Methods for Obtaining of Management Decisions during Evaluating the Controlled Parameters by Qualitative Categories

Jamil Al-Azzeh[1] [0000-0002-3525-5471], Alexandr Litvinenko[2] [0000-0002-8862-8032], Dmytro Kucherov[3] [0000-0002-4334-4175], Ivan-Farkhod Kashkevych[4] [0000-0002-3525-5471] and Zhenis Bagisov[5] [0000-0002-8084-1234]

[1]Al-Balqa Applied University, Al-Salt, Jordan
[2, 3, 4]National Aviation University, Kyiv, Ukraine
[5] M. Narikbayev KAZGUU University, Astana, Kazakhstan
azzehjamil@gmail.com, litvinen@nau.edu.ua, d_kucherov@ukr.net, ikashkevich@gmail.com

Abstract. Expert control systems emulate the decision making ability of a human expert for solving complex problems by reasoning about knowledge. Artificial intelligence techniques are usually used for the purpose of representing knowledge and for generating control decisions through an appropriate reasoning mechanism. In this paper, the generalized form of knowledge representation models in expert control systems is represented. Furthermore, an algorithm for deriving managerial decisions based on the method of resolving is described. Unified control models are proposed that allow one to determine combinations of control operations that can bring the control object to normal if it goes beyond the permissible ranges of several characteristics. It is proved that when assessing the characteristics of the state of the control object in qualitative categories, the task of deriving a managerial decision is reduced to solving a system of linear equations with Boolean variables or combinatorial optimization problems. Algorithms for solving such problems that implement the idea of a directed enumeration of options are indicated.

Keywords: expert systems, intelligent control, logical models, decision making, optimization.

1 Introduction

The mathematical basis of expert control systems [1-9] is formed by logical models of knowledge representation (control models) [10-14] in conjunction with the algorithms for logical inference of managerial decisions [15-16] corresponding to these models.

Practice shows that the main difficulties in developing such systems arise at the stage of constructing logical models since there is no single methodology for their formation today. The variety of forms of control models causes additional difficulties associated with the need to develop new inference algorithms oriented to a specific model or to adapt known methods to its structure.

The task of finding management decisions arises in those cases when one or more characteristics of the state of the managed object go beyond the specified acceptable ranges. In this case, the following abnormal situations are possible, each of which requires the implementation of an appropriate algorithm for deriving a management decision [15, 16]:

- one characteristic is outside the permissible range and one control operation is enough to normalize it;
- one characteristic is outside the permissible range, but its normalization requires the simultaneous execution of several control operations (for example, in the case of a side effect, when the implementation of one or another control operation to change the anomalous value of any one characteristic can lead to a change in the values of other characteristics within acceptable ranges);
- the several characteristics of the state of the managed object are out of the acceptable ranges.

Characteristics of the state of the managed object can be quantified or evaluated in qualitative categories. Assessing the characteristics of the state of the managed object with qualitative categories requires a special approach to the development of managerial decisions, which will be described below.

An analysis of the experience accumulated in publications [1-16] provides the basis for constructing a generalized logical control model that includes many predicate expressions of four types:

1. Expressions describing possible ways of influencing the managed object (control operations), the implementation of which can lead to a change in the values of the characteristics of its state;
2. Expressions describing the conditions for the implementation of control operations (necessary system connections and functional dependencies, availability of required resources, etc.);
3. An expression that has the following meaning: if there is a control operation that can bring the managed object into a normal state, and the conditions for its practical implementation are met, then it must be performed;
4. An expression reflecting the hypothesis about the possibility of implementing a control operation that can lead to the necessary change in the value of that state characteristic that is outside the allowable range.

The conclusion of the desired managerial decision based on such a model formally reduces to proving its logical truth or inconsistency [16, 18]. For this, in expert control systems, the most commonly used resolution method is J. Robinson [16, 19]. This method has the completeness property and guarantees to find a solution to a problem in all cases when it objectively exists but has several significant drawbacks. The main ones are:

1. Cumbersomeness and semantic duplication of logical expressions included in the model;
2. Poor focus on the selection of clauses for resolution, as a result of which it is necessary to process a large amount of information that is not used in the future;

3. The impossibility of taking into account the side effect, in which the control operation performed with the aim of the required change in the value of one or another characteristic of the managed object state can lead to unacceptable changes in the values of other characteristics;
4. The impossibility of finding combinations of control operations in the case of simultaneous exceeding the limits of the permissible ranges of several characteristics of the managed object condition;
5. The inability to optimize the solution to the problem of choosing control operations according to a given criterion.

These shortcomings necessitate the development of unified management models that adequately reflect the logic of the expert's reasoning and allow the use of simpler algorithms in the search for managerial decisions.

Such unified models must meet the following requirements that determine their use in expert systems of various purposes:

1. Accounting for side effects;
2. The ability to find complex management decisions that provide for the simultaneous execution of combinations of control operations that can normalize the state of the managed object as in the case of a side effect, and when going beyond the acceptable ranges of several characteristics of the states of the managed object;
3. The ability to optimize the desired management decisions according to specified criteria.

A side effect is manifested in the fact that the control operation, which is implemented to bring some characteristics into the acceptable range, can cause unacceptable changes in the values of other characteristics of the state of the managed object. In turn, the implementation of control operations that compensate for negative changes in the values of these other characteristics can lead to unacceptable deviations of the next group of characteristics of the managed object condition that are not connected with the general control operations directly with the initial characteristic, etc.

Taking into account the side effect requires the preliminary determination of the full set of characteristics of the state of the managed object, which can change their values as a result of the implementation of control operations aimed at bringing one or more of the characteristics into acceptable ranges. To do this, using the special step-by-step procedure described below.

We need to find complex management decisions that arise in two cases: when the values of several characteristics of the state of the managed object are simultaneously outside the acceptable ranges, as well as when there is a side effect (regardless of the number of characteristics that have left the acceptable ranges of values).

Unified logical models of control proposed to build according to the "resource" & "action" → "result" scheme [20], which can be considered the canonical form for most decision-making tasks in real expert control systems. In this case, "action" means the performance of one or more control operations, the "resource" reflects the funds necessary for the implementation of each such operation (technological reserve of the operation), and the required "result" determined by the current state of the managed object.

It is possible to streamline the process of interviewing experts [21, 22] for unified forms of logical models, automate the process of generating knowledge bases [23], and use simple but fairly effective algorithms to derive management decisions.

The task of finding a combination of control operations is multivariant and combinatorial [24]. Therefore, to solve it, an algebraic model is formed that is adequate to the logical control model and is a system of combinatorial equations of linear structure. The independent variables in the algebraic model are Boolean variables, mapped to predicates that are part of the logical model, and describe possible control operations.

The transformation of the problem of searching for a combination of control operations from the area of mathematical logic to the field of combinatorial analysis makes it possible to optimize the desired management solution according to a given criterion. For this, the system of combinatorial equations is supplemented by a linear function, the coefficients of which characterize the degree of preference for certain control operations.

In this way, the task of finding a complex managerial solution reduced to solving a system of combinatorial equations [25-27] or (in the presence of a criterial function) to the problem of combinatorial optimization [26-28].

To solve this system (task), modified algorithms are used that implement the strategy of directed enumeration of options [20].

2 Research method

2.1 Generalized Management Model

Summarizing the experience accumulated in publications [1–8], we can conclude that in the vast majority of cases, the basis of logical control models is predicate expressions of four types.

1. A set of predicate expressions describing possible ways of influencing the OS (control operations), the implementation of which can lead to a change in the values of the characteristics of its state:

$$F_j = \forall y[P(u_j, y) \rightarrow D(f_j, y)]; \;\; j = \overline{1, l} \;, \tag{1}$$

where y is the conditional element of the managed object, the state characteristics of which change as a result of the implementation of the considered control operations;

P is a predicate meaning “to be implemented”;

u_j is the identifier of the *i*th control operation capable of changing the values of the state characteristics of the element y;

D is a predicate describing possible changes in the characteristics of the state of the managed object;

f_j is a function that specifies changes in the characteristics of the state of the managed object elements as a result of the implementation of the *j*th control operation;

l is the number of control operations provided by the logical control model.

2. A lot of predicate expressions describing the conditions for the implementation of control operations (necessary system connections and functional dependencies, the availability of required resources, etc.):

$$F_{j+l} = \forall y[R(y, c_j) \rightarrow Q(u_j)] \; ; \; j = \overline{1, l} \; , \tag{2}$$

where R is a predicate whose values reflect the fulfillment or non-fulfillment of the conditions for the implementation of control operations;

c_j is a constant characterizing the current state of the resource necessary for the implementation of the jth control operation;

Q is a predicate that reflects the possibility of practical implementation of control operations.

3. A predicate expression that carries the following meaning: if there is a control operation that can bring the managed object into a normal state, and the conditions for its practical implementation are met, then it must be performed:

$$F_n = \forall x[E(x) \,\&\, Q(x) \rightarrow P(x)]; \; j = \overline{1, l} \tag{3}$$

where x is the identifier of the desired management decision, that is, the management operation that must be implemented in the current situation;

$E(\;)$ is a predicate stating the existence of a control operation that can lead to the desired result.

4. A predicate expression that displays the hypothesis about the possibility of implementing a control operation that can lead to the necessary change in the characteristics of the state of an element:

$$F_{n+1} = \forall y \exists x[E(x) \rightarrow D(f_j, y)], \; 1 \leq j \leq l \tag{4}$$

Expressions (1) - (4) together form a common logical control model:

$$M = \{F_j ; \; j = \overline{1, n+1}\} . \tag{5}$$

2.2 Algorithm for deriving managerial decisions based on a generalized model

The conclusion of the managerial decision based on model (5) is to find such a function among the set of functions that, when substituted into the formula instead of the predicate variable, would ensure the logical following of this formula from the set of formulas. The establishment of such a fact formally reduces to proving the truth (for at least one interpretation) of a logical expression:

$$\mathop{\wedge}_{j=1}^{n} F_j \rightarrow F_{n+1} .$$

This is equivalent to proving (by the principle of “the opposite”) the inconsistency of the inverse formula:

$$\rceil(\bigwedge_{j=1}^{n} F_j \to F_{n+1}) = \rceil(\rceil \bigwedge_{j=1}^{n} F_j \vee F_{n+1}) = \bigwedge_{j=1}^{n} F_j \& \rceil F_{n+1} .$$

To this end, expert management systems often use the resolution method of J. Robinson [9]. It provides for the identical transformation of each of the formulas into the corresponding set of clauses with the further formation of a complete clausal set:

$$K = \bigcup_{j=1}^{n+1} K_j .$$

The resolution method is based on the following theorem: a set of clauses is contradictory when there is a logical conclusion from it an empty clause. It is customary to call empty a clause that does not contain any letters and therefore is false for any interpretation.

Before solving the problem of finding a managerial decision, the general management model (5) is set up for the current situation, which consists of the following actions:

Fixation of the managed object element in which the failure occurred: $y = e$.

Determination of predicate values $R(e, c_j)$, $j = \overline{1, l}$, reflecting the availability of resources necessary for the implementation of control operations. If the resource necessary for the implementation of the jth control operation exists, then the predicate $R(e, c_j)$ takes the value true, otherwise, the value false.

The inclusion in the composition of the clausal set K of the inversion of the expression that specifies the necessary result of the control action on the managed object in the current situation: $\rceil D(f_j, e)$.

The logical conclusion of an empty clause from the set of clauses K supplemented by the expression $\rceil D(f_j, e)$ is carried out by sequentially resolving pairs of clauses containing counter-letters. In the process of resolving, the predicate arguments (constants, variables, and functions) of one of the clauses are substituted into the positions of the arguments of the other clause occupied by the variables. The desired solution to the problem is determined by the identifier of that control operation u_{j^*}, $1 \le j^* \le l$, which, at the time of receipt of the empty clause, will occupy the position of the variable x.

The described method, based on the use of the logical model (5) and the disjoint resolution algorithm, has the completeness property and guarantees the finding of a solution to the problem in all cases when it objectively exists, but has several significant drawbacks. The main ones include:

1. cumbersomeness and semantic duplication of logical expressions included in the model;
2. poor focus on the selection of clauses for resolution, as a result of which it is necessary to process a large amount of information that is not used in the future;
3. the impossibility of taking into account the side effect, in which the control operation performed with the aim of the required change in the value of one or another

characteristic of the managed object condition can lead to negative changes in the values of other characteristics;

4. the impossibility of finding combinations of control operations in the case of simultaneous exceeding the limits of allowable ranges of several characteristics of the managed object condition;
5. the inability to optimize the solution to the problem of choosing control operations according to a given criterion.

These shortcomings necessitate the development of unified management models that adequately reflect the logic of the expert's reasoning and allow applying simpler algorithms to finding managerial decisions.

2.3 Unified models and algorithms

The task of finding management decisions arises in those cases when one or more characteristics of the state of the control object go beyond the specified allowable ranges. The following abnormal situations are possible, each of which requires the implementation of an appropriate algorithm for deriving a managerial decision:

- one characteristic is outside the permissible range and one control operation is enough to normalize it;
- one characteristic is outside the permissible range, but its normalization requires the simultaneous execution of several control operations (for example, in the case of a side effect, when the implementation of one or another control operation to change the anomalous value of any one characteristic can lead to a change in the values of other characteristics within acceptable ranges);
- out of the acceptable ranges are several characteristics of the state of the managed object.

The characteristics of the managed object condition can be quantified or evaluated in qualitative categories.

Unified control models and their corresponding algorithms should provide the opportunity to find control operations in all these cases. Similar models and algorithms focused on the quantitative measurement of the characteristics of the managed object state are considered in [10].

Assessing the characteristics of the state of the managed object with qualitative categories requires a specific approach to the development of managerial decisions, which will be described below.

In most cases, logical control models are built according to the scheme "resource" & "action" → "result". In this case, "action" refers to the performance of one or more control operations, the "resource" reflects the means necessary for the implementation of each such operation (technological reserve of the operation), and the required "result" is determined depending on one or another state of the managed object.

Let $z = (z_i \,|\, i = \overline{1, m})$ is the vector of characteristics of the managed object state.

When assessing the characteristics of the managed object condition with qualitative categories, the logical control model constructed according to the described scheme can be represented by the following formula:

$$(\forall i = \overline{1, m})(\forall j \in J_i)[M_j \rightarrow D(z_i, a_{ij})], \qquad (6)$$

where

$$M_j = R(r_j, s_j) \,\&\, X(u_j, r_j),$$

J_i is a lot of numbers of control operations, the implementation of which leads to a change in the value of the ith state characteristic of the managed object;

u_j is the jth identifier of the control operation;

r_j is the identifier of the resource necessary for the implementation of the jth control operation;

s_j is an indicator of the state of the resource r_j;

a_{ij} is the indicator of changes in the characteristics z_i of the managed object condition under the influence of the jth control operation;

$R(r_j, s_j)$ is the predicate that, after setting up the model for the situation, reflects the fact of the presence [if $R(r_j, s_j) = 1$] or absence [if $R(r_j, s_j) = 0$] of the resource necessary for the implementation of the control operation u_j;

$X(u_j, r_j)$ is the predicate reflecting the fact of performing [at $X(u_j, r_j) = 1$] a control operation u_j using a resource r_j;

$D(z_i, a_{ij})$ is the predicate reflecting the fact of a change in the [at $D(z_i, a_{ij}) = 1$] ith characteristics of the managed object condition as a result of the implementation of the control operation u_j.

Depending on the specifics of the managed object, the parameters of the model (6) can carry different semantic load. For example, an indicator s_j of the state of a resource r_j can state a certain fact ("ON", "OFF") or reflect a quantitative characteristic of the resource necessary for performing the jth control operation. The indicator a_{ij} indicates the direction of change in the characteristics z_i of the managed object state under the influence of the jth control operation ("INCREASE", "DECREASE").

Let z_{i^*} be a characteristic of the managed object condition, the value of which is outside the allowable range, and let b_{i^*} be a pointer to the direction of its required change.

The algorithm for finding a control operation capable of bringing this characteristic into an acceptable range provides for the following actions:

1. The formation of many control operations numbers that can lead to the desired change in this characteristic:

$$J_{i^*}^D = \{ j \in J_{i^*} : a_{i^*, j} = b_{i^*} \}.$$

2. Determination of a subset $J_{i^*}^D$ of numbers of control operations that make up the set, for the implementation of which there are necessary resources:

$$J_{i^*}^R = \{ j \in J_{i^*}^D : R(r_j, s_j) = 1 \}.$$

If it turns out that $J_{i^*}^R = \varnothing$, this means that model (6) does not provide for the possibility of changing the value of the characteristic z_{i^*} in the current situation.

3. The choice (at $\left|J_{i^*}^R\right| > 1$) the most preferred (according to a given criterion) control operation u_{j^*}, $j^* \in J_{i^*}^R$, to be implemented.

Suppose now that the implementation of control operations requires the availability of several types of resources. In this case, the management model takes the following form:

$$(\forall i = \overline{1,m})(\forall j \in J_i)[M_j^T \to D(z_i, a_{ij})], \tag{7}$$

where

$$M_j^T = R^T(r_j^T, s_j^T) \,\&\, X(u_j, r_j^T),$$

$$R^T(r_j^T, s_j^T) = \begin{cases} R(r_j, s_j) & for \ \left|T_j\right| = 1, \\ \underset{t \in T_j}{\wedge} R(r_{jt}, s_{jt}) & for \ \left|T_j\right| > 1. \end{cases}$$

T_j is the many types of resources necessary for the implementation of the jth control operation;

r_{jt} is the resource identifier of tth type;

s_{jt} is the indicator of the state of the resource r_{jt}.

The algorithm for finding the control operation remains the same, except that a subset of the numbers of control operations for the implementation of which the necessary resources are available is determined by the formula:

$$J_{i^*}^R = \{ j \in J_{i^*}^D : \underset{t \in T_j}{\wedge} R(r_{jt}, s_{jt}) = 1 \}.$$

2.4 A side effect

A side effect can be manifested in the fact that the control operation $j^* \in J_{i^*}^R$, which is carried out to bring the characteristic z_{i^*} into the acceptable range, can cause unacceptable changes in the values of other characteristics z_i, $i \in I_1^E(i^*)$ the state of the managed object, where

$$I_1^E(i^*) = \{ i \in \{1,\ldots,m\} \setminus \{i^*\} : J_{i^*}^R \cap J_i^R \neq \varnothing \}.$$

In turn, the implementation of control operations that compensate for negative changes in the values of the characteristics z_i, $i \in I_1^E(i^*)$, can lead to unacceptable deviations of another group of characteristics of the state z_i, $i \in I_2^E(i^*)$ of the managed object, not related to the general control operations directly with the characteristic z_{i^*}, etc.

Obviously, there is no side effect if $I_1^E(i^*)=\varnothing$. Otherwise, to normalize the state of the managed object, it is necessary to implement a comprehensive management solution that provides for the simultaneous execution of some combination of control operations. To establish such a combination, it is necessary, first of all, to determine the full set of characteristics $I^E(i^*)$ of the state of the managed object, which can change their values as a result of the implementation of the control operation aimed at bringing the characteristics z_{i^*} into the allowable range.

To do this, use the following step-by-step procedure.

Initially accepted:

$$I_0^E(i^*)=\{i^*\},\ J_0^E(i^*)=J_{i^*}^R .$$

Further, at each *k*th step, the following sets are sequentially determined:

$$I_k^E(i^*)=\{i\in\{1,\dots,m\} : J_i^R \bigcap J_{k-1}^R(i^*)\neq\varnothing\}\ ; \qquad (8)$$

$$J_k^R(i^*)=\bigcup_{i\in I_k^E(i^*)} J_i^R\ ;\ k=1,2,\dots \qquad (9)$$

The procedure ends if $J_k^R(i^*)=J_{k-1}^R(i^*)$ or, equivalently, $I_k^E(i^*)=I_{k-1}^E(i^*)$. Formed in the described manner, the set $I^E(i^*)=I_k^E(i^*)$ contains numbers of all characteristics of the managed object condition (including), the values of which can change as a result of performing a control operation aimed at bringing the characteristic z_{i^*} into an acceptable range.

Given the side effect, the logical management model takes the following form:

$$(\forall i^*=\overline{1,m})[\bigvee_{j\in J_{i^*}} M_j^T \rightarrow \bigwedge_{i\in I^E(i^*)} D(z_i,a_{ij})]\,. \qquad (10)$$

The task of determining the combination of control operations, the implementation of which can bring the characteristic z_{i^*} of the managed object state to the acceptable range while maintaining the acceptable values of all other characteristics z_i $i\in I^E(i^*)\setminus\{i^*\}$, is multivariate and combinatorial in nature. Therefore, its solution is based on the use of an algebraic model that adequate to the logical model (10).

To build such a model, you must:

To give indicators a_{ij} and b_i, evaluated by qualitative categories, a quantitative measurement; $i\in I^E(i^*)$; $j\in J_i^R$.

Let, for example, a_{ij} = 1 if the value of the characteristic z_i as a result of the implementation of the *j*th control operation increases, and if a_{ij} = -1 it decreases. Similarly, if b_i = 1 it is necessary to increase the value of the characteristic z_i; if b_i = -1 it needs to be reduced, and b_i = 0 it left unchanged.

Match each predicate $X(u_j;r_j^T)$ to a Boolean variable $x_j\in\{0,1\}$, $j\in J_{i^*}^R$.

The meaning of Boolean variables is as follows: if as a result of solving the problem it turns out that some variable $x_{j'} = 1$, this will mean that the control operation $u_{j'}$ is subject to implementation; when $x_{j'} = 0$ this statement is false; $j' \in J^R_{i^*}$.

The introduced assumptions allow us to reduce the procedure for determining the desired combination of control operations to the solution of a system of linear combinatorial equations:

$$\sum_{j \in J_i^R} a_{ij} x_j = b_i, \quad i \in I^E(i^*), \tag{11}$$

where

$$[\forall i \in I^E(i^*) \setminus \{i^*\}] (b_i = 0).$$

Example. Let assumes the managed object state described by five characteristics z_i, $i = \overline{1,5}$, and the numbers of control operations capable of changing their values are given by the following sets:

$$J_1^R = \{1,2,3\}; \; J_2^R = \{2,4,6\}; \; J_3^R = \{5,7\}; \; J_4^R = \{8,9\}; \; J_5^R = \{4,6\}.$$

Let the characteristic z_1 is outside the allowable range.

The procedure for determining the full set $I^E(i^*)$ of characteristics of the state of the managed object, which can change their values as a result of the implementation of control operations $I^E(i^*)$ designed to bring the characteristics z_{i^*} into the acceptable range, consists in sequentially performing the following actions:

1. The fixation of the initial conditions:

$$i^* = 1; \quad I_0^E(1) = \{1\}; \quad J_0^R(1) = \{1, 2, 3\};$$

2. The definition of the set $I_1^E(1)$ of numbers of characteristics of the state of the managed object, which can change their values as a result of the implementation of control operations $j \in J_0^R(1)$, following by (8):

$$J_1^R \cap J_0^R(1) = \{1, 2, 3\} \cap \{1, 2, 3\} = \{1, 2, 3\} \neq \varnothing;$$

$$J_2^R \cap J_0^R(1) = \{2, 4, 6\} \cap \{1, 2, 3\} = \{2\} \neq \varnothing;$$

$$J_3^R \cap J_0^R(1) = \{5, 7\} \cap \{1, 2, 3\} = \varnothing;$$

$$J_4^R \cap J_0^R(1) = \{8, 9\} \cap \{1, 2, 3\} = \varnothing;$$

$$J_5^R \cap J_0^R(1) = \{4, 6\} \cap \{1, 2, 3\} = \varnothing.$$

Then

$$I_1^E(1) = \{1, 2\}.$$

3. The definition of the set $J_1^R(1)$ of numbers of control operations designed to change the values of the characteristics z_1 and z_2 in according to (9):

$$J_1^R(1) = \{1, 2, 3\} \bigcup \{2, 4, 6\} = \{1, 2, 3, 4, 6\} .$$

4. The definition of the set $I_2^E(1)$ of numbers of characteristics of the state of the managed object, which can change their values as a result of the implementation of control operations $j \in J_1^R(1)$:

$$J_1^R \bigcap J_1^R(1) = \{1, 2, 3\} \bigcap \{1, 2, 3, 4, 6\} = \{1, 2, 3\} \neq \varnothing ;$$
$$J_2^R \bigcap J_1^R(1) = \{2, 4, 6\} \bigcap \{1, 2, 3, 4, 6\} = \{2, 4, 6\} \neq \varnothing ;$$
$$J_3^R \bigcap J_1^R(1) = \{5, 7\} \bigcap \{1, 2, 3, 4, 6\} = \varnothing ;$$
$$J_4^R \bigcap J_1^R(1) = \{8, 9\} \bigcap \{1, 2, 3, 4, 6\} = \varnothing ;$$
$$J_5^R \bigcap J_1^R(1) = \{4, 6\} \bigcap \{1, 2, 3, 4, 6\} = \{4, 6\} \neq \varnothing .$$

Then

$$I_2^E(1) = \{1, 2, 5\} .$$

5. The definition of the set $J_2^R(1)$ of numbers of control operations designed to change the values of the characteristics z_1, z_2, and z_5:

$$J_2^R(1) = \{1, 2, 3\} \bigcup \{2, 4, 6\} \bigcup \{4, 6\} = \{1, 2, 3, 4, 6\} .$$

Since $J_2^R(1) = J_1^R(1)$, the procedure ends.

The full set of characteristics $I^E(1)$ of the managed object state, which can change their values as a result of the control operation aimed at bringing the characteristics z_1 into the acceptable range, is determined by the formula:

$$I^E(1) = I_2^E(1) = \{1, 2, 5\} .$$

Conclusion: to compensate for the side effect, in the system of equations (11), it is necessary to include expressions corresponding to the characteristics of the managed object condition z_1, z_2, and z_5:

$$a_{11}x_1 + a_{12}x_2 + a_{13}x_3 = b_1 ,$$
$$a_{22}x_2 + a_{24}x_4 + a_{26}x_6 = 0 ,$$
$$a_{54}x_4 + a_{56}x_6 = 0 ,$$

where $b_1 \in \{-1, 1\}$, depending on the direction of the required change in characteristics z_1.

To solve this system, a modified algorithm can be used that implements a strategy of directed enumeration of variants [10, 11].

The numbers of variables x_j, $j \in J^R(1) = J_2^R(1) = \{1, 2, 3, 4, 6\}$ that, as a result of solving this system of equations take a value of unity, determine the set of control operations u_j that must be performed to bring the characteristics z_1 into an acceptable range under the side effect.

2.5 Definition of combinations of control operations

Let I^* be the set of numbers of characteristics of the state of the managed object, the values of which are outside the allowable ranges, and $b_i \in \{1, -1\}$, $i \in I^*$ let be the direction indicators of the required changes in their values.

In the absence of a side effect, the logical control model is presented in the form (7), and in its presence, in the form (10).

The corresponding systems of combinatorial equations are formed from expressions of the form (11). In the first case, they are formed separately for each $i \in I^*$. In the second - for everyone $i \in I^E(I^*)$, where $I^E(I^*)$ is the set of numbers of all characteristics of the managed object condition, the values of which can change as a result of control operations implemented to bring the totality of characteristics z_i, $i \in I^*$ into an acceptable range. Wherein

$$[\forall i \in I^E(I^*) \setminus I^*](b_i = 0) .$$

To determine the set $I^E(I^*)$, the step-by-step procedure described above is used, during the execution of which it is initially accepted:

$$I_0^E(I^*) = I^*; \; J_0^E(I^*) = \bigcup_{i \in I^*} J_{i^*}^R .$$

Further, at each *k*th step, the following sets are sequentially determined:

$$I_k^E(I^*) = \{i \in \{1,\ldots,m\} : J_i^R \cap J_{k-1}^R(I^*) \neq \varnothing\} ; \tag{12}$$

$$J_k^R(I^*) = \bigcup_{i \in I_k^E(I^*)} J_i^R ; \; k = 1, 2, \ldots \tag{13}$$

The procedure ends with finding the set $I_k^E(I^*) = I_{k-1}^E(I^*) = I^E(I^*)$.

Example. Suppose the managed object state is described by seven characteristics z_i, $i = \overline{1,7}$, and the numbers of control operations capable of changing their values are given by the following sets:

$$J_1^R = \{1,3\} ; \; J_2^R = \{2,4\} ; \; J_3^R = \{1,5\} ; \; J_4^R = \{7,9\} ;$$

$$J_5^R = \{4,6\} ; \; J_6^R = \{10,11\} ; \; J_7^R = \{5,6\} .$$

Suppose that the characteristics z_1 and z_2 are outside the allowable range.

The procedure for determining the full set $I^E(I^*)$ of characteristics of the state of the managed object, which can change their values as a result of the implementation of control operations designed to bring the characteristics z_i, $i \in I^*$ into the acceptable range, consists in sequentially performing the following actions:

1. The fixation of the initial conditions:

$$I_0^E(I^*) = I^* = \{1,2\}; \quad J_0^E(I^*) = \{1,3\} \bigcup \{2,4\} = \{1,2,3,4\}.$$

2. The definition of the set $I_1^E(I^*)$ of numbers of characteristics of the state of the managed object, which can change their values as a result of the implementation of control operations $j \in J_0^R(I^*)$ following by (12):

$$J_1^R \bigcap J_0^R(I^*) = \{1, 3\} \bigcap \{1, 2, 3, 4\} = \{1, 2, 3, 4\} \neq \varnothing;$$
$$J_2^R \bigcap J_0^R(I^*) = \{2, 4\} \bigcap \{1, 2, 3, 4\} = \{1, 2, 3, 4\} \neq \varnothing;$$
$$J_3^R \bigcap J_0^R(I^*) = \{1, 5\} \bigcap \{1, 2, 3, 4\} = \{1\} \neq \varnothing;$$
$$J_4^R \bigcap J_0^R(I^*) = \{7, 9\} \bigcap \{1, 2, 3, 4\} = \varnothing;$$
$$J_5^R \bigcap J_0^R(I^*) = \{4, 6\} \bigcap \{1, 2, 3, 4\} = \{4\} \neq \varnothing;$$
$$J_6^R \bigcap J_0^R(I^*) = \{10, 11\} \bigcap \{1, 2, 3, 4\} = \varnothing;$$
$$J_7^R \bigcap J_0^R(I^*) = \{5, 6\} \bigcap \{1, 2, 3, 4\} = \varnothing.$$

Therefore

$$I_1^E(I^*) = \{1, 2, 3, 5\}.$$

3. The definition of the set $J_1^R(I^*)$ of numbers of control operations designed to change the values of the characteristics z_1, z_2, z_3 and z_5 according to (13):

$$J_1^R(I^*) = \{1, 3\} \bigcup \{2, 4\} \bigcup \{1, 5\} \bigcup \{5, 6\} = \{1, 2, 3, 4, 5, 6\}.$$

4. The definition of the set $I_2^E(I^*)$ of numbers of characteristics of the state of the managed object, which can change their values as a result of the implementation of control operations $j \in J_1^R(I^*)$:

$$J_1^R \bigcap J_1^R(I^*) = \{1, 3\} \bigcap \{1, 2, 3, 4, 5, 6\} = \{1, 2, 3, 4, 5, 6\} \neq \varnothing;$$
$$J_2^R \bigcap J_1^R(I^*) = \{2, 4\} \bigcap \{1, 2, 3, 4, 5, 6\} = \{1, 2, 3, 4, 5, 6\} \neq \varnothing;$$
$$J_3^R \bigcap J_1^R(I^*) = \{1, 5\} \bigcap \{1, 2, 3, 4, 5, 6\} = \{1, 5\} \neq \varnothing;$$
$$J_4^R \bigcap J_1^R(I^*) = \{7, 9\} \bigcap \{1, 2, 3, 4, 5, 6\} = \varnothing;$$
$$J_5^R \bigcap J_1^R(I^*) = \{4, 6\} \bigcap \{1, 2, 3, 4, 5, 6\} = \{4, 6\} \neq \varnothing;$$
$$J_6^R \bigcap J_1^R(I^*) = \{10, 11\} \bigcap \{1, 2, 3, 4, 5, 6\} = \varnothing;$$
$$J_7^R \bigcap J_1^R(I^*) = \{5, 6\} \bigcap \{1, 2, 3, 4, 5, 6\} = \{5, 6\} \neq \varnothing.$$

Thus

$$I_2^E(I^*) = \{1, 2, 3, 5, 7\}.$$

5. The definition of the set $J_2^R(I^*)$ of numbers of control operations designed to change the values of the characteristics z_1, z_2, z_3 and z_5:

$$J_2^R(I^*) = \{1, 3\} \cup \{2, 4\} \cup \{1, 5\} \cup \{5, 6\} = \{1, 2, 3, 4, 5, 6\}.$$

Since $J_2^R(I^*) = J_1^R(I^*)$, the procedure ends.

The complete set $I^E(I^*)$ of characteristics of the state of the managed object, which can change their values as a result of the implementation of the control operation aimed at bringing the characteristics z_1 into the acceptable range, is determined by the formula:

$$I^E(I^*) = I_2^E(I^*) = \{1, 2, 3, 5, 7\}.$$

Conclusion: to compensate for the side effect, in the system of equations (11), it is necessary to include expressions corresponding to the characteristics of the managed object condition z_1, z_2, z_3 and z_5:

$$a_{11}x_1 + a_{13}x_3 = b_1,$$
$$a_{22}x_2 + a_{24}x_4 = b_2,$$
$$a_{31}x_1 + a_{35}x_5 = 0,$$
$$a_{54}x_4 + a_{56}x_6 = 0,$$
$$a_{75}x_5 + a_{76}x_6 = 0,$$

where $b_i \in \{-1, 1\}$, $i \in \{1, 2\}$, depending on the directions of the required change in characteristics z_1 and z_2.

The numbers of variables x_j, $j \in J^R(I^*) = J_2^R(I^*) = \{1, 2, 3, 4, 5, 6\}$ that, as a result of solving this system of equations take the value of unity, determine the set of control operations u_j that must be performed to bring the characteristics z_1 and z_2 into the acceptable range under the side effect.

The task of finding a combination of control operations that can bring the managed object into a normal state is of a multivariate and, therefore, optimization nature. Therefore, in addition to the system of combinatorial equations (11), in the mathematical model of this problem, it is necessary to include the criterion function:

$$f(x) = \sum_{j \in J^X} v_j x_j, \tag{14}$$

where J^X is the set of identifiers of the considered control operations:

$$J^X = \bigcup_{i \in I^X} J_i^R$$

I^X is the many numbers of characteristics of the state of the managed object, such that $I^X = I^*$ in the absence of a side effect and $I^X = I^E(I^*)$ if there is one;

v_j is the coefficients reflecting the degree of preference for certain control operations (for example, the costs of their implementation, technological advantages, etc.); $j \in J^X$;

x is the vector of independent Boolean variables:

$$x = (x_j \mid j \in J^X);\ x_j \in \{0,1\};\ j \in J^X .$$

In a formal statement, the problem is reduced to finding a vector of values of Boolean variables $x = (x_j \mid j \in J^X)$ that turn into an optimum (maximum or minimum) criterion function (14) subject to a system of constraints (11).

To solve it, an algorithm can be used that implements the idea of a directed enumeration of options in adaptation to the structure of the constraint system [20].

3 Discussion of results

The following research results obtained:

- A generalized logical control model proposed, which can be considered the canonical form of knowledge representation in intelligent control systems using a resolution algorithm or any other deductive inference algorithms to find management solutions.
- Unified forms of logical control models have been developed that allow one to find optimal (according to a given criterion) integrated management decisions in conditions of a side effect and simultaneously out beyond the acceptable ranges of several characteristics of the managed object.
- A new approach to finding managerial solutions proposed, providing for the construction of an algebraic model adequate to the logical control model. It is proved that when assessing controlled parameters by qualitative categories, the basis of such an algebraic model is a system of linear combinatorial equations with a unimodular coefficient matrix. This makes it possible to use effective algorithms that implement a strategy of directed enumeration of options to find managerial decisions.

The transition from logical control models to algebraic forms allows you to:

- set complex management decisions (combinations of control operations) in cases when several characteristics of the state of a managed object that go beyond the acceptable ranges simultaneously;
- to compensate for the side effect when the control operation performed with the aim of the required change in the value of one or another characteristic of the managed object condition leads to unacceptable changes in the values of other characteristics;
- to optimize integrated management decisions according to specified criteria.

Formalized procedures:

- determining the set of control operations that can bring the managed object into a normal state and possess the resources necessary for their practical implementation;
- determination of the characteristics of the state of the managed object, to which it is necessary to apply control operations in the condition a side effect;

- construction of algebraic models adequate to unified logical control models.

The following research results have scientific novelty:

- a generalized logical management model, creating the basis for standardizing the methodology of interviewing experts in the subject area under consideration;
- unified forms of logical control models that allow using simple and effective algorithms to find optimal integrated management solutions;
- a formalized procedure for determining the characteristics of the state of the managed object, for which it is necessary to apply control operations in the face of a side effect;
- a formalized procedure for determining the set of control operations that can bring the managed object into a normal state and have the resources necessary for their practical implementation;
- a formalized procedure for constructing algebraic models adequate to unified logical control models.

The practical value of the research results is that the application of the proposed methods allows you to:

- standardize the methodology of interviewing experts in the subject area;
- automate the process of formalizing knowledge gained from experts;
- reduce the design time of software of intelligent control systems;
- reduce the cost of computing time to find managerial decisions during the operation of such systems;
- increase the effectiveness of management decisions by using optimization algorithms.

4 Conclusions

The contribution of this study lies in the proposal of unified logical control models, as well as search algorithms based on them for complex management decisions.

The given logical models are the result of the generalization of various forms of knowledge representation in intelligent control systems for various purposes. This proves their adequacy to the real tasks of making managerial decisions based on logical models that reflect the logic of the reasoning of a person - an expert in the subject area under consideration.

The developed models allow us to determine the optimal (according to the given criteria) integrated management decisions that can bring the managed object to a normal state, taking into account the available resources necessary for the practical implementation of control operations, and a side effect. Also, they make it possible to standardize the procedure for interviewing experts, to automate the process of formalizing the knowledge gained from them, as well as the technology for designing relevant knowledge bases.

Converting the presented logical control models to algebraic form allows us to transform the search for managerial solutions to solving a system of linear equations with Boolean variables or (if there is a criterion function) to solving a combinatorial optimization problem. For this, simple, but quite effective algorithms for directional enumeration of options are used.

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