Dependence Modeling of “Price/Quality” of Human-Machine System from the Ratio of the Elements Duration of the "Work: Rest" Cycle

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Abstract—**The article shows dependence modeling of “price/quality” of human-machine system from organizational parameters of an operator’s labor activities on the basis of simulation model in the manner of interval sequences of work and rest. Influence modeling of ratio of the elements duration of the "work: rest" cycle on quality parameters and costs in human-machine system. Set of curves of dependences of quality and cost parameters from number of regulated breaks according to different valuations of initial efficiency, weariness intensity and an operator’s recreation were found.**

Keywords- modeling; human-machine system; cost/quality ratio; an operator’s activity; scheduled operations

I. Introduction

Important task is a mathematical modeling of functioning of different human-machine systems (SCHM).

Cost/quality ratio is used for assessment of performance of human-machine system. The smaller the value of this ratio (lower cost with high quality), the more effectively this SCHM is used. Thus the research task of influence of different factors and parameters of the system on cost/quality ratio for SCHM is highly urgent.

Quality of SCHM is the totality of characteristics focused on satisfaction of announced requirements of a human or (and) society. Such characteristics are taken into account while designing of human-machine systems system, they are embodied while manufacturing and they are functioning while using SCHM. Measurable parameter of this or that characteristic of the system, considered in the framework of definite conditions of its creation or using, is called quality parameters of SCHM [1]. By “cost” we mean total price of expenses both at the stage of the system formation and at the stage of usage.

The main and decisive element of any SCHM is a man (worker or operator), as parameters of his activity influence efficiency of the system functioning appreciably.

In the works [2-4] that describe SCHM quality, valuations of quality and costs are viewed as constant and are determined parameters by the parameters of the system. In this case cost/quality ratio is also constant. As indices of an operator’s functioning state influences organization of labor activity [5], it is reasonable to view dynamics of quality valuations of SCHM during a working day depending on parameters of labor activity. In a number of papers that describe system modeling and its management [6] of parameters of labor activity organization on the system is not considered.

Thus revealing dependence of SCHM efficiency from parameters of an operator's labor activity, it is possible to organize an operator's activity in the system and thus to advance efficiency of its usage by the criterion of minimization of cost/quality ratio.

The aim is simulated modeling of dependence of cost/quality ratio valuation of "human-machine systems" from parameters of an operator's labor activity. Traditional quality parameters of SCHM are used: operating speed, reliability, accuracy, promptness and labor safety. Quantity of regulated breaks between separate working operations are viewed as a parameter of labor activity.

II. Dependence Modeling of Quality Parameters of SCHM from Quantity of Regulated Breaks for Rest between Separate Labor Activities

An operator's work during a working day whose duration is equal to T is presented in the form of periodic through-time sequence of his labor activity stages, during which working efficiency declines, and exhaustion rises. These stages are divided with temporary breaks for rest of an operator (micropauses, regulated breaks and breaks for urgent private

978-1-5090-6742-8/17/$31.00 ©2017 IEEE

needs, dinner break), during which level of fatigue declines and working efficiency restores [7].

Let us assume that $B(t)$ is correspondence of working efficiency level with time; n is number of activity intervals; Tw is duration of each activity interval; Tr is duration of each rest interval; Td is duration of lunch break; μ_u, μ_v are intensities of exhaustion accumulation and efficiency restoration correspondingly; B_0 is initial (maximum) level of operator's working efficiency [7-8]. In fact, the value of n is determined by the ratio of the durations Tw and Tr, i.e. the ratio of the elements duration of the "work: rest" cycle.

Let us introduce the function $BS(n)$ of integration of valuation of an operator's working efficiency during intervals of activity. This function characterizes an operator's efficiency during a working day, taking into account that the operator's activity is considered only at intervals of activity and is not considered at the intervals of rest and lunch break:

$$BS(n)=\sum_{j=1}^{n/2}\int_{(Tw+Tr)(j-1)}^{(Tw+Tr)j-Tr}B(t)\,dt+\sum_{j=n/2+1}^{n}\int_{(T+Td)/2+(Tw+Tr)(j-n/2-1)}^{(T+Td)/2+(Tw+Tr)(j-n/2)-Tr}B(t)\,dt\,.$$

We use the simulation results of quality indicators dynamics of human-machine system obtained in [8].

An average processing time of information $\overline{T_t}(n)$ of n-number of regulated breaks in SCHM is reasonably presented as:

$$\overline{T_t}(n)=k_t\frac{Tw}{BS(n)}+\sum_{i=2}^{m}t_i\,,$$

where t_i is time delay of information processing in i-member of SCHM, m is amount of members of SCHM connected in sequence that can be presented both by technical devices and by operators; k_t is a proportional coefficient (real number), empirically introduced.

An average value of an operator's work accuracy during a working day:

$$\overline{Y}(n)=k_m\left(B_0-\frac{BS(n)}{T-Td-(n-2)Tr}\right),$$

where k_m is proportionality factor, empirically determined.

An average valuation of reliability indicator (by convention) is presented as follows:

$$\overline{P_c}(n)=k_c\frac{BS(n)}{T}\,,$$

where k_c is proportionality factor, empirically determined.

An average value of probability of solving problems in time during a working day:

$$\overline{P_{ts}}(n)=k_{ts}\frac{BS(n)}{T}\,.$$

where k_{ts} is proportionality factor, empirically determined.

An average value of general indicator of reliability:

$$\overline{P_{SCHM}}(n)=k_ck_{ts}\frac{\left(BS(n)\right)^2}{T^2}\,.$$

An average value of probability of safe operation during a working day:

$$\overline{P_{SW}}(n)=1-\sum_{i=1}^{q}P_{EM\,i}k_{ER\,i}\frac{T-Td-(n-2)Tr}{BS(T)}\,,$$

where $P_{EM\ I}$ is probability value of arising of dangerous and damaging manufacturing situation for an operator of i-type; $P_{ER\ I}$ is probability of incorrect actions of an operator in situation i; $k_{ER\,i}$ is proportionality factor in situation i.

To get this correspondence let us conduct a set of computer-experiments, setting the dynamics $B(t)$ in the intervals of activities and exhaustion according to the exponential law [6]. Changing valuation of the parameters B_0, μ_u, μ_v, let us repeat the set of experiments to determine correspondences $\overline{T_t}(n)$, $\overline{Y}(n)$, $\overline{P_c}(n)$, $\overline{P_{ts}}(n)$, $\overline{P_{SCHM}}(n)$, $\overline{P_{SW}}(n)$, where n is from 2 to 40. It is necessary to conduct a set of experiments because valuations of B_0, μ_u, μ_v depend upon biological property of an operator and his present functional state.

The experiments resulted in the fact that $\overline{T_t}(n)$, $\overline{Y}(n)$, $\overline{P_c}(n)$, $\overline{P_{ts}}(n)$, $\overline{P_{SCHM}}(n)$, $\overline{P_{SW}}(n)$ depends upon an operator's special features, in particular, upon valuations of B_0, μ_u, μ_v. Values of $\overline{T_t}(n)$, $\overline{Y}(n)$ decreases when number n of rest breaks increases. Values of $\overline{P_c}(n)$, $\overline{P_{ts}}(n)$, $\overline{P_{SCHM}}(n)$ increases when number of break intervals n grows, and then decreases in case of further growth of n. Value of $\overline{P_{SW}}(n)$ increases in case of growing of number n of break intervals.

III. Dependence Modeling of Integral Performance Index of SCHM upon Number of Regulated Breaks for Rest between Separate Manufacturing Operations

General (integral) performance index of the human-machine system is defined as totality of all its main characteristics discussed above. In this case efficiency of the human-machine system is calculated with the aid of particular quality indicators of SCHM that also help to evaluate the system, thus characterizing their importance within the system.

So, integral value of quality of the human-machine system (according to determination) looks like:

$$Q_{SCHM}=\sum_{i=1}^{n}a_iQ_i\,,\qquad (1)$$

where a_i are weight coefficients that determined empirically (sometime heuristically) and sum of these coefficients equals one; n is the number of partial accounted indicators; Q_i is a normalized value of i-type partial indicator.

If partial indicator is raising from point of view its impact on efficiency (reliability, safety, timeliness, etc.), then the valuation is performed according to this:

$$Q_i = E_i / E_{max\,i},$$

If partial indicator is reducing (time of solving the task, error, etc.), then the valuation is calculated by the formula:

$$Q_i = E_{\min i} / E_i,$$

where E_i is absolute value of i-type partial indicator; $E_{\max i}$ and $E_{\min i}$ are max and min value of i-type partial indicator, which has similar existing or projected human-machine system.

At the process of normalization of values from right side of formula (1) combined value Q_{SCHM} takes values from zero to one. We can assume that the value of Q_{SCHM} actually is coefficient of efficiency of the SCHM [2].

Consider the effect of the number of periods for the regulated recreation of the working day by the value of the integral evaluation of quality of the human-machine system. We single out partial indicators of quality of the SCHM: speed, accuracy, reliability, timeliness and safety. Then the expression (1) can be written as

$$Q_{SCHM}(n) = a_1 \frac{T_{t\,\min}}{T_t(n)} + a_2 \frac{\overline{Y}_{\min}}{\overline{Y}(n)} + a_3 \frac{\overline{P_c}(n)}{P_{c\,\max}} + a_4 \frac{\overline{P_{ts}}(n)}{P_{ts\,\max}} + a_5 \frac{\overline{P_{SCHM}}(n)}{P_{SCHM\,\max}} + a_6 \frac{\overline{P_{SW}}(n)}{P_{SW\,\max}}. \quad (2)$$

Fig. 1 shows the results of conducted mathematical modeling, where graphically showed the behavior of a family of curves $Q_{SCHM}(n)$ for different values of coefficients a_i. Analysis of laws shows that the integral quality assessment SCHM depends on the individual properties of the operators and the number of rest intervals n.

IV. Dependence Modeling of an Economic Costs in the SCHM from the Number of Regulated Operator's Breaks for Rest Between the Individual Production Operations

We will evaluate economic indicator of the human-machine system by the formula of full produced costs:

$$W_{SCHM} = C_o + E_n(C_{op} + C_p),$$

where C_p are costs of the creation (production) system; C_{op} are costs of training operators; C_o are operating costs; E_n is a normative coefficient of economic efficiency of capital expenditures.

We will consider costs C_p, C_{op} and the part of cost C_o as constant values at the considering the impact of the number of regulated breaks at the W_{SCHM}. We will consider another part of cost C_o as the part of lost profit due to the difference of productivity per working day from the maximum possible value.

We assume (this is justified by economic theory and the experience of production) that labor productivity at the current time is directly proportional to operator efficiency and profit is directly proportional to the performance of his work. Accordingly, the productivity of the working day is defined by the formula

$$Prod(n) = k_{prod}\, BS(n),$$

and the profit,

$$C_{prof}(n) = k_{prof}\ \ Prod(n),$$

where k_{prod}, k_{prof} are coefficients of proportionality chosen empirically.

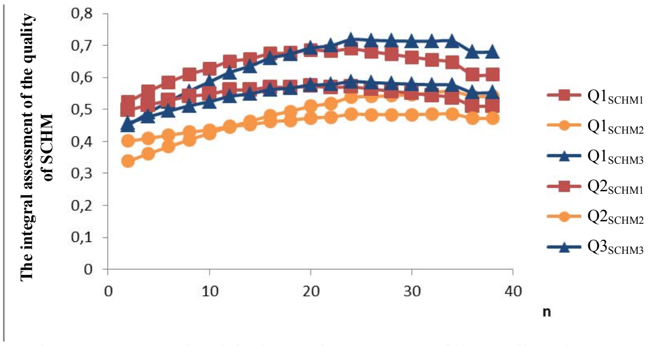

Figure 1. Example of the integral assessment of the quality of SCHM depending on n the number of regulated breaks for rest

The maximum profit is obtained with a maximum value of operator's performance throughout the whole working day. Consequently, we have the relations

$$Prod_{\max} = B_0\ \ T,$$

$$C_{prof\_max} = k_{prof} \cdot Prod_{max}.$$

Thus, the total cost of the operation of SCHM will be written as

$$W_{SCHM}(n) = k_{prof}\,(Prod_{\max} - Prod(n)) + C_{SCHM}, \quad (3)$$

where C_{SCHM} are costs that do not depend on the organization of work and operator's recreation.

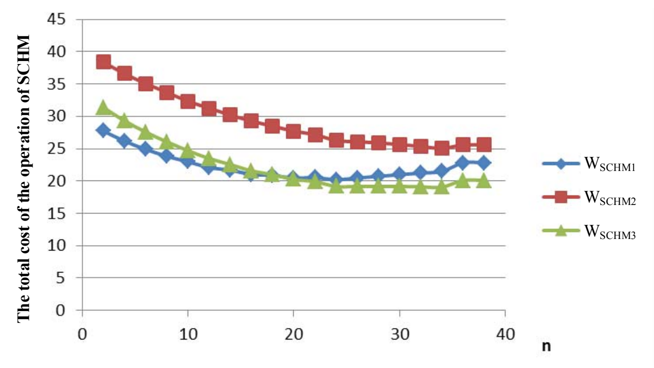

Figure 2. Example of a family of curves of dependencies $W_{SCHM}(n)$

Fig. 2 shows the results of the conducted mathematical modeling, which graphically shows a family of curves of dependencies $W_{SCHM}(n)$ for the three operators. The analysis shows that the total production cost of the human-machine system per working day essentially depends on the individual properties of the operators and initially decreases with increasing number of intervals of rest and increases with further increase of intervals of rest then.

V. Dependence Modeling of "Price/Quality" of the SCHM from the Number of Regulated Operator's Breaks for Rest Between the Individual Production Operations

We'll determine the "price / quality" ratio (WQ_{SCHM}) as relation of expressions (3) and (2). It is obvious that this ratio will depend on the number of regulated breaks:

$$WQ_{SCHM}(n) = \frac{W_{SCHM}(n)}{Q_{SCHM}(n)}.$$

Fig. 3 shows the results of the conducted mathematical modeling, where graphically showed a family of curves $WQ_{SCHM}(n)$ for different values of coefficients a_i. The analysis shows that the integral assessment of the quality of the SCHM depends on the individual properties of the operators and the number of intervals of rest.

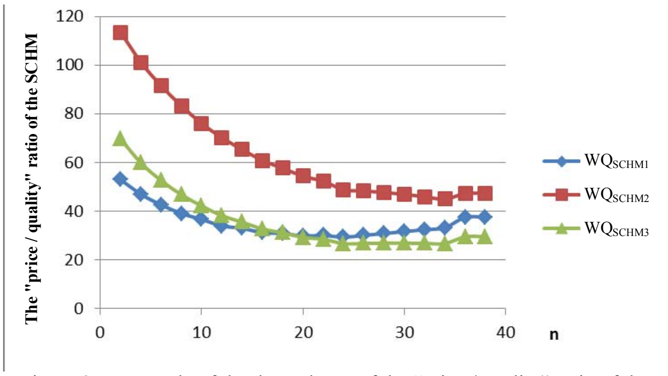

Figure 3. Example of the dependence of the "price / quality" ratio of the SCHM from n the number of regulated breaks for rest

After analyzing the results of the simulation performed, it is possible to draw key conclusions:

First, the ratio of "price / quality" of the SCHM is a function of the number of regulated breaks n, moreover, this dependence (depending on the values of the coefficients a_i) has a maximum $WQ_{SCHM}(n_{opt})$ at the value of the argument n_{opt}.

Second, the value itself $n_{opt}= f(B_0, \mu_u, \mu_v)$ in each analyzed dependency $WQ_{SCHM}(n, B_0, \mu_u, \mu_v)$ is a non-constant function of the parameters B_0, μ_u, μ_v.

Third, it is necessary to set the optimum values n_{opt} of regulated breaks for each operator on the basis of his biological properties and certain values of B_0, μ_u, μ_v to achieve the maximum efficiency of the SCHM activity and the "price / quality" ratio.

Conclusion

Thus, the actual simulation problem of dependence of the SCHM's "price / quality" ratio from the ratio of the elements duration of the "work: rest" cycle is solved. This dependence is objective measure of the effectiveness of the SCHM's activity because modeling proved qualitative effect of the number of regulated breaks on quality indicators and the costs of the system. Moreover, modeling has identified the quantitative aspects of this influence.

Results of conducted modeling showed that the method of regulation of rest breaks (in this method, quantitative values are constant and depend only from the type of production work) has a significant drawback, which is caused by the fact that there is no account of current values B_0, μ_u, μ_v, which can reduce the value of the "price / quality" indicator and do not reach planned value. It is important to note that the values B_0, μ_u, μ_v can be determined by testing before starting work of the SCHM, the results of which can estimate the intensities of fatigue and recovery and the maximum operator efficiency.

It is also recommended to evaluate the value n_{opt} for each operator depending on their individual characteristics as well as on the purpose of the system and its most important properties.

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