IDENTIFYING THE REASONS FOR FAILURES IN LARGE-SCALE SYSTEMS

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Abstract: The functioning of complex man-machine systems (CMMS) (for example, aviation-transport systems (ATS), networks of railways, atomic power stations, oil pipelines, etc.) is formed by interrelations and interactions of various processes: command-information process; process of actions of executors (operators, crew, dispatchers, etc.); process of functioning of equipment; power supply process; process of maintenance by raw materials, accessories, cargo, passengers, etc.; process of interaction with the environment, etc. Traditional substantive provisions, models and methods of technical diagnosing of small objects are not effective for complex (large-scale) man-machine systems. This paper contributes to the studies of new models and methods for identification of the reasons of failures in such systems.

Keywords: Complex man-machine systems, automaton, cause-effect relation, control, diagnostic, accident, binary relation.

Introduction

Complete model of CMMS cannot be mathematical structure in the form of the table, the column, matrixes, systems of the logic equations, etc. These symbolical discrete structures are not suitable for representation of systems of the big dimension and are isolated from mathematical idealization of actual infinity, infinitesimal, continuity, limiting process, summation of infinite series, etc. For representation of processes of functioning of CMMS it is offered to use result of combination of discrete structures with the continuous numerical analytically set structures: the geometrical curve or analytically set numerical sequences.[1] The scheme of analyzing variant of processes of functioning, control and diagnosing, restoring and parrying of functional failures of system are presented on Figure 1. We consider next six processes from unlimited set of interconnected and interacted processes in CMMS: command-information process (P_1); process of actions of executors (operators, crew, dispatchers, etc.) (P_2); process of functioning of equipment (P_3); power supply process (P_4); process of maintenance by raw materials, accessories, cargo, passengers etc. (P_5); process of interaction with an environment etc. (P_6).

Hence, CMMS it is investigated as the object, having the material nature, in which are operated command-information processes, processes of thinking and actions of crews, dispatchers, operators etc. For concrete type of CMMS are choose set of properties R_1, R_2..., R_k and are considered sets of values W_1, W_2, ... , W_k. It is supposed, that on these properties are full enough and precisely characterized six base processes and all variants of interactions of these processes.

New Model of Process of Functioning of CMMS

For discrete determined automaton A = (S, X, Y, δ, λ, s_0) with infinite set of states, finite sets of inputs X and outputs Y signals, next-state functions $\delta : S \times X \to S$ and outputs functions $\lambda : S \times X \to Y$, initial state $s_0 \in S$ and dynamics equations s(t+1) = δ (s(t), x(t)), y(t) = λ(s(t), x(t)), where $t \in N^+$, is considered automaton mapping $\rho^A_{s_0} = \{(p, y) : p \in X^* \,\&\, y \in Y \,\&\, \{(\exists p' \in X^*)$

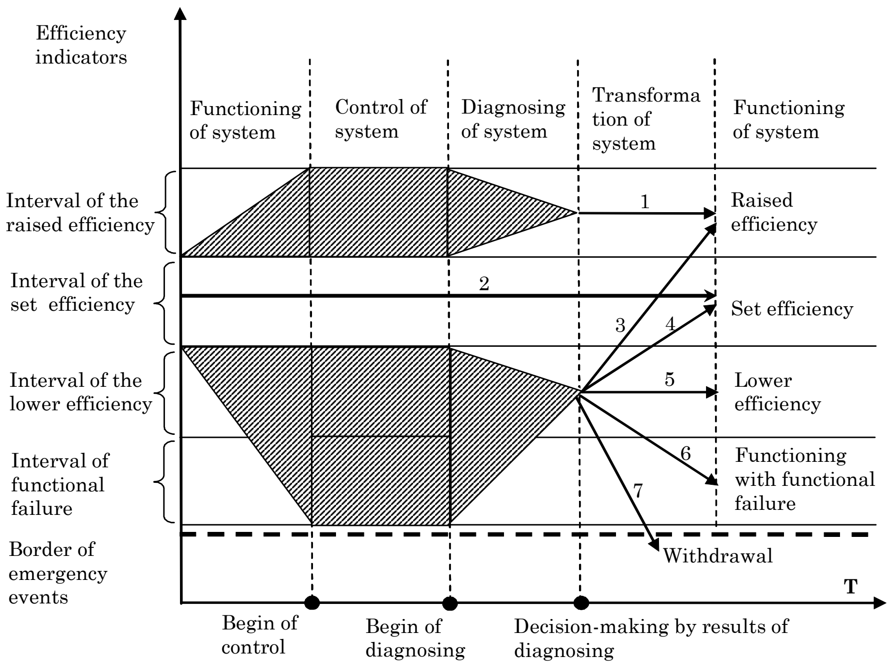

Figure 1: The scheme of connection of stage of functioning, control, diagnosing, transformation with variants of efficiency of functioning.

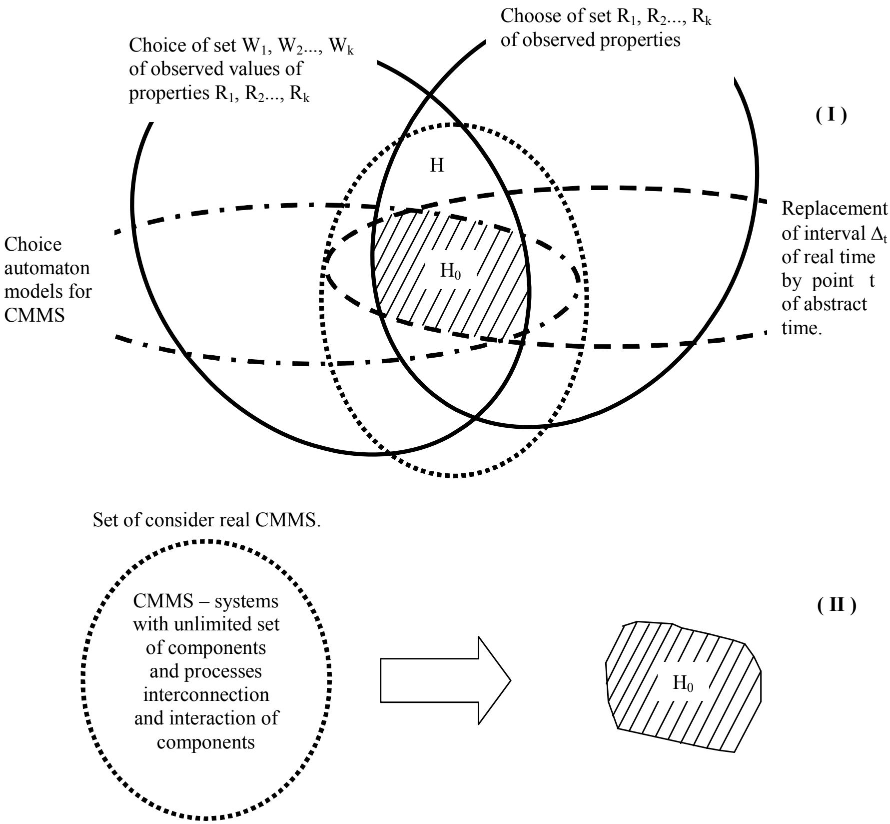

Figure 2: Schemes (I) and (II) of restriction of investigated set H of CMMS to set of H_0 in result of choice set of R_1, R_2..., R_k of observed properties, choice of set W_1, W_2..., W_k of observed values of properties, replacement of interval of real time to point and use only automaton models.

$(\exists x \in X) \,\&\, p = p'x \rightarrow y = \lambda(\delta(s_0, p'), x)\}\}$, where $\delta(s_0, p')$ - function expansion δ to function of kind $\delta : S \times X^* \rightarrow S$, according to equations of dynamics. On sets X^* and Y are entered linear orders ω_1 and ω_2. The rules for a linear order ω_1 on X *:

Rule 1: On the X set, we introduce some linear order (which is denoted as ω_1);

Rule 2: The order of ω_1 on X will be distributed to a linear order on X*, assuming that:

- for any unequivalent words $p_1, p_2 \in X^*$, for which $|p_1|<|p_2|$, p_1 will be less than p_2;
- for any nnequivalent words p_1, $p_2 \in X^*$, for which $|p_1|=|p_2|$, their position will be defined according the order of their first unequal letters on X.

The rules for a linear order ω_2 on Y * are defined by the same way as ω_1 on X *. The set of pairs $\rho_{s_0}^{A}$ is represented graph G ($\rho_{s_0}^{A}$, (X^*, ω_1), (Y, ω_2)) in system of coordinates with an abscissa axis (X^*, ω_1) and an ordinate axis (Y, ω_2). The set of pairs $\rho_{s_0}^{A}$ transformed to symbolical graph G ($\rho_{s_0}^{A}$, (X^*, ω_1), (Y, ω_2)), we will name (symbolical) geometrical image of laws of functioning of automaton A and to designate $\gamma_{s_0}^{A}$. Symbolical graph G ($\rho_{s_0}^{A}$, (X^*, ω_1), (Y, ω_2)) (see Figure 1) is replaced with numerical graph G′ replacement of each point of a kind (p, y) a point (r_1(p), r_2(y)), where r_1 (p) (r_2 (y)) - number of p (y) on a linear order ω_1 (ω_2). Graph G′ is isomorphically put in the first angle of rectangular Cartesian system of coordinates on a plane. As a result automatic display $\rho_{s_0}^{A}$ appears the presented graph with integer positive coordinates of points. Graphs G and G′ rely in the numerical geometrical images of laws of functioning of the automaton A . Integer coordinates of points (r_1 (p), r_2 (y)) $\in$ G′ can be replaced by non-integer co-ordinates (r'_1 (p), r'_2 (y)) $\in$ G′′ with preservation of linear orders on sets X^* and Y.

Automaton A with infinite set of states S , considered as model of complex system, as a rule, will be partially set. Therefore, graphs G, G′ and G′ - are partially defined. The numerical form of graphs G′ and G′ allows to regularization their by classical methods of interpolation of Newton, Stirling, Gauss, the least-squares etc. Model of process of functioning of CMMS it is necessary automaton A, presented by graph G′ (or graph G′) and a hypothesis – the chosen method of interpolation.

Let efficient complex system R_0 and set of its defects I are presented by automatons A_0 and $\alpha = \{A_i\}_{i \in I}$, where A_i = (S_i, X, Y, δ_i, λ_i, s_{0i}), and automatons are set by geometrical images $\rho_{s_0}^{A}$ and $\beta = \{\rho_{s_{0i}}^{A_i}\}_{i \in I}$, located on analytically set geometrical curves: $y=f_0$ (x) and $y_i=f_i$ (x), $i \in I$. Then on the basis of decisions of the equations of

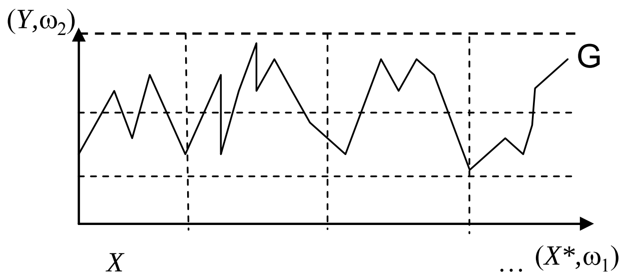

Figure 3: Graph G ($\rho_{s_0}^{A}$, (X^*, ω_1), (Y, ω_2)).

a kind $f_0=f_i$ ($i \in I$), $f_i=f_j$ ($i, j \in I$) and of inequalities of a kind $f_0 \neq f_i$ ($i \in I$), $f_i \neq f_j$ ($i, j \in I$) subsets of set X^*, corresponding to areas of the inefficient control and diagnosing, are defined.

New Structure of Means of Reception of The Information of Functioning of Complex System

In introduction are allocated six processes, interrelations and which interactions represent process of functioning of CMMS. For search of the reasons of defects (including FF) of complex systems it is required to analyze not only the information on these separate processes, but also the information on interactions of these processes in variants of combinations on two, on three etc. interaction of all six processes. We receive 63 variants of various means of reception of the information on process of functioning of complex system. Not all variants of interactions of some subset of six processes are essential. On Figure 4 is presented for the first time developed interrelations of the reason and a condition 1 for realization of a cause-effect relation in group of the reason, a consequence and a condition 2 after realization of a cause-effect relation and a kernel – the mathematical description of transformation of group of the reason the structure to consequence group. The group of cause consists of actively formed part (cause) and passive (given, available) parts – condition 1, and consequence group make a consequence (a part connected with target mission of system) and a condition 2 arising after realization of a cause-effect relation. Earlier works of the author present an algebra of constructing cause and effect complexes and language of the formulas, defining complexes' structure.[2]

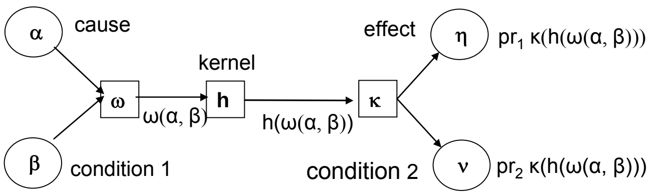

Figure 4: Structure of cause-effect relationship.

Binary Relations in Definition of the Process of Functioning of CMMS

At recognition of the reasons of failures of CMMS the analyzed information contains indicators of separate six processes and indicators of variants of interactions of processes. System functioning is represented as functioning of automaton $A = (S, X, Y, \delta, \lambda, s_0)$. By means of reception of the information on functioning process are partially observed input sequence p(1, c) =x(1) x(2) … x(c), output sequence q(1,c) =y(1) y(2) … y(c) and sequence of changes of states u(1, c+1) =s(1) s(2) … s(c+1). In automaton mapping $\rho_{s_0}^A$ the sequence u(1,c+1) changes of states during c steps obviously is not presented. In a geometrical image $\gamma_{s_0}^A$ the sequence of changes of statuses u(1, c+1) is presented obviously on the basis of equality $\delta(s_p, x) = s_{px}$, where $p \in X^*$, $x \in X$ and $s_0 = s_\varepsilon$ - at ε, considered as unit in free semi-group ($X^*, \cdot$) on operation of concatenation «·». It means, that according to entered on X^* linear order ω_1 , axis of abscissa (X^*, ω_1) is segmented from left to right on m = | X | points and sequence of parts one-to-one is correlated the sequence of states $s_\varepsilon, s_{x_1}, \ldots, s_{x_m}, s_{x_1 x_1}, \ldots$.

In a geometrical image $\gamma_{s_0}^A$ to each point with the first co-ordinate *px* where $p \in X^*$ and $x \in X$, are correlated a state s_p and state $\delta(s_p, x) = s_{px}$. On the basis of it linearly ordered and unequivocally defined on X^* sequence of points in system of coordinates with an axis of abscissa (X^*, ω_1) and an axis of ordinates (Y, ω_2) is possible to consider as the task of laws of functioning of the discrete determined automaton, that is as a geometrical image $\gamma_{s_0}^A$ for the task of automaton mapping of kind $\rho_{s_0}^A$.

If means of reception of the control and diagnostic information on process of functioning of complex system receive the information on sequences p(1, c), q(1, c) and u(1, c+1) this information we will present as sequence of a kind

$$\varphi\begin{pmatrix} x(1) \\ s(1) \\ y(1) \end{pmatrix} = \begin{pmatrix} w_1(1) \\ w_2(1) \\ \ldots\ldots \\ w_k(1) \end{pmatrix}, \ \varphi\begin{pmatrix} x(2) \\ s(2) \\ y(2) \end{pmatrix} = \begin{pmatrix} w_1(2) \\ w_2(2) \\ \ldots\ldots \\ w_k(2) \end{pmatrix}, \ \ldots, \ \varphi\begin{pmatrix} x(c) \\ s(c) \\ y(c) \end{pmatrix} = \begin{pmatrix} w_1(c) \\ w_2(c) \\ \ldots\ldots \\ w_k(c) \end{pmatrix},$$

where function φ map signals and states in observed at the moment of time t indicators (w_1 (t), w_2 (t)..., w_k (t)) properties R_1, R_2..., R_k.

Let's assume, that for properties R_1, R_2..., R_k are considered following sets of values W_1, W_2 , ... , W_k. According to the entered designations and their interpretation during c steps of CMMS is possible to present process of functioning by sequence of values of properties changing in time ξ = <(w_1 (1), w_2 (1)..., w_k (1)), (w_1 (2), w_2 (2)..., w_k (2)), …, (w_1 (c), w_2 (c)..., w_k (c))>.

Let $W = \times_{i=1}^{k} W_i$ and in interpretation of elements of sets W_i, $1 \le i \le k$, are presented all variants of combinations of indicators of the properties, corresponding regular (regular, normal, etc.) system state, a state with defect (an error in algorithm, the program, in the instruction; erroneous actions of the operator, crew, traffic controller; malfunctions of equipment; infringement in power supply, etc.), to a state with functional refusal; to a state with actions on liquidation of defect or with refusal parrying, etc.).

The binary relation ρ kind $\rho \subset W \times W$ defines all variants of direct connections of states, and degree ρ^n on multiplication of binary relations defines communication of statuses with intermediate n-2 statuses. We will enter following classifications of sets of statuses and binary relations.

At the analysis of the reasons of failures of CMMS it is possible to consider specification of binary relations with use of restriction of binary relations. There are four kinds of restrictions of the binary relation ρ : $\rho \cap \sigma$, $\Delta_{U_1} \circ \rho \circ \Delta_{U_1}$, $\rho \circ \Delta_{U_1}$, $\Delta_{U_2} \circ \rho$, where $\sigma \subset W \times W$; $U_1, U_2 \subset W$ and $\Delta_{U_i} = \{(w, w) : w \in U_i\}$, $i \in \{1, 2\}$.

Let's consider model for technical diagnosing of the complex system presented by means of the theory of binary relations. Specific events in the control and diagnosing of complex man - machine systems are:

1. Occurrence or defect display (a):
   - Malfunctions in the technician and the equipment;
   - Errors of executors (crew etc.);
   - Errors in algorithm or the control program, in technological materials;
   - Disturbance in system power supply;
   - Negative influence of an environment;
   - Negative influence of the external human factor;
2. Detection (b) of event [a] by devices (control devices and diagnosing) or executors;
3. Influence (c) of actually occurred event [a] (and also of false defined event or prospective event) on system functioning;
4. Appearance of functional failure (FF), that is, such loss by system of one or several basic properties, which does not allow system to achieve the aim in full or in part functioning with maintenance of safety of functioning;
5. Detection FF;
6. Events - actions on liquidation of defect [a];
7. Events - actions on parrying of FF.

Sequences of regular situations, events with defects, events - functional failures, events with actions on liquidation of defects, events with parrying of FF and events of incidents (failures, accidents) are divided by borders. Essential indicator for maintenance of safety of functioning and at changes of processes of functioning of CMMS is the actual order in time between events:

a. appearance (or displays) of defect and functional failure;
b. detection of appearance of defect and FF;
c. influences of defect and FF on system functioning.

At technical diagnosing of "small objects" is carried out the following sequence of these events in time, as a rule,

$$a \rightarrow c \rightarrow b \qquad (1)$$

At technical diagnosing of CMMS of event a, b, c can settle down in time in any order:

$$a \rightarrow b \rightarrow c,\ a \rightarrow c \rightarrow b,\ b \rightarrow a \rightarrow c,$$

$$b \rightarrow c \rightarrow a,\ c \rightarrow a \rightarrow b,\ c \rightarrow b \rightarrow a\ .$$

If time intervals between events a, b, c are small, that events can be appearance in the same interval (moment) of time.

Specificity of interposition of the effects of appearance (a), detection (b), influences (c) defects and FF on functioning of CMMS.

1. It is supposed, that interpositions of intervals of the effects a, b, c can (at false detection of defect) arrangement on a real time axis in any order.
2. It is supposed, that defect is the reason of functional failure in actual sequence of the events, making functioning of system.
3. It is supposed, that in real and assumed processes of functioning of system of the effects a, b, c, FF can arrangement in various combinations and on the common for them intervals.
4. It is supposed, that at the control and diagnosing of CMMS there is partially known model of actual functioning of system and construction the prospective model not contradicting the actual information.
5. It is supposed, that the basic part, making prospective model of complex system is the mathematical structure in the form of sequence of events. Such sequences of events are represented in the discrete determined automaton with finite or infinite set of states.

Malfunctions in instrumentations and the equipment, erroneous forecasts and assumptions of executors (crews, drivers, operators, etc.), generating a false information about defects in the absence of defects or the erroneous information on absence of defects in the presence of defects can result:

- To actions on parrying of nonexistent defects of system;
- To wrong construction of cause-effect relationship of kind "defect → functional failure";
- To generation of new functional failures, owing to wrong actions on parrying.

Let U is a universe of events, that is set of all actually possible and prospective events. All other classes of events we let as subsets of set U. At the first level the model defines sequence of classes of the events entering into the following set of classes of events:

- Class U_R of the events, considered as a regular situation, corresponding to stages (to the making parts, etc.) Without appearance of presence and influence of defects and FF on system;
- Class U_d of events in which in system arise or influence defects;
- Class U_φ of events in which arise or influence functional failures;
- Class $U_{n\varphi}$ of the events, containing actions on parrying of FF;
- Classes U_i, U_a, U_k the events representing incidents, accidents and disasters;
- Class U_{nd} of the events containing actions for liquidation of defects.

For formal definition of relation of events in functioning of complex system we will use the binary relations defined on classes of events:

- $\rho_R \in U_R \times U_R$ (relationships of regular situations);
- $\rho_d \in U_d \times U_d$ (relationships of events with defects);
- $\rho_\varphi \in U_\varphi \times U_\varphi$ (relationships of events with FF);
- $\rho_{nd} \in U_{nd} \times U_{nd}$ (relationships of events with defects and actions on liquidation of defects);
- $\rho_{n\phi} \in U_{n\varphi} \times U_{n\varphi}$ (relationships of events with FF and events with actions on parrying of FF);
- $\rho_i \in U_i \times U_i$ (relationships of events with incidents);
- $\rho_a \in U_a \times U_a$ (relationships of events with accidents);
- $\rho_d \in U_k \times U_k$ (relationships of events with disaster).

$(\rho_z \in U_z \times U_z, z \in \{i, a, k\})$.

The binary relations defining borders of relationships of heterogeneous events:

- $\rho_{Rd} \in U_R \times U_d$ (relationships of regular situations with events with defects);

- $\rho_{dnd} \in U_d \times U_{nd}$ (relationships of events with defects with events with defects and actions on defect liquidation);
- $\rho_{d\phi} \in U_d \times U_\varphi$ (relationships of event with defect with event with FF);
- $\rho_{\varphi n\varphi} \in U_\varphi \times U_{n\varphi}$ (relationships of event with FF with event with parrying of FF);
- $\rho_{ndR} \in U_{nd} \times U_R$ (relationships of event with defect and actions on liquidation of defect with event - a regular situation);
- $\rho_{n\varphi R} \in U_{n\varphi} \times U_R$ (relationships of event with FF and actions on parrying of FF with event - a regular situation);
- $\rho_{\varphi z} \in U_\varphi \times U_z$, where $z \in \{i, a, k\}$ (relationships of event with FF with event – incident /accident, disaster/).

Figure 5 presents a structure of variants of functioning of system. Numbering of subsequences of homogeneous events in the scheme (Figure 5) of variants of sequences of events in functioning processes complex system:

- 1, 2, 17, 20 - sequences of regular situations;
- 3, 5, 8 - borders of appearance of defect and FF;
- 9, 14, 16 - sequences of events with actions on liquidation of defects or actions of parrying of FF;
- 7, 10 - sequences of events with functional failure;
- 4 - sequence of events with defects;
- 6 - sequence of events with defects and actions on liquidation of defects;
- 11 - communication of events, representing transition from event with FF in event - incident, accident, disaster;

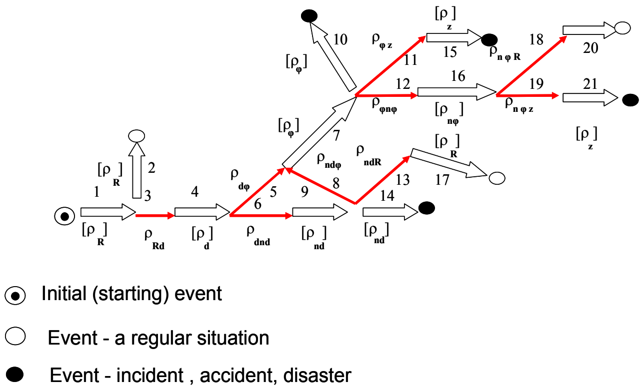

Figure 5: The scheme of structure of variants of functioning of system.

- 12 - borders of the beginning of parrying of FF;
- 13 - communication of the events, representing transition from event with actions for liquidation of defect to a regular situation;
- 15, 21 - sequences of the events, representing incident, accident or disaster;
- 18 - communication of the events, representing transition from event with actions on parrying of FF to a regular situation;
- 19 - communication of the events, representing transition from event with actions on parrying of FF to events - incidents, accidents , disaster.

Following rules of consecutive specification of model of complex system on the basis of expansion and specification of the control and diagnostic information are offered.

Summary

The functioning of real CMMS is presented by interactions of command-information process, process of actions of executors, process of functioning of the equipment, power supply process, process of maintenance by raw materials, accessories, etc. Ordering of interactions of these processes is presented by model - the dynamic discrete determined system, i.e. discrete determined automaton $A = (S, X, Y, \delta, \lambda)$. Process of functioning of real system is observed by diverse means of reception of the control and diagnostic information. Such information is shown in sets of values of properties R_1, R_2, …, R_k , chosen for supervision. Sequences of such sets of values of properties define real processes of functioning of system. The defects, arising in system, are presented by subsequences. It means, that sets of values of properties, correspond to regular situations, to events with defect, to events with functional refusals, to events - failures, and also transitions between events of different types.

The cause-effect approach (see [3]), with the developed algebra of a composition of cause and effect units, language of formulas of cause-effect structures allow both on intuitive, and on formal levels to orientated in complexes of cause and effect interactions in any application domain. Accuracy of representation of process of functioning of real system by sequence of observable values of properties w(1), w(2), …, w(c) depends on interval of real time, by which divides directly next sets w(t) and w (t+1), where $1 \leq t \leq c-1$.

All variants of directly next sets of values w (t) and w (t+1) considered properties is possible to present by binary relation ρ_t of kind $\rho_t \subset W \times W$. It allows to represent sequence w (1), w (2), …, w (c) various variants of multiplication of binary relations. Generally, we receive $\rho_1 \circ \rho_2 \circ ... \circ \rho_{c-1}$, $\rho_v \circ \rho_{v+1} \circ ... \circ \rho_{v+t}$, where $1 \leq v < v+t \leq c-1$. We receive the apparatus for flexible representation of communications of sets of values of properties, not necessarily direct the next:

$$w(\nu), w(\nu + t) \in \rho_\nu \circ \rho_{\nu+1} \circ ... \circ \rho_{\nu+t} .$$

Enough general description of regular situations, events - defects, events - functional failures, events - transitions between events of different types, events with actions on liquidation of defects, events with parrying of functional failures are subsequences of sets of values of properties $w(\nu), w(\nu+1), ..., w(\nu+t)$. To research of communications of sets of values of properties we will apply the apparatus of the theory of the binary relations, by which means can be formalized reduction of the binary relations, defining communications as directly next sets of values of properties in sequence w(1), w(2), …, w(c), and in its subsequence. The reductions of binary relations, specifying communications in pair of sets of values of properties, are possible in the various ways, basic of which are following reductions (which we will name filters): $\Delta_1 \circ \rho$, $\rho \circ \Delta_2$, $\Delta_1 \circ \rho \circ \Delta_2$, $\rho \cap \sigma$, where $\sigma \subset W \times W$ - the specifying binary relation, and Δ_1 and Δ_2 - the identical binary relations, used for restriction of the binary relation ρ on its sets of the first and second projections.

The observable model w(1), w(2), …, w(c) concrete process of functioning of real CMMS at definition of the reasons of defects, functional failures, accidents, etc. should be constructed and specified before unequivocally certain events $w^0(1)$, $w^0(2)$, …, $w^0(c)$ with use of the available and in addition received information on the process, represented in the form of restrictions of binary relations.

Notes:

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[1] For methodological detail see Vladimir A. Tverdokhlebov, *The geometrical images of laws of functioning of finite state machines* (Saratov: Science book, 2008).

[2] Vladimr A. Tverdokhlebov, “Methods of Interpolation in Technical Diagnostics,” *Control Sciences* 2 (2007): 28-34; A.F. Rezchikov and Vladimir A. Tverdokhlebov, *Cause-effect models of manufacturing system* (Saratov: Science book, 2008; A.F. Rezchikov and Vladimir A. Tverdokhlebov, “Cause-effect Complexes of Interaction in Manufacturing Processes,” *Control Sciences* 3 (2010): 51-60.

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