 1, recurrent procedures (13) and (15) with Coacher’s instructions (14) and (16) provided a fairly quick adjustment of the upper and lower classification assessments to their stationary values.

5.3. Energy efficiency ratings

The Disciple weekly determines production energy efficiency ratings $r_t$, using index $y_t$, assessment (13) or (15), and decision rule of classification (8). To do this, the Disciple uses one of the following alternative procedures.

1. If the current index is non-negative ($y_t \geq 0$), then the production energy efficiency belongs to the 3rd or 4th domain according to the decision rule (8):
\[ y_t \in \begin{cases} D_3 = [0, a_t^+] & \text{if } y_t < a_t^+ \\ D_4 = [a_t^-, 1] & \text{if } y_t \geq a_t^+ \end{cases} \]  

(17)

**Figure 1.** Indexes and assessments of energy efficiency during the year.

Denote classification procedure (17) as \( C^+ \). Based on results of classification (17), by using (9) Disciple determines production energy efficiency rating 3 or 4:

\[
r_t = R^+(y_t, a_t) = \begin{cases} 4 & \text{if } y_t \in D_4 \\ 3 & \text{if } y_t \in D_3 \\ 4 & \text{if } y_t^* \geq a_t^+ \\ 3 & \text{if } 0 \leq y_t < a_t^+ \end{cases}
\]

(18)

2. If the current index is negative \((y_t < 0)\), then the production energy efficiency belongs to the 1st or 2nd domain according to the decision rule (8):

\[
y_t \in \begin{cases} D_1 = [-1, a_t^-] & \text{if } y_t < a_t^- \\ D_2 = [a_t^-, 1] & \text{if } a_t^- \leq y_t < 0 \end{cases}.
\]

(19)

Denote the classification procedure (19) as \( C^- \). Based on results of classification (19), Disciple determines production energy efficiency rating 1 or 2 using (9):

\[
r_t = R^-(y_t, a_t) = \begin{cases} 2 & \text{if } y_t \in D_2 \\ 1 & \text{if } y_t \in D_1 \\ 2 & \text{if } 0 \geq y_t^* \geq a_t^- \\ 1 & \text{if } y_t < a_t^- \end{cases}.
\]

(20)

Combining (18) and (20) we get the formula for determining of all ratings:

\[
r_t = R_C(\bar{a}_t, y_t) = \begin{cases} 4 & \text{if } y_t \geq a_t^+ \\ 3 & \text{if } 0 \leq y_t < a_t^+ \\ 2 & \text{if } a_t^- \leq y_t < 0 \\ 1 & \text{if } y_t < a_t^- \end{cases}
\]

(21)

where \( \bar{a}_t = (a_t^+, a_t^-) \), and \( R_C(\bar{a}_t, y_t) \) is the Disciple's complex rating procedure. Figure 2 shows a graph of ratings \( r_t \) calculated by (21).
Figure 2. Ratings of energy efficiency during the year.

Note that the upper classification assessment $a^+_t$ is the lower limit of the energy efficiency ($y_t$) corresponding to excellent work of the personnel. The lower classification assessment $a^-_t$ is the lower limit of the energy efficiency ($y_t$) corresponding to satisfactory work of the personnel. If the index $y_t$ is below this assessment $a^-_t$, then management intervention in the work of personnel is required.

5.4. Energy efficiency stimuli

The Disciple determines stimulus in accordance with rating $r_t$ by (10). To do this, the Disciple uses one of the following alternative procedures.

1. If the current index is non-negative ($y_t \geq 0$) then in accordance with (10):

$$ i_t = I^+(r_t) = \begin{cases} \varphi_4 & \text{if } r_t = 4 \\ \varphi_3 & \text{if } r_t = 3 , \quad t = 0.53 \end{cases} $$

where $\varphi_k$ is the stimulus in case of rating $k$ assignment, $k = 3, 4$, $\varphi_3 < \varphi_4$, and $I^+(r_t) \uparrow r_t$.

2. If the current index is negative ($y_t < 0$) then in accordance with (10):

$$ i_t = I^-(r_t) = \begin{cases} \varphi_2 & \text{if } r_t = 2 \\ \varphi_1 & \text{if } r_t = 1 , \quad t = 0.53 \end{cases} $$

where $\varphi_k$ is the stimulus in case of rating $k$ assignment, $k = 1, 2$, $\varphi_1 < \varphi_2$, so $I^-(r_t) \uparrow r_t$.

Combining (22) and (23) we get the formula for determining of all stimuli:

$$ i_t = I_C(r_t) = \begin{cases} \varphi_4 & \text{if } r_t = 4 \\ \varphi_3 & \text{if } r_t = 3 \\ \varphi_2 & \text{if } r_t = 2 , \quad t = 0.53 \\ \varphi_1 & \text{if } r_t = 1 \end{cases} $$

where $I_C(r_t)$ is the Disciple’s complex stimulation procedure, $\varphi_k$ is the stimulus in case of rating $k$ assignment, $k = 1, 4$, $\varphi_1 < \varphi_2 < \varphi_3 < \varphi_4$. 


5.5. Complex Decision Support Systems with Coacher

A set of procedures of assessment $F^+$ (13), classification $C^+$ (17), rating $R^+$ (18), and stimulation $I^+$ (22) form DSSC $\Sigma^C = (F^+, C^+, R^+, I^+)$. A set of procedures of assessment $F^−$ (15), classification $C^−$ (19), rating $R^−$ (20), and stimulation $I^−$ (24) form another DSSC $\Sigma^C = (F^−, C^−, R^−, I^−)$. Remember that $F^+$ and $F^−$ are obtained from (7), $C^+$ and $C^−$ - from (8), $R^+$ and $R^−$ - from (9), $I^+$ and $I^−$ - from (10). Thus both $\Sigma^C$ and $\Sigma^C$ satisfies the conditions of Theorem, and provides the minimum energy consumption in kind (in particular, the consumption of fuel, electricity, gas, etc.).

Now consider complex DSSC $\Sigma = (F^+, F^−, C^+, C^−, R, I)$ where $R$ is the complex rating procedure determined by (21), and $I$ is the complex stimulation procedure determined by (24). In fact this complex DSSC $\Sigma$ joining all the procedures of DSSC $\Sigma^C$ and $\Sigma^C$.

Exploring the possibilities of the complex DSSC $\Sigma$ by means of method used to prove the Theorem. According to (24) $I^C(\tau_i) \uparrow \tau_i$. Then taking into account (21) and (24), we find that the higher the index $y_i$, the higher the personnel stimuli. In addition, according to (13) and (15), the higher the index $y_i$, the lower the assessments $a^+_\tau$ and $a^-_\tau$ using for classification and rating in future periods, $\tau = t+1, t+0$. Thus, with an increase in the index $y_i$, the personnel receives not only higher reward today. Also “reward bars” ($a^+_\tau$ and $a^-_\tau$) for it in the future goes down. This further interests the personnel in the disclosure of its potential of energy efficiency. This ensures the minimum energy consumption. Thus, using the idea of the proof of the theorem, we actually obtained the following statement.

**Corollary.** Complex DSSC $\Sigma = (F^+, F^−, C^+, C^−, R, I)$ ensures the maximum energy efficiency of manufacturing.

6. Conclusions

The possibility of research and innovative interpretations in the field of Big Data and Data Analytics is shown, taking into account the activity of the elements a manufacturing system whose goals do not necessarily coincide with the purpose of the system as a whole.

Effective data processing and decision-making algorithms have been developed, optimized taking into account the human factor. These algorithms are combined into DSSC under uncertainty allowing the use of various technique and applications in Big Data. The proved Theorem and the considered practical example show that such DSSC can be an effective tool for processing data and supporting decision-making in the field of efficiency manufacturing in the face of uncertainty.

In practice, managers use various decision support systems. Combining with them DSSC developed above, we can get more complex systems for the functioning of smart organizations. Accordingly, the development of more complex decision support systems with coacher's instructions for data processing and decision making, optimized taking into account the human factor, will be required.

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