Control systems design: the method of the generalized criterion composition for multi-criteria optimization

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Abstract. The article deals with optimization issues in design of an automatic control system (ACS). The method of multicriteria optimization is presented, which combines simulation of ACS and optimization procedure based on a genetic algorithm and implemented by the MATLAB / Global Optimization Toolbox. The method of the generalized criterion composition based on the initial particular criteria is also proposed. The use of this generalized criterion makes it possible to reduce the complexity of determining the optimal parameters of the ACS and allows to take into account the constraints when searching for the optimal solution.

1. Introduction
Developers of automatic control systems (ACS) should take into account a complex of various requirements associated with systems’ characteristics [1-5]. The basic requirements usually include desired static and dynamic properties of systems. First, these are requirements for control accuracy and errors that occur in various modes of operation of the control system. Secondly, ACS developers apply system performance criteria based on minimizing the transient time, energy consumption, etc. It should be noted that the requirements for the ACS are often contradictory. Therefore, several indicators of system quality are being considered for ACS development [4, 6, and 7]. As a result, to create a system that meets the requirements, the problem of its multicriteria optimization must be posed and solved.

When multiple criteria are used, a certain solution should be selected among the feasible solutions and declared as the best one. One of the fundamental concepts of decision making theory is the concept of Pareto optimal (or effective) decision [8, 9]. A founded solution is considered as a Pareto-optimal one if the value of any criterion can be improved only by worsening the values of the other criteria. According to the Edgeworth–Pareto principle formulated in [8], the best solutions of the problem should be chosen among the Pareto optimal solutions.

When optimizing control systems, it is often required to reduce the original multi-goal problem to problems with a single criterion [4, 5, and 7]. At the same time, it is necessary to form a single quality criterion for the automatic control system, the extreme value of which corresponds to the optimal system design. This generalized criterion should be based on the initial particular requirements. The paper proposes a method for the formation of a generalized criterion to solve the problem of multicriteria optimization of the control system.
2. The problem statement. Control system requirements

We consider the statement of the multicriteria optimization problem in ASC design on the complex system example. The deaerator of an nuclear power plant (NPP) power unit is presented as a typical automation object [2, 6, and 9].

The controller of the ASC, designed to control steam pressure and prevent a decrease of pressure in the deaerator, generates control commands for the actuators of the control valves. The controller (pressure in the deaerator) must ensure stable operation and the absence of self-oscillations in the control loop, while the requirements for limiting the operating frequency of the actuator must be met. This frequency of operation at constant load of the power unit should not exceed 6 operations per minute. The controller must not allow sudden pressure changes resulting in water boiling on the suction side of the feed pumps and their steaming.

The deaerator pressure controller implements a single-pulse control system: a signal of the measured steam pressure in the deaerator (pressure pulse) is fed to the controller input. The error signal is generated as the difference between the setpoint and current pressure value signals.

The diagram of the mathematical model of the ACS pressure is shown in Figure 1. The model was developed by MATLAB / Simulink tools [11, 12], which are designed to perform scientific and engineering calculations.

![Figure 1. The simulation model of the pressure control system.](image)

The control loop model contains a controller, an actuator with a control valve, and a control object. In the system under consideration, a typical relay-pulse controller is used, which generates output pulses with a duty cycle associated with the PD dependence with a change in the error signal.

The controller together with the constant speed actuator approximately implements the PI control law [3, 6, and 7]. The main adjustable parameters of the controller are the gain $k_p$ and the integration time constant $T_i$.

The control valve model equipped with an actuating mechanism implements a gain (100% open / $T_{AM}$) based on the $T_{AM}$ valve opening time and an integrator limited from 0 to 100% open.

The model of the controlled object, i.e. of the channel "position of the control valve - pressure in the deaerator" is realized by an inertial unit.

The control valve model equipped with an actuating mechanism implements a gain (100% opening/$T_{AM}$) that takes into account the valve opening time ($T_{AM}$) and an integrator limited from 0 to 100% opening. The model of the controlled object, i.e. of the channel "position of the control valve - pressure in the deaerator" is realized by an inertial unit.
Let us consider the case when, when designing an ACS, it is required to minimize the control error in the steady state, as well as control costs. To do this, we will supplement the model with blocks that calculate the adopted control quality indicators. For a period of time \( T \) (taken not less than the duration of the transient), the following quadratic integral criteria are calculated:

- a criterion characterizing the magnitude and duration of the existence of the control error \( \varepsilon(t) \) (deviation of the controlled parameter from the setpoint)

\[
\tilde{F}_1(X) = \int_0^T \varepsilon^2(t) \, dt;
\]

- a criterion that takes into account control costs (\( u \) is the output signal of the controller)

\[
\tilde{F}_2(X) = \int_0^T u^2(t) \, dt;
\]

- a criterion counting the number of pulses \( N \) generated by the controller (AM actuations)

\[
\tilde{F}_3(X) = N.
\]

Since these criteria have different ranges of variation, to bring them to the range from 0 to 1, they are normalized by the formula

\[
F_i(X) = \tilde{F}_i(X)/\tilde{F}_i^{max}, \quad i = 1,3, \quad \tilde{F}_i^{max} = \max \tilde{F}_i(X).
\]

In addition, when optimizing the ACS, we need to take into account the constraints that are imposed on the ratios of the parameters \( k_p \) and \( T_i \). For relay-pulse controllers, self-oscillations may occur due to the presence of nonlinearity (relay characteristic) in the structure of the controller. In order for self-oscillations to be absent, the following condition must be met

\[
G(X) = k_p T_i / \Delta - (k_p T_i / \Delta)_{crit} < 0.
\]

Here \( \Delta \) is the dead zone of the relay characteristic of the controller, and \( (k_p T_i / \Delta)_{crit} \) is the critical ratio of the parameters, which is determined experimentally \([4, 7]\).

Thus, it is necessary to optimize the pressure control system, that is, to select such values of the parameters \( X = (k_p, T_i) \), which minimize the adopted indicators \( F_i(X), \quad i = 1,3 \), to ensure performance, no overshoot, and reduce the number of AM actuations, taking into account the constraint \( G(X) \) as well.

3. Theory
As the previous experience in designing ACS has shown \([4, 6, 7]\), the minimum values of the particular quality criteria \( F_i(X), i = 1,3 \), are achieved with different parameters of the ACS. Therefore, we need to reach a compromise between the criteria when optimizing the system.

The set of particular criteria \( F_i(X), i = 1,3 \) forms a vector criterion of optimality (vector objective function) \( F(X) \in \{F\} \), where \( X \in \{X\} \) is the vector of variable parameters; \( \{X\}, \{F\} \) are the spaces of parameters and vector criteria, respectively. We need to minimize each of the particular criteria in the same range of acceptable parameter values

\[
D_X \in D_X' \cap D_X'', \quad D_X' = \{X \mid k_p^{min} \leq k_p \leq k_p^{max}, T_i^{min} \leq T_i \leq T_i^{max} \}, \quad D_X'' = \{X \mid G(X) < 0 \}.
\]

Here \( X = (k_p, T_i) \) is the vector of varied parameters; \( G(X) = k_p T_i / \Delta - (k_p T_i / \Delta)_{crit} \) is the constrain function; \( k_p^{min}, k_p^{max}, T_i^{min}, T_i^{max} \) are the minimum (maximum) feasible values of the parameters \( k_p \) and
It is possible to say that:

$$
\min_{X \in D_X} F(X) = F(X^o) = F^o,
$$

where $X^o$ and $F^o$ are solutions of the problem. We understand expression (6) in the sense that in order to optimize the ACS, it is desirable to minimize each of the particular criteria.

In accordance with the formal definition of the Pareto set, the vector criterion $F(X)$ maps the set of feasible parameters $D_X$ into the set $D_F$ of the criteria space, which is called the set of achievable goals (criterion set) of the multicriteria optimization problem (6).

On the set $D_X$, a preference relation is introduced, denoted by the symbol $\succ_X$. It is possible to say that the vector $X' \in D_X$ is preferable to the vector $X'' \in D_X$, that is, $X' \succ_X X''$, if among the equalities and inequalities $F_i(X') \le F_i(X'')$, $i = 1, m$, $X'' \in D_X$, and there is at least one strict inequality (when the relation $X' \succ_X X''$ is also said that the solution $X'$ dominates the solution $X''$).

The preference relation $\succ_X$, given on the set of possible parameters, generates the preference relation $\succ_F$ on the set of possible vectors $F(X) \in D_F \subset \{F\}$:

$$
F(X') \succ_F F(X'') \iff X' \succ_X X'' \text{ if } X', X'' \in D_X \subset \{X\}
$$

This means that the vector $F' = F(X')$ is preferable to the vector $F'' = F(X'')$ (i.e. $F' \succ_F F''$) if and only if the solution $X'$ is preferable to the solution $X''$ (i.e. $X' \succ_X X''$).

According to the Edgeworth-Pareto principle [17], we should always choose the best solutions to a multicriteria problem within the Pareto set of solutions $P_F(X)$, defined by the relation:

$$
P_F(X) = \{X^o \in D_X \subset \{X\} \mid \text{there is no } X \in D_X \subset \{X\} \text{ such that } F_i(X) \le F_i(X^o), i = 1, m, F_i(X) \ne F_i(X^o)\},
$$

that is, the components of the vector $F(X^o)$ are not greater than the corresponding components of the vector $F(X)$, and at least one component of the vector $F(X^o)$ is strictly less than the corresponding component of the vector $F(X)$.

Simultaneous minimization of the $F_i(X), i = 1, m$ criteria corresponds to the construction of a set of Pareto-optimal solutions $P_F(X)$, that is, such feasible solutions that cannot be improved (decreased) by any of the available criteria without deterioration (increase) by some at least one other criterion. Obtaining a set of Pareto-optimal solutions $P_F(X)$ is not yet the final decision for us when choosing a variant of system parameters, since it is necessary to obtain not several, but one preferred solution. That is, after the set of Pareto-optimal solutions has been obtained, we have the problem of narrowing it [9]. When there is a small number of elements in the set of Pareto-optimal solutions (variants of various parameters), the ACS developer can view them all for comparison, analysis of advantages and disadvantages, and make the final choice of one solution based on his preferences.

To solve the problem of multicriteria optimization of the pressure control system, we used the approach that we proposed and tested to optimize traditional relay-pulse control system [4, 10].

The approach we propose is a modification of the lexicographic approach [9], according to which information about the relative importance of the criteria is first revealed. Further, on the basis of this information, we need to choose two main particular criteria for which to construct a set of Pareto solutions. After that, we need to narrow the Pareto set taking into account the existing constraints (remove the vectors of parameters that do not satisfy the constraints). We narrow the resulting subset of the original Pareto set, alternately using the next most important criteria, until the search for a single solution is completed. The solution of the problem of multicriteria optimization of the pressure control system based on the proposed approach includes the following four stages.
At the first stage, from the accepted quality indicators \( F_i(X) \), \( i = 1,3 \), we select the main particular criteria \( F_1(X) \) and \( F_2(X) \), which characterize the accuracy of regulation and control costs. Further, we consider the optimization problem as a two-criterion one. We take into account that according to the Edgeworth-Pareto principle, the best solutions to a multicriteria problem should always be chosen within the Pareto set of solutions.

At the second stage, for the main criteria \( F_1(X) \) and \( F_2(X) \), we construct a set of Pareto-optimal solutions \( P_r(X) \). Since the set of Pareto-optimal solutions is not yet the final decision when choosing a variant of the ACS parameters, we need to narrow it down.

First, to narrow the set of Pareto-optimal solutions \( P_r(X) \), we need to take into account the constraint \( G(X) \) imposed on the control system parameters. Therefore, at the third stage, we exclude from consideration those solutions (vectors of parameters \( X \)) that do not satisfy the constraint \( G(X) \). As a result, we find a restricted set of Pareto-optimal solutions \( P_r(X) \), and \( P_r(X) \subset P_r(X) \subset D_X \subset \{X\} \) is included.

At the final, fourth stage, to select a single set of ACS parameters as an additional criterion, we introduce the \( F_3(X) \) criterion. We seek the minimum value of the criterion \( F_3(X) \) among the narrowed (subject to the constraint \( G(X) \)) set of Pareto solutions obtained by the criteria \( F_1(X) \) and \( F_2(X) \).

That is, we are looking for a solution to the one-criterion problem \( X^o_3 \in \arg\min F_3(X) \) and, if the set of solutions consists of a single point, the process of choosing a variant of the parameters is completed: \( X^o = X^o_3 = (k_p,T_i) \). If the minimum of \( F_3(X) \) provides not one vector of parameters, but several, the problem of narrowing the obtained solutions set \( X^o_3 \) again arises ( \( X^o_3 \subset P_r(X) \subset P_r(X) \subset D_X \subset \{X\} \) holds).

Among the solutions obtained, a vector of parameters is selected that provides a minimum to the most important criterion \( F_3(X) \) (characterizing the control accuracy). As the final version, the solution of the one-criterion problem \( X^o = \arg\min X^o \subset X^o_3 \) is accepted and the vector criterion \( F(X^o) = (F_1(X^o),F_2(X^o),F_3(X^o)) \) is determined.

4. The method of multi-criteria optimization of the control system. Simulation results

To construct a set of optimal solutions, we used the Pareto approximation method based on the genetic algorithm (GA). The genetic algorithm is a method for finding optimal solutions based on copying the mechanisms of biological natural selection and genetic inheritance [13]. It is known that the advantage of GA in comparison with traditional optimization methods is that the solution is sought from a set of points. The operations of calculating the suitability of an individual and selection for convergence to the Pareto front are specific to the problem of constructing a Pareto set.

To construct a set of Pareto solutions and simulate ACS, we developed MATLAB scripts that perform multiple calls to the ACS Simulink model, set GA options and control the optimization. We used a multipurpose genetic algorithm implemented on the basis of the NSGA-II (Non-Dominated Sorting Genetic Algorithm) genetic Pareto-approximation algorithm [14, 15].

To use the genetic algorithm as an “individual”, we took the vector of the ACS parameters: \( X = (k_p,T_i) \). At the same time, the number of individuals in the population of the genetic algorithm was set in the range from 30 to 150. To obtain the results, we needed from 5 to 15 generations of GA.

Figure 2 shows the optimization result (for one of the implementations) as a solution to a two-criteria problem using the main criteria \( F_1(X) \) and \( F_2(X) \). The mapping of the parameter plane (the Pareto set of solutions) is carried out on the criterion plane (the Pareto set of vector criteria).
Figure 2. Mapping the parametric space into the criterial one when optimizing the pressure ACS using GA: a) – a set of Pareto solutions; b) – Pareto set for criteria $F_1(X)$ and $F_3(X)$.

On the criterion plane with the axes $F_1(X)$ and $F_2(X)$, an approximation of the Pareto front is shown (that is, a set of points of non-improving solutions for these criteria) obtained during optimization using GA. Individuals of the genetic algorithm (approximation of the Pareto set of vector criteria) and the corresponding Pareto set of solutions $P_F(X)$ are shown as asterisks. Points of the restricted set of Pareto-optimal solutions (satisfying the constraint $G(X)<0$) and the corresponding set of vector criteria are circled and dashed lines.

As a result of invoking the additional criterion $F_3(X)$ from the narrowed set of points of the Pareto-optimal parameters of the ACS, we chose the only solution (highlighted by a circle with a larger diameter) corresponding to the minimum of the criterion $F_3(X)$.

The graphs of the transient characteristics of the ACS of the steam pressure (disturbance by the setting of the controlled parameter) are shown in Figures 3a–c (to minimize the criteria $F_1(X) – F_3(X)$, respectively). On the graphs, the dashed line corresponds to the controlled parameter, the dash-dotted line – to the valve position, and the continuous line – to the controller pulse output.

For clarity, Figure 3d shows the graphs of the transient processes of all three cases on an enlarged scale for the controlled parameter (pressure) (curve 1 – at $F_1 = \text{min}$; 2 – at $F_2 = \text{min}$; 3 – at $F_3 = \text{min}$; 4 – set pressure value). Let’s look at the figures: in Figure 3a, the transient process (at the minimum value of the criterion $F_1(X)$) is characterized by self-oscillations. This is due to the fact that the point corresponding to $F_1 = \text{min}$ does not belong to the set of points satisfying the constraint $G(X)<0$ (as shown in Figure 2). The transient process at the minimum value of the criterion $F_3(X)$ is not only characterized by a large number of controller operations (Figure 3b), but also has overshoot. In addition, this transient process is prolonged in time (Figure 3d, curve 2).

At the same time, an ACS with parameters corresponding to the minimum criterion $F_3(X)$ (among the narrowed set of effective solutions for the criteria $F_1(X)$ and $F_2(X)$, taking into account the imposed constraint $G(X)<0$, has significantly better dynamic characteristics (Figure 3c). It can be seen that the transient process is without overshoot and with good response speed (Figure 3d, curve 3), as well as with a small number of controller actuations and without self-oscillations (Figure 3c).
Figure 3. Transient characteristics of the ACS as a result of searching for the minimum $F_3(X)$ among the set of effective solutions for the criteria $F_1(X)$ and $F_2(X)$. It should be noted that the good quality of the control process when optimizing the ACS was observed in all the obtained implementations. The parameter values were selected from the accepted ranges: $k_p \in [0.01; 1]$ and $T_i \in [1; 70]$. Next, we will consider how we propose to construct a generalized criterion, i.e. reduce the multipurpose task of optimization of the ACS to a task with a single quality criterion.

5. The method of composing a scalar criterion for the synthesis of ACS. Optimization results

We performed the transformation of the multicriteria ACS optimization problem into a scalar problem on the basis of our approved approach. We form a scalar criterion based on the results obtained in solving the multicriteria optimization problem, when $F_1(X)$ and $F_2(X)$ were taken as the main particular criteria, and the additional criterion was $F_3(X)$. The choice in the Pareto set is reduced to the choice of the weighting coefficients $\lambda_i$ for particular criteria of linear convolution $J(X) = \sum_{i=1}^{m} \lambda_i F_i(X), \sum_{i=1}^{m} \lambda_i = 1; \lambda_i \geq 0; i = \overline{1,m}$. Since any minimum point on the set $X$ of the linear convolution of criteria at $\lambda_i \geq 0; i = \overline{1,m}$ is Pareto-optimal, then the choice within the indicated limits of the coefficients of the linear convolution and minimization of its value on the set $D_X$ leads to Pareto-optimal options. This means that we reduce the problem of obtaining linear convolution to the problem of finding the weight coefficients.

For the final choice of parameters, a solution was found that corresponds to the minimum of the criterion $F_3(X)$ among the set of Pareto solutions for the criteria $F_1(X)$ and $F_2(X)$. That is, the expression $J(X) = \lambda_1 F_1(X) + \lambda_2 F_2(X)$ is taken as a scalar criterion. Then the graph of the straight line $\lambda_1 F_1(X) + \lambda_2 F_2(X) = C$ on the plane of the criteria $F_1(X)$ and $F_2(X)$ must touch the Pareto front at the solution point (for $F_3(X) = \min$), and its slope is determined by the ratio of the weights $\lambda_i, i = \overline{1,2}$. Due to the complexity of constructing the tangent to the Pareto front approximation (which has a discontinuous character), instead of the tangent, the secant nearest to it is constructed (Figure 4).
Figure 4. Formation of a scalar criterion: a) the case of a convex Pareto front; b) the case of a non-convex Pareto front; c) it is impossible to determine the parameters.

This straight line passes through two points of the front, one of which corresponds to the optimal point (highlighted by a circle with a larger diameter). This point is obtained for the minimum value of the criterion $F_i(X)$. The second point was the one closest to the optimal point in the case of a convex Pareto front. That is, in the event that, when drawing a straight line, all the points of approximation of the Pareto solutions were not lower than it (Figure 4a).

If the points of approximation of Pareto solutions turned out to be on both sides of a straight line (non-convex Pareto front, Figure 4b, dotted line), the nearest point was found again and a new straight line was constructed, for which all points of the Pareto front were not lower than it (Figure 4b, dashed line). We took the parameters of the found straight line ($\lambda_i, i=1, 2$) as the desired weight coefficients of the scalar criterion.

Figure 4c shows a third possible case: for a non-convex Pareto front, it is impossible to draw a tangent through the optimal point so that all points of approximation of Pareto solutions are not lower than a straight line. It should be noted that we observed such a picture in no more than 10% of realizations that were excluded from consideration when forming the scalar criterion. For practical use, the generalized criterion is taken in a form that allows one to take into account the ranges of variation of the parameters included in the particular criteria. The main criteria $\bar{F}_1 = \int_0^T \varepsilon^2 \, dt$ and $\bar{F}_2 = \int_0^T u^2 \, dt$

(instead of the normalized criteria $F_i(X)$ and $F_j(X)$) are brought together in the expression of the scalar criterion

$$J(X) = J(k_p, \tau_i) = \int_0^T \left[ \varepsilon^2(t) + \lambda u^2(t) \right] dt$$

(7)

The first summand characterizes the accuracy over the entire control interval, and the second one determines the total control costs. The weight coefficient for the second term, taking into account the ratio of the weights $\lambda_i, i=1, 2$: $\lambda^2 = \frac{\lambda^2 F_i \bar{F}_1^{\text{max}}}{\lambda^2 F_j \bar{F}_2^{\text{max}}}$.

As a result of the study, the boundaries of the region of admissible parameters of the ACS of steam pressure were obtained. In this case, the recommended values of the parameters $k_p$ and $\tau_i$ deliver the minimum to the adopted generalized quality functional (7). We selected the value of the weighting coefficient ($\lambda = 1$) from the range of $\lambda \in [0.5, 1.5]$ obtained in the modeling (Figure 4a).

For a visual representation of the results obtained, Figure 5a shows an image of the area of admissible parameters on a three-dimensional graph of the generalized criterion (7)
Figure 5. Range of recommended parameters: a) $J(k_p, T_i) = \int_0^T [e^2(t) + u^2(t)] dt$; b) $J(k_p, T_i) = \int_0^T e^2 dt$.

Figure 5a, in addition to the graph of the surface of the generalized criterion (1), shows images of the constraints. The vertical plane (2) passes through the ACS stability boundary. The three-dimensional image of the constraint (3) passes through the boundary of the self-oscillation region. We see that the minimum value of the criterion corresponding to the optimal parameters of the ACS (in Figure 5a, this point is shown by the line) is in the range of admissible parameters. For comparison, Figure 5b shows a graph of the surface of the generalized criterion, which does not take into account the control costs during the operation of the pressure controller. Figure 5b shows that the minimum value of the criterion is not in the region of feasible parameters, but is located in the region of self-oscillations outside the boundary (3). This result indicates the need to take into account control costs: this prevents self-oscillations in the system. Also, the obtained result confirms the correctness of the generalized criterion composition in the form (7).

6. The discussion of the results

When we determined the optimal parameters, we noted that the nature of the processes in the system with parameters that are outside different boundaries of the permissible region is different. In case of unstable operation (the area to the left of the plane (2), Figure 5), the processes in the system are divergent, the oscillation amplitudes of the controlled parameter and the position of the actuator increase with time. We found that in the region of parameters to the right of the constraint (3) (in Figure 5), self-oscillations are observed. Although their amplitude is not large for the controlled parameter and the position of the actuator (see Figure 3a), nevertheless, this nature of the process is unacceptable. Under normal operating conditions, self-oscillations are unacceptable, since they cause the danger of overheating of the electric motor of the actuator from frequent reverse switching.

As a result of the research carried out, it was concluded that we need to choose the ACS parameters from the range of recommended parameters that ensure stable operation of the system without self-oscillations. At the same time, we recommend not to choose parameters near the stability border in order to ensure sufficient stability margins. To optimize the ACS, it seems to us expedient to use a generalized criterion that allows us to take into account the restrictions imposed on the search area. It should be noted that although criteria of this type are widely used in the optimization of ACS [3, 5], however, they are not always recommended for use, since the weight coefficients for particular indicators are determined most often subjectively. Therefore, the proposed approach to the choice of...
the scalar criterion weighting coefficients can find application in solving problems of optimization of control systems for various objects.

7. Conclusion
We have performed multi-criteria optimization of the pressure control system using simulation and optimization software based on genetic algorithms. We have proposed a method for reducing a multicriteria problem to a problem with a single criterion. The use of such a generalized criterion, which is a weighted sum of particular criteria, makes it possible to simplify the search procedure for the solution of the optimization problem. This is especially important when it is necessary to optimize the ACS parameters directly at the control object.

In addition, to solve the problem as a single criterion, methods of searching for optimal parameters can be used, which allow taking into account the constraints imposed on the search area. Another advantage is the ability to use modern visualization tools for plotting generalized criteria in order to control the results obtained. As a result of the study, we concluded that the obtained generalized criterion is suitable for making decisions when choosing the parameters of the synthesized ACS.

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