An Approach to Modeling the Interrelations Variability at Elements of Production Systems with a Variable Structure

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Abstract. The problems in modeling the interrelationships of production systems elements with a variable structure are considered, which generates a number of difficulties in description and research. The study of the functioning processes of complex production systems is fundamentally important due to the growing requirements for their efficiency and resource intensity. In enterprises where rapid changeover and/or rapid composition change o of production equipment is required, it is necessary to take into account the variability of the relationships between the elements. Changeover refers to the process of transition, for example, of a machine from the production of one product or part to the production of another by replacing molds, clamping joints, and so on.In most cases, modern production systems have a multicomponent composition, which imposes restrictions on the possibilities of modeling the relationships of their elements due to the dimension problem of the model. The component composition enlargement of production systems causes possible information losses in the description of each element associated with the analysis of the element significance and its relationships with other elements, taking into account the variable structure. An aggregated approach is proposed that takes into account the uniqueness degree of system components, changes in their significance by taking into account the component inclusion degree in the system, which will allow making informed decisions on CPS reconfiguration taking into account the variable structure.

Keywords: Production system · Variable structure · Component inclusion · Elements significance · Connections significance · Model enlargement

1 Introduction

The study of the functioning processes of complex production systems (CPS) is fundamentally important due to the growing requirements for their efficiency and resource intensity. In enterprises where rapid changeover and/or rapid composition change o of production equipment is required, it is necessary to take into account the variability of the relationships between the elements. Changeover refers to the process of transition, for example, of a machine from the production of one product or part to the production of another by replacing molds, clamping joints, and so on.

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When using the methods of rapid changeover (Single-Minute Exchange of Dies (SMED), it is possible to reduce the time of equipment setup and changeover operations. It is known that there are two main types of SMED: operations that are performed after the equipment is stopped; operations that can be performed during the operation of the equipment [1, 2].

At the same time, a number of problems arise:

- The time required for changeover may exceed the critical level, according to the requirement of efficiency;
- Maintaining the components of the reconfigurable equipment in a “hot” reserve is problematic and expensive, however, in certain cases, the components of such equipment can be implemented on the principle of flexible production and transfer of functions to elements with similar or complex functions;
- Modeling of relationships between CPS elements should take into account different categories of relationships and the elements themselves;
- In addition, the significance of the links and the significance of the components themselves in the system may be incommensurable and non-stationary. Incommensurability is reflected either in the discrepancy of the measurement scales, or in a significant spread of values on a homogeneous scale. For example, the time to failure of CPS equipment can reach hundreds of hours, and the average time to implement one operation is several milliseconds. Non-stationarity is mainly associated with changes in indicators (for example, values or weights of components) over time.

A decrease in the number of states should not lead to a loss of accuracy in estimating the system output characteristics. When calculating approximate values of these characteristics, errors should be estimated, which complicates the mathematical model [3, 4]. The phase enlargement principles o have been developed, the essence of which is that the phase space of the initial system is split into a finite number of disjoint classes. The states of each class are “glued” into one state, and the probabilities of the initial states are summed up. An enlarged system is being built in a new, enlarged phase space [4]. This approach is based on asymptotic methods.

The synthesis of a complex system should take into account two aspects: the functional binding of functions (as a service) to the structural elements of the system and the uncertainty in the functional and structural components during the cycle of this system functioning. Functional binding means that there is a basic relationship between the elements of the system and the functions inherent in these elements. On the other hand, local changes of function bindings to structural elements are possible under certain conditions [3, 5]. The inconsistency of these two aspects can be solved by identifying stable (basic) structural elements with a clear binding of functions, as well as subsets of structural elements with a limited functional binding.

In [3], various methods of enlargement are considered and it is indicated that, unlike the existing ones, the author’s method consists in the fact that the states of the enlarged system are described by the same characteristics as the original one, that is, isomorphism of the original and enlarged system is ensured, including the enlarged system retains the markovity property. The idea of enlarging states by functional attribute, that is, by the functions performed by the system in each state, is considered.

The tasks of analyzing the elements significance in most cases are associated with the definition of methodological and computational aspects of technogenic risks in system functioning within the framework of applied subject areas [5], which, for the most part, concerns applied software.

The method presented in [6] for estimating the weighting coefficients of organizational and technical systems involves calculating the values of the objective function of the system without each element in turn. A tuple of the obtained values of the system objective function $F = < f1 \ldots fs \ldots fS >$, is constructed, where *fs* – the indicator value of the objective function with the excluded *s–th* element. The value of the redistributed weighted average coefficient, which is the same for all remaining elements of the system, is calculated as $w^* = 1/(S - 1)$. It is assumed that this approach will reduce the volume of expert assessments [7–11].

Thus, the existing studies [12–15], for the most part, do not focus on the non-stationarity of the weight functions that determine the significance of the component or its relationship with other CPS components [16, 17]. In addition, with the enlargement of multicomponent systems, the significance of boundary elements and their connections may change due to the formation of a new phase space of states of the system.

2 Problem Statement

The purpose of the study: modeling the variability of the interconnections of elements in the CPS by taking into account the inclusion degree of the component in the system and measures of components cross-inclusions in order to clarify solutions for managing the functioning of the CPS variable structure, for example, reducing the time for reconfiguration.

Let ‘s introduce a number of notations. Let be $f_i -$ Let be a function (service) that must be implemented by some component of CPS, $i = \overline{1, I}$, where I - is a finite number of CPS functions; F- is a finite set of IS functions; $S -$ a set of structural units, where $s_j -$ structural element of CPS, $j = \overline{1, J}$, J - s a finite number of structural elements of CPS.

Let’s denote the significant subsets of the set $F = \{F_{if},\ F_f,\ F_s\}$, $F_{if} -$ (inflexible) a subset of functions that are rigidly bound to the structural units of the CPS, but can be implemented on other elements; $F_f -$ (flexible) a subset of flexible functions that are not tied to the structural units of the CPS, $F_s -$ stationary (fixed) functions that are distributed to certain components of the CPS. Examples F_{if} may be functions assigned to a specific section of the program code of a numerically controlled machine (CNC), which implies their binding to a specific structural unit of the CPS. The function of some intermediate type of product data control, on the contrary, can be implemented in various subsystems: a subsystem for data collection, a subsystem for their analysis or storage, which makes it possible to define it as F_{if}. The function of making a decision on the products rejection, for example, can only be in the corresponding subsystem and is generally defined as F_f.

In Fig. 1 shows possible combinations of subsets in the structure of the CPS, dotted lines A, B and C reflect possible connections of flexible functions and rigidly functionally oriented elements of the CPS.

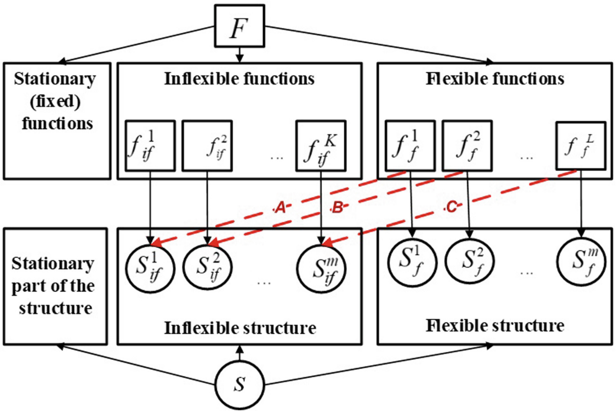

Fig. 1. The correspondence scheme of CPS structural elements and functions, taking into account their decomposition into stationary, flexible and inflexible.

The definition of these functions subsets that are rigidly tied to the structural units of CPS and flexible functions, as well as the construction of possible implementations of structures depending on various requirements for this system, are very problematic [16]. In order to simplify the description of the methods, a subset of stationary rigidly functionally oriented CPS structures is excluded from further consideration.

3 Methods and Results

Let us consider s_i and s_j – some components of the system S with weighting coefficients determining their significance in CPS: w_i and w_j respectively; l_{ij} and l_{ji}– he type of relationship between the components s_i,.. And their weighting coefficients w_i and w_j respectively. Then, in the general case, CPS can represent a tuple taking into account the variable structure (flexibility):

$$\begin{aligned} &S_{if}\left\langle s_{if}^{i} | w_{if}^{i},\ s_{if}^{j} \middle| w_{if}^{j},\ l_{if}^{ij} \middle| w_{if}^{ij},\ l_{if}^{ji} \middle| w_{if}^{ji} \right\rangle, \\ &S_{f}\left\langle s_{f}^{k} | w_{f}^{k},\ s_{f}^{m} \middle| w_{f}^{m},\ l_{f}^{km} \middle| w_{f}^{km},\ l_{f}^{mk} \middle| w_{f}^{mk} \right\rangle. \end{aligned} \tag{1}$$

With the nonstationarity of the weighting coefficients of the links for some $t_p \in T$ they can be represented by a weighting function of time:$w_i(t_p)$ and $w_j(t_p)$. Then expressions (1), taking into account their functionality, will take the form:

$$S_{if}\left\langle \begin{array}{l} (s_{if}^{i}:f_{if}^{i},f_{f}^{i})|w_{if}^{i}(t_p), \\ (s_{if}^{j}:f_{if}^{j},f_{f}^{j})\Big|w_{if}^{j}(t_p), \\ l_{if}^{ij}\Big|w_{if}^{ij}(t_p),\ l_{if}^{ji}\Big|w_{if}^{ji}(t_p) \end{array} \right\rangle,$$
$$S_{f}\left\langle \begin{array}{l} (s_{f}^{k}:f_{f}^{k})|w_{f}^{k}(t_p), \\ (s_{f}^{m}:f_{f}^{m})\Big|w_{f}^{m}(t_p), \\ l_{f}^{km}\Big|w_{f}^{km}(t_p),\ l_{f}^{mk}\Big|w_{f}^{mk}(t_p) \end{array} \right\rangle. \tag{2}$$

The entry $(s_{if}^{i}:f_{if}^{i},f_{f}^{i})|w_{if}^{i}(t_p)$ means, that the i-th element of the CPS structure s_{if}^{i} has an inflexible function f_{if}^{i} and can perform some additional function f_{f}^{i} provided the weight function $w_{if}^{i}(t_p)$ is entered.

Compliance with the structural element s_{if}^{i} of a certain weight function $w_i(t_p)$ is some assumption implemented by the decision maker (DM), since when transferring the function f_{f}^{i}, the value of the weight function may change.

Setting the weighting coefficients w_i is usually not difficult and the DM is implemented, while finding the weighting function $w_i(t_p)$ is problematic due to the presence of uncertainty and non-stationarity. It is proposed to use for these purposes the degree of inclusion of the element s_i in CPS. The expression for the degree of inclusion of the component in the system, taking into account (2), in general form can be written as

$$u_{s_i}(t)=\frac{\sum_{i=1}^{N} w_i^{out}(t)\sum_{j=1}^{M} w_{ij}^{out}(t)}{\sum_{l=1}^{L} w_l^{in}(t)\sum_{h=1}^{H} w_{hl}^{in}(t)} \tag{3}$$

where *N, M, L, H* – the cardinalities of the sets of external (out) and internal (in) components S, external and internal connections, respectively, relative to the S_i component.

The measure of component inclusion s_j in as a normalized number of intersections of their properties in is proposed to be evaluated as follows:

$$W(s_i,s_j)=m(s_i\cap s_j)/m(s_i) \tag{4}$$

In the case under consideration, the relation (4) can be interpreted as a normalized number of intersections l_{ij} and l_{ji} taking into account w_{ij} and w_{ji}. Then taking into account (4) for $t_p \in T$ the expression (3) will take the general form:

$$u_{s_i}(t_p)=\frac{W(s_i,s_j)\Big(\sum_{i=1}^{N} w_i^{out}(t_p)\sum_{j=1}^{M} w_{ij}^{out}(t_p)\Big)}{W(s_j,s_i)\Big(\sum_{l=1}^{L} w_l^{in}(t_p)\sum_{h=1}^{H} w_{hl}^{in}(t_p)\Big)} \tag{5}$$

To account for the impact of flexible functionality, it is advisable to use the expression (6):

$$u_{s_{if}^i, s_{if}^j}(t_p) = \frac{W\left[s_{if}^i; s_{if}^j\right]\left(\sum_{f_{if}^i, f_f^i}\left(\sum_{i=1}^{N} w_{if}^{i,out}(t_p)\sum_{j=1}^{M} w_{if}^{ij,out}(t_p)\right)\right)}{W\left[s_{if}^j; s_{if}^i\right]\left(\sum_{f_f^i, f_{if}^i}\left(\sum_{l=1}^{L} w_{if}^{l,in}(t_p)\sum_{h=1}^{H} w_{if}^{hl,in}(t_p)\right)\right)}, \quad (6)$$

where the designation $\sum_{f_{if}^i, f_f^i}(\bullet)$ is an abbreviated description of the summation process by weight coefficients at a time $t_p \in T$ for various functions (flexible or inflexible) introduced into this element of the structure, which can significantly change $u_{s_{if}^i, s_{if}^j}(t_p)$. The estimation of this indicator may be complicated by the variability of the typification of connections l_{ij} and l_{ji}, n this study, this aspect is not taken into account, but will be considered in the future.

To model the variability of relationships between CPS elements, we introduce the assumption that in the simplest case, structural elements and functions coincide and can be represented by states [17–19]. For example, the operation of the software module controlling the changeover corresponds to the transition of the CPS to the changeover state [20–24]. Thus, under a number of assumptions, Fig. 2 presents a graph of states for the model under consideration in the following phase space:$E = \{E0, E1, E2, E3, E4\}$, where

E0—CPS operating state,
E1—CPS failure state,
E2—CPS recovery state after failure,
E3—CPS changeover state,
E4—failure state—is a state from which a transition can be made to a failure state, after which recovery is required, or to an initial state without recovery.

Thus, E4 is a state in which system recovery is not required. Transitions between states are indicated by arrows, there are stable states of the type in the model, reflecting the situation when at some control point in time the system did not switch to another state from the current one.

The transformation of the CPS block diagram into a state model is valid under the following assumptions:

Phase enlargement of the model with generalized states is applied in order to form a preliminary scheme for sequential reconfiguration of CPS changeover processes;

The assumption of one-sided functional and structural correspondences is introduced, Fig. 1.

When solving the problem of modeling the process of CPS functioning (without taking into account the flexible binding of functions during readjustment), it is obvious that at various stages of its functioning before the onset of degradation and after the development of degradation processes, the weights of the corresponding states, as a reaction to changes in the weight functions of elements or their functionality, may change: $w_1(t_1) > w_1(t_0)$, $w_4(t_1) < w_4(t_0)$, for $l_{0,4}$, $l_{0,1}$ accordingly:$w_{0,1}(t_0) < w_{0,4}(t_0)$. At the next stage $t_0 < t_1$ of the CPS operation, the values of the weight functions may change: $w_{0,1}(t_0) > w_{0,1}(t_1)$, $w_{0,4}(t_0) < w_{0,4}(t_1)$, for example, due to readjustment.

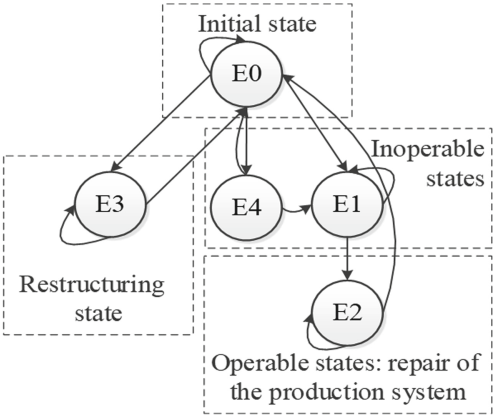

Fig. 2. The graph of states of the CPS.

Calculation procedures have shown that, for example, for some parameters:
$w_{1,2} = 0.41$, $w_{2,1} = 0.22$,
$w_1(t_1) = 0.41$, $w_1(t_0) = 0.79$,
$w_2(t_1) = 0.61$, $w_2(t_0) = 0.83$,
$w_{2,1}(t_0) = 0.38$, $w_{2,1}(t_1) = 0.87$,
$w_{1,2}(t_0) = 0.62$, $w_{1,2}(t_0) = 0.49$,
evaluations $u_{s_4}(t_p)$ equal:$u_{s_4}(t_0) \approx 0.068$, $u_{s_4}(t_1) \approx 0.057$.

This means that the inclusion degree of the CPS component (state E4) responsible for readjusting (for example, the corresponding algorithm of the control module) into the system, taking into account the normalized number of intersections, is reduced for $t_0 < t_1$, that is, at the beginning of degradation processes, the subsystem for registering short-term failures that do not require restoration is absorbed by the subsystem for registering all types of failures, which is associated with the enlargement these states.

Taking into account the flexible binding of functions during changeover with the same initial data, the state graph (Fig. 2) taking into account Fig. 1 is transformed into the graph shown in Fig. 3.

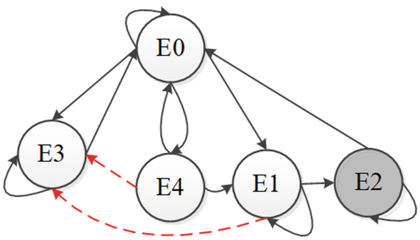

Fig. 3. The modified graph of states of the CPS Markov model with flexible binding of functions.

Assuming that

$$(s_2 : f_{if}^2, f_f^2) \rightarrow (s_3 : f_{if}^3, f_f^2); \quad (7)$$

$$(s_4 : f_{if}^4, f_f^4) \rightarrow (s_3 : f_{if}^3, f_f^4) \Rightarrow (s_3 : f_{if}^3, f_f^2, f_f^4). \quad (8)$$

This means that in the CPS recovery state after a failure (E2), part of the functions of the structural component responsible for recovery can be implemented on the structural components of the changeover.

When modeling the relationships of elements in these assumptions, estimates $u_{s_{if}^i, s_{if}^j}(t_p)$ are obtained:

$$u_{s_4,\,s_3}(t_0) \approx 0.066,\ u_{s_4,\,s_3}(t_1) \approx 0.049,\ u_{s_4,\,s_3}(t_2) \approx 0.044,$$
$$u_{s_3}(t_0) \approx 0.051,\ u_{s_3}(t_1) \approx 0.088,\ u_{s_3}(t_2) \approx 0.089,$$
$$u_{s_2\,s_3}(t_0) \approx 0.094,\ u_{s_2\,s_3}(t_1) \approx 0.055,\ u_{s_2\,s_3}(t_1) \approx 0.043.$$

Therefore, for example, when transferring part of the functional from s2 to s3, the transition of the CPS to the E2 state can be replaced by the trajectory (7), and in case of a short-term failure, the trajectory (8) can be implemented with the transfer of the functional to the system element associated with the changeover. Thus, the involvement degree of the component responsible for restoring the system over time decreases from 0.094 at time t0 to 0.055 at time t1, which indicates the readjustment and absorption of the corresponding function and the importance of s3 increases from 0.051 to 0.088.

Figure 4 shows the results of comparing the obtained modeling results of relationships variability of production system elements with a variable structure. The given example of CPS reconfiguration with a variable structure is abstract and can be replaced by real CPS reconfiguration trajectories.

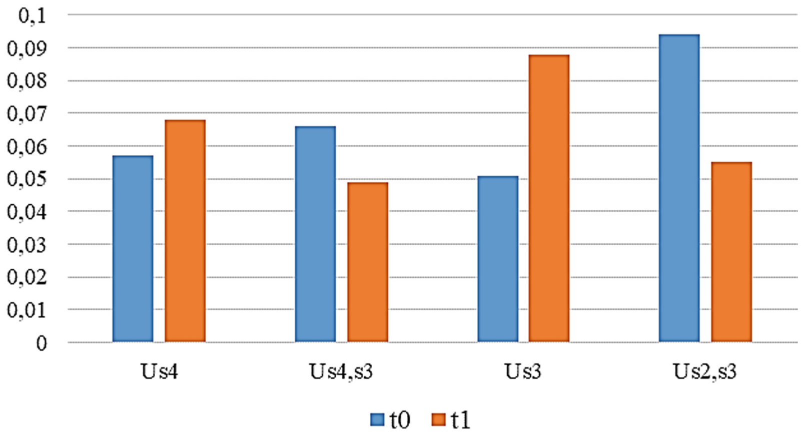

Fig. 4. Comparison results of estimates $u_{s_4}(t_p)$ and $u_{s_{if}^i, s_{if}^j}(t_p)$.

The results of modeling estimates of the elements interrelationships in CPS indicate a noticeable spread of values in various situations requiring the use of the concept of flexible functions, which can be useful when making decisions about reducing the cost and resource intensity of processes in CPS, for example, when readjusting taking into account the degradation processes of the elements of production systems themselves.

4 Conclusion

The enlargement of the component composition of production systems causes possible loss of information in the description of each element associated with the analysis of the element significance and its relationships with other elements, taking into account the variable structure. The proposed aggregated approach takes into account the uniqueness degree of system components and changes in their significance by taking into account the inclusion degree of the component in the system. This makes it possible to refine solutions for managing the functioning of production systems, taking into account the variable structure. Using the example of the problem of modeling the degradation process of the production system as a whole and applying the proposed approach, it is possible to take into account the uniqueness degree of the system components and the change in the significance of the system components due to degradation processes.

The authors suggest further research in the direction of creating a decision support system for a preliminary assessment of the resource intensity and efficiency of the CPS reconfiguration process.

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