Application of fuzzy models of evolutionary development in optimal control of the system of planned preventative maintenance and repair of equipment for multistage production

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***Abstract*—The paper presents a mathematical model of control of planned preventative maintenance and repair of equipment under fuzzy conditions, when the state of the repairable unit in question may deviate from the one specified by the technical documentation. Introduction of an informational system for performing repair and routine preventative maintenance works together with RFID technology ensure efficient control of one of the crucial components of production, that is, of maintenance and repair system. The suggested control model is intended for supporting quick making of management decisions in emergencies. One can see the result of the suggested model implementation by the example of a paper industry enterprise.**

***Keywords*—fuzzy models, optimal control, planned preventative maintenance and repair of equipment, RFID technology**

I. Introduction

When studying industrial production economic efficiency and also evaluating opportunities for the enterprise growth and development, special attention is paid to technical and economic indices showing the production equipment performance level [1,2]. These indices include equipment downtime under repair per a repairable unit, repair prime cost per a repairable unit, the number of breakdowns and unplanned repairs per equipment unit, maintenance and repair manpower labour efficiency, etc.

Maintenance and repair unit of the enterprise performs equipment maintenance and repair intended to keep the equipment in constant working order. Achieving this goal in the most cost-saving way implies minimization of the total costs caused by the equipment breakdown and keeping this equipment in good working order.

Planned preventative maintenance and repair system implies performing preventative works for equipment maintenance and planned repairs every certain number of equipment operation hours; the sequence and schedule of these works are determined by the special features of the equipment and its operation environment. Besides following the set maintenance and repair standards (such as repair cycles and their structure, repair complexity categories, repair works labour input and materials consumption together with mate-rial inventories for the repair needs), maintenance and repair unit staff must be able to apply modern means of equipment status diagnostics, implement automatization of equipment maintenance and repair, introduce innovative technological equipment and apply new efficient methods of maintenance and repair planning and management, etc.

The production equipment full working capacity being crucial for the enterprise general operation and successful development, the paper suggests creating a model of optimal control of a fuzzy continuous system of planned preventative maintenance and repair of the said equipment.

In the management process, it is necessary to operate with qualitative in-formation, which is the main cause of uncertainty and explains the use of the concept of fuzziness in this paper [3,4,12]. The problem of managing fuzzy systems is relevant and is the subject of research into solving applied problems [eg, 5,6].

II. Task Assignment for Controlling the System of Planned Preventative Maintenance and Repair

At industrial enterprises, equipment is divided into several groups, each of which includes several units, which, in their turn, consist of tens or hundreds of elements.

For instance, according to paper production technology, there are 9 groups of equipment [7]: for raw material preparation M_1, for pulping M_2, for pulp receiving, rinsing, sorting, thickening and bleaching M_3, for chemicals preparation and regeneration M_4, for wood pulp production M_5, for paper pulp preparation M_6, for paper and cardboard production M_7, for marketable cellulose production M_8, for paper and cardboard finishing, cutting, sorting and packing M_9.

According to maintenance and repair schedule, each production equipment element undergoes maintenance, which consists of routine interrepair maintenance and periodical preventative repair operations, and also of planned maintenance and repair, which, in its turn, includes routine and full maintenance and repair.

Considering control of planned preventative maintenance and repair (PPMR) system, one should take into account control system fuzziness, as equipment may break down during operation due to heavy workload, defects, insufficient quality of the previously conducted maintenance and repair, and so on.

Then it is necessary to make quick decisions on emergency repair or replacement of equipment component parts, on modernization, on searching for alternative component parts, etc., when the data, goals and limitations are too complex and unclear [8].

Let us consider the enterprise production system σ as an aggregation of fuzzy systems with multistep control U_N, where

S_N is a step of controlling element i of subsystem M_n,
N is the number of a control step for element n,
M is a group of equipment,
i is the number of an element in group M, $i = [1, n]$,
X_N is the subsystem status achieved by control U_N,
U_N – space of controls of subsystem M.

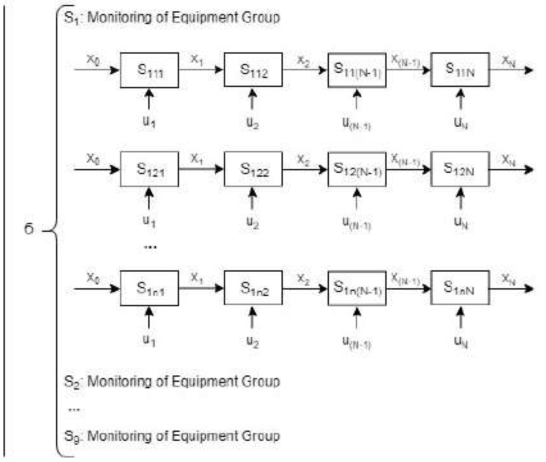

Figure 1. Monitoring of Equipment Group.

Let us suppose that at step $N = 1$ element n of equipment group M is put in-to operation, at $N = 2$ the element is undergoing preventative maintenance, at $N = 3$ planned maintenance and repair are in progress, and so on up to final step N, when the equipment is beyond repair (for instance, the service life is over). Besides the stages of the planned preventative works which are set by the regulations, the equipment control subsystem may experience emergencies.

Therewith, the task of the production technological system optimal control is to keep the enterprise production equipment in good working order.

Management decisions aimed at improving production equipment operation may include personnel training, maintenance process control, checking the inventories of component parts and repairable units, balancing the work-load of maintenance and repair workshops, reducing maintenance time by applying innovative technologies, reducing human error influence, reducing error probability during equipment operation, and monitoring the funds allocated for supporting operation reliability of the production equipment.

III. Modeling a Fuzzy System Using Fuzzy Relations

Let us demonstrate a generalized formal mathematical model of control for a single production unit under conditions of fuzziness. From now on, when considering the control task, we will use one modification of fuzzy relations composition.

Let X, Y and Z be certain sets. Let us assume that at a $X \times Y$ set a fuzzy relation A with membership function μ_A is defined and at a $Z \times Y$ set a fuzzy relation B with membership function μ_B is defined. Therefore, the $A \circ B$ composition of fuzzy set A and B is the fuzzy relation in $X \times Z$ space with the membership function

$$\mu_{A \circ B}(x, z) = \sup_{y \in Y} \min[\mu_A(x, y), \mu_B(y, z)] \quad (1)$$

(see eg. [3]).

Let's now assume that in X space the fuzzy set R with membership function μ_R is defined. Therefore, the fuzzy relation μ_A induces the fuzzy set $R \circ A$ in the Y space. In accordance with (1) the membership function $\mu_{R \circ A}$ of $R \circ A$ set is given by an equation

$$\mu_{R \circ A}(y) = \sup_{x \in X} \min[\mu_R(x), \mu_A(x, y)].$$

Let us assume that at X set the fuzzy relation S with membership function μ_S is defined. Further, let us assume that in X space G set with membership function μ_G is also defined. Therefore we can determine the $S \circ G$ composition of fuzzy sets S and G and following (1) the membership function $\mu_{S \circ G}$ of $S \circ G$ set will be defined by equation

$$\mu_{S \circ G}(x_1) = \sup_{x_2 \in X} \min[\mu_S(x_1, x_2), \mu_G(x_2)]. \quad (2)$$

One can readily see, for each $x_1 \in X$ the membership degree of $\mu_{S \circ G}(x_1)$ of x_1 the fuzzy set G is defined by equation (2).

It is equation (2) that we will further consider as a model of a fuzzy system.

IV. States Evolution Control

Let X and U be certain compact metric spaces. Let us consider $\mathfrak{H}$ is control system when X is state space and U is control space.

Let's assume that evolution of $\mathfrak{H}$ system state is characterized by the fuzzy relation S representing fuzzy set S in $X \times U \times X$ pace with membership function μ_S, provided that the initial state $x_0 \in X$ is defined.

As a result of choosing of $u_0 \in U$ control the system goes into some new state x_1 which was earlier unknown. It is only known that with u_0 and x_0 fixed, x_0, u_0, and x_1 variables are related by the fuzzy relation S with membership function $\mu_S(x_0, u_0, x_1)$. In other words, with u_0 and x_0 fixed at point of time $n = 0$ the state x_1 can be defined only by value of membership function $\mu_S(x_0, u_0, x_1)$. However, at point of time $n = 1$ we can observe exact value of state x_1.

Let us consider that the control aim is characterized by fuzzy goal set G in X space with membership function μ_G. Let us also assume that both functions μ_S and μ_G are continuous in the range of their definition.

Now let's assume that time N of end of system work is defined. The control problem is to search the sequence

$$u_0, u_1, ..., u_{N-1} \quad (3)$$

of points of U set maximizing the membership degree of x_0 states to fuzzy set G with fuzzy relations with membership functions

$$\mu_S(x_0, u_0, x_1), \mu_S(x_1, u_1, x_2), ..., \mu_S(x_{N-1}, u_{N-1}, x_N).$$

Therefore, the fuzzy set G is the control aim and the problem consists in searching the control sequences (3) providing the maximal membership degree of the state x_0 to the fuzzy set G with which the evolution of system state is described as the composition of fuzzy sets S and G. By equation

$$D_N = \underbrace{S \circ ... \circ S \circ G}_{N}$$

let's put for consideration the fuzzy set D_N being conditional for variables (3) in the X space with membership function μ_{D_N} satisfying the equation

$$\mu_{D_N}(x_0 \mid u_0, u_1, ..., u_{N-1}) = \max_{x_1, x_2, \ldots, x_N} \min[\mu_S(x_0, u_0, x_1), \mu_S(x_1, u_1, x_2), ..., \mu_S(x_{N-1}, u_{N-1}, x_N), \mu_G(x_N)].$$

Therefore according to equation (2) $\mu_{D_N}(x_0 \mid u_0, u_1, ..., u_{N-1})$ the values of function μ_{D_N} have the form of the membership degree of the state x_0 to G set with the use of any fixed sequence of control of (3) kind. Let us set

$$u_N(x_0) = \max_{u_0, u_1, \ldots, u_{N-1}} \mu_{D_N}(x_0 \mid u_0, u_1, ..., u_{N-1}). \quad (4)$$

Following [9], let us consider the initial task in the context of task family where x_0 and N are variable values. Therefore, with $N = 0$ the required membership degree x_0 to G set with the fuzzy relation S is described by the equation

$$u_0(x_0) = u_G(x_0). \quad (5)$$

Function μ_0 is continuous by convention over all of the intervals at X set. Moreover because of continuity of functions it is easy to note that for each function f which is defined and continuous over all of the intervals at X and possesses values at the interval $[0, 1]$, the function

$$g(x_0, u_0, x_1) = \min[\mu_S(x_0, u_0, x_1), f(x_1)]$$

is continuous over all of the intervals. But X and U spaces are compact. Therefore, the function

$$h(x_0) = \sup_{u_0, x_1} \min[\mu_S(x_0, u_0, x_1), f(x_1)] = \max_{u_0, x_1} \min[\mu_S(x_0, u_0, x_1), f(x_1)]$$

is continuous over all of the intervals at X set. Provided that

$$\max_{u_0, u_1, \ldots, u_N} \mu_{D_{N+1}}(x_0 \mid u_0, u_1, ..., u_N) = \max_{u_0, x_1} \min[\mu_S(x_0, u_0, x_1), \max_{u_0, u_1, \ldots, u_N} \mu_{D_N}(x_1 \mid u_1, u_2, ..., u_N)]$$

(see, eg. [9]).

Then by virtue of (4) for certain N the equation

$$u_{N+1}(x_0) = \max_{u_0, u_1} \min[\mu_S(x_0, u_0, x_1), u_N(x_1) \quad (6)$$

is executed where $u_{N+1}(x_0)$ is the maximal membership degree of the state x_0 to the G set with the relation S and the condition where end of system work time is equal to $N + 1$, and $u_N(x_1)$ is the maximal membership degree of the state x_1 to the G set with relation S and the condition where end of system work time is equal to N.

One can readily see that recurrence relationship (6) with the condition (5) is similar to Bellman's functional equation for classical problems of dynamic programming. This relationship interprets the control u_0 as function of time N and the state x_0, i.e.

$$u_0 = u_0^*(x_0, N), N = 1, 2, ... \quad . \quad (7)$$

Now let us note that for each N the function μ_{N+1} is defined. In addition, if in equations

$$\min_{x_0 \in X} \mu_G(x_0) > 0$$

and

$$\min_{x_0, u_0, x_1} \mu_S(x_0, u_0, x_1) > 0$$

are executed, then for all $N = 0, 1, 2, \ldots$ the in equation

$$\mu_N(x_0) > 0$$

is correct.

It is obvious that in this case we can always imply a well-defined task.

V. Implementation of the System of Optimal Control of the System of Planned Preventative Maintenance and Repair of Production Equipment Exemplified by a Vertical-type Hydraulic Pulper

A hydraulic pulper is a machine for pulping waste and broken paper with a rotating bladed disk located at the bottom or at the side of a cylindrical tank. Around the disk there are stationary blades and a sieve for extracting the pulp [4].

According to the technical documentation, hydraulic pulper preventative check-up is done during the idle periods. The PPMR system sets the hydraulic pulper interrepair cycle of 17t hours. This period includes four sessions of routine maintenance and repair 8 hours each, 1 medium maintenance and re-pair lasting 24 hours and 1 full maintenance and repair that takes 72 hours.

In order both to ensure quickest possible handling of emergencies and to check whether preventative maintenance and repair works are performed by the maintenance and repair unit staff in full scope and in due time, the enterprise chief mechanic decided to introduce an informational system of repairs prevention, which includes a database keeping the information on all control stages for every equipment unit.

Furthermore, each individual equipment unit is identified with RFID (Radio Frequency Identification) technology, which implies using an RFID-tag and an RFID-reader [10-11]. An RFID-tag contains unique tag number and transfers data to the RFID-reader, which registers data transmission, reads the information from the tag and transfers it to the informational system.

Further on, during equipment operation (including check-ups on keeping to regulations and standards of performing maintenance and repair works), a staff member can use a tablet to see all the necessary information on the equipment unit in question (fig. 2 – the data the staff member sees on the tablet screen).

For instance, the screen document template (fig.2) contains the information on "hydraulic pulper" equipment with ID (number), shows the data on performing routine maintenance and repair, preventative checks-ups, planned and full maintenance and repair. The "Comments" field says what elements need special attention during further maintenance; in case the equipment unit suffered a failure, the field states the failure cause and the ways to avoid experiencing this emergency once again.

Application of the chosen control method results in reducing equipment downtime under repair together with the number of breakdowns, failures and unscheduled maintenance and repairs per equipment unit; maintenance and repair prime cost is also reduced by performing timely preventative works.

VI. Conclusions

The suggested model of control of the system of planned preventative maintenance and repair describes control of technological units of equipment at an enterprise under conditions of continuous production.

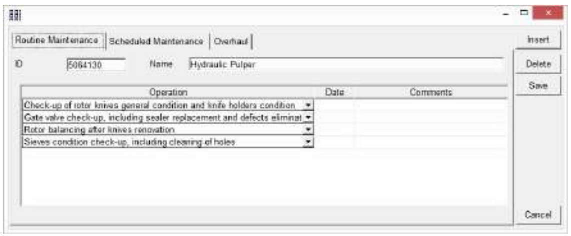

Figure 2. Example of software implementation of the model of maintenance and repair system control under conditions of fuzziness.

Application of this model reduces the time of making decisions in emergencies and also facilitates efficient management of planned and routine maintenance and repair of the equipment. The mathematical model of control of planned preventative maintenance and repair under fuzzy conditions is applicable at any industrial enterprise having continuous production cycle.

VII. Acknowledgements

The research was supported by the Russian Foundation for Basic Research (project 17-07-01339).

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ОПТИМАЛЬНОЕ УПРАВЛЕНИЕ СИСТЕМОЙ ПЛАНОВО-ПРЕДУПРЕДИТЕЛЬНОГО РЕМОНТА ОБОРУДОВАНИЯ МНОГОСТАДИЙНОГО ПРОИЗВОДСТВА С ПРИМЕНЕНИЕМ НЕЧЕТКИХ МОДЕЛЕЙ ЭВОЛЮЦИОННОГО РАЗВИТИЯ

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В работе представлена математическая модель управления системой планово-предупредительного ремонта оборудования в условиях нечеткости, когда состояние рассматриваемой ремонтной единицы может иметь отклонение от состояния, предусмотренного технической документацией.

Внедрение информационной системы по проведению ремонтных и текущих профилактических работ в совокупности с технологией RFID позволяют эффективно управлять одной из важнейших составляющих производства – системой технического обслуживания и ремонта.

Предложенная модель управления направлена на поддержку быстрого принятия управленческих решений при аварийных и внештатных ситуациях. Приведен результат применения предложенной модели на примере предприятия бумажной промышленности.

Received 10.12.18