A study of reconfigurable production system performance

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Abstract. The article studies the methods of evaluating the effectiveness of production is built on the basis of a flexible, reconfigurable systems capable of performing fast-changing market demands. Examines the history of formation of the concept of efficiency of organization of flexible production and its main parameters estimation. Based on the performance of the production system as a communication channel, describes the main performance characteristics of the configurable production systems. Described indicators are General and do not depend on the specific application of the system, which is especially important to determine the appropriate standard values. The time required for calculation of the indicators is determined on the basis of the known methods and the proposed approach, which provides a clear semantic definition of universality, flexibility, mobility and productivity, thus strictly linking the indicators together.

1 Introduction

Production performance in machine-building industry is influenced by a variety of different technical, economic, social and organizational factors.

The problem of the production performance in machine-building sector comes out on all production stages: from design and development of specifications to warranty service. However, to a great extent, the performance is determined by the quality of production process preparation, including the design phase and implementation of process technology, engineering, manufacturing, debugging, tooling and process planning.

Given the fact that modern machine-building facilities are inherently discrete, with a very high degree of variability of process solutions and production organization, we need to examine the methods for evaluating the performance of facilities built on flexible and reconfigurable systems capable of meeting the fast-changing market demands.

The assessment of reconfigurable production system performance has been at issue for a long time. Franz Pleshak proposes using the degree of flexibility compliance with its actual potential value as a criterion to assess the performance of flexible production systems (FPS) [1]. At the same time, the concept of potential flexibility introduced by him is understood as the ability of the system to respond to changes in input and output variables, as well as production conditions without any loss of stability and effectiveness. In other words, the

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faster the system provides an adequate response to changes in operating conditions, the higher is its potential flexibility.

V.N. Vasiliev believes that FPS performance should be determined by the degree of the process cycle reorganization, which results in replacing humans with more effective robots, ensuring integration of production, reduced duration of the production cycle, and increased productivity and quality [2]. He suggests assessing the system flexibility by performance groups, such as versatility, adaptability, tolerance to deviations of blank parameters, and repeatability, i.e. the ability to return to the work performed before the system was reconfigured.

P.I. Chinayev, V.V. Cherednikov, and V.E. Bolnokin suggest using a poly-criterial system of indicators to assess the FPS performance [3]. The performance may be assessed using the indicators from groups, such as the FPS performance, capital expenditures and return on investment, cost, energy consumption, material consumption and labor intensity of production.

G.A. Vasiliev and Y.V. Lapaiev suggest assessing the FPS performance by blocks [4]. The assessment system is based on the principle of search for unused reserves (equipment productivity growth, skill development, increased tool stability, etc.).

V.G. Sokolov and V.A. Smirnov believe that the availability of reserves is a compulsory, but not the only principle of evaluating the FPS performance [5]. A key approach to improve performance is to increase structural flexibility of the system, while assessment of flexibility, adaptability and mobility of the system is the main path to assess the FPS performance.

2 Formulation of the problem

Thus, the assessment of reconfigurable production system performance, its operation and development is a very complex and ambiguous task, the solution of which requires a continuous comparison between the current and future (prospective) performance. The current trend of increasing the level of industrial production automation and continuously changing preferences of the customer (consumer) require applying a performance criterion of a reconfigurable production system, such as continuous improvement of its flexibility. Production flexibility is an essential characteristic of any modern competitive enterprise defining its performance in general. Stabilization of the flexibility level at any point to be reached in the future may lead to a reduced customer satisfaction, lower product quality, and higher cost. Consequently, these processes cause a decrease in demand for the manufactured products, production volumes, increased costs and reduced effectiveness.

Presentation of the production system by a communication channel can be used to generate design solutions. One of the most important provisions of the information theory is the fact that an optimal message transmission rate is achieved only when the communication channel parameters are calculated based on the structural and statistical analysis of the message flow. In other words, the proper characteristics of a particular order flow input into the production system determine the optimal process environment for this flow.

Inflow of orders shall mean a set of information models of the products being considered (in time) in the order they are received. Like any data flow, the inflow of orders can be fully characterized by the amount of information transmitted per unit of time (determining the production system performance), semantic (meaningful, qualitative) content of this information (determining the technological methods of the production system) and, in conjunction with the first characteristic, adaptive capabilities of the production system.
3 Formulation of the problem

Let’s consider the basic performance characteristics of reconfigurable production systems (RPS).

The versatility of the system ($m_c$) is the convolution of quality characteristics of the products reproduced by the system. In quantitative terms, $m_c$ option is defined by the expression:

$$m_c = \sum_{i}^{s} \mu_i .$$

where $s$ is the quantity (number of descriptions) of various characteristics (range) reproduced by the system;

$\mu_i$ is the power of each characteristic of the PS 'consumer' quality.

For example, for a lathe, the versatility to reproduce cylindrical surfaces is defined as the ratio of the diameter range $(D_{\text{max}} - D_{\text{min}})$ vs the discrete (error) by axis $Y(\Delta Y)$.

Potential system flexibility level ($f_c^{\text{max}}$) is the level of RPS reactions diversity versus the time resource used for this purpose ($T_c$):

$$f_c = \frac{\log_2 m_c}{T_c}, \text{ bit/s} .$$

Where $T_c$ is the time to reproduce $m_c$ characteristics, i.e. lead-time.

RPS flexibility level ($f_c$) is the actual level of a variety of system reactions versus the actual system time consumption:

$$f_c = \frac{-\sum_{i}^{m_c} P_i \sum_{j}^{m_c} P(j/i) \log_2 P(j/i)}{T_c}, \text{ bit/s}$$

where $P_i$ is the probability of using the $i$-th state of the system during the order flow processing (during $T_c$ time);

$P(j/i)$ is the probability of RPS transition from the $i$-th to the $j$-th state (during $T_c$ time).

As follows from expression (2), the RPS flexibility level is determined by both system characteristics and structure of a particular inflow of orders.

The system throughput ($ST_c$) is the overall performance or PS release pace:

$$ST_c = \frac{I_0}{T_c} .$$

Thus, the PS conformity to its official designation is determined by implementation of a system of inequalities:
The difference between the planned and actual indicators determines the system redundancy.

The nontrivial conclusions should include the fact that (as follows from expressions (1) and (2)), the system flexibility level (reaction diversity) depends on the total time of the system operation (and not only on the re-adjustment time).

However, if the RPS product consumer does not care what resources were used to fulfill its order within the required time, the internal structure of the time consumed is paramount and crucial for the product manufacturer and system creator. Therefore we need to introduce additional RPS performance indicators:

System response time \((T_R)\):

\[
T_R = \sum_{i}^{m_c} P(j/i) t(j/i), \text{ s}
\]  

(4)

where \(t(j/i)\) is the time of the system transition from the \(i\)-th state to the \(j\)-th.

System mobility \((M_c)\) is the RPS reaction implementation pace:

\[
M_c = - \frac{\sum_{i}^{m_c} P(j/i) \log_2 P(j/i)}{T_R}, \text{ bit / s}
\]  

(5)

Just like in relation of the reaction diversity level, it is advisable to measure the potential mobility (based on the condition of equal probability of the realization of all states) of the system:

\[
M_{c, \text{max}} = \frac{\log_2 m_c}{T_R}, \text{ bit / s}
\]  

(6)

As follows from expression (5), the system mobility is characterized by the average speed of the RPS state change (re-adjustment) and, in contrast to the flexibility level, it only takes into account the time to prepare the RPS to generate a desired shape and structure of a new product. The value reciprocal to mobility describes the delay time to change the system status.

System shape and structure formation performance \((PS_f, PS_s)\):

\[
PS_f = \sum_{i}^{m_{sc}} \frac{I_{di}}{t_{di}}; \quad PF_s = \sum_{j}^{m_{sc}} \frac{I_{sj}}{t_{sj}} \quad \text{b.u. / s}
\]  

(7)
RPS shape forming performance in a $j$-th state is defined by formulas (3) and (5). One should distinguish between the system shape formation performance and its element shape formation performance (modules, lines, sections etc.). In the first case, $t_f$ value should cover all stages of transforming information about the product into the finished product, so the RPS shape formation performance will be determined by the subsystem at the minimum capacity.

The time required to process $I_0$ information volume consists of four components, the readjustment time ($T_n$), time for shape and structure formation ($T_s, T_f$), and time for production optimization ($T_{opt}$) and unproductive time loss ($T^*$):

$$T_c = T_{opt} + T_n + T_f + T_s + T^* \leq T_0.$$ 

During production, RPS processes the amount of information greater (very often much greater) than the value of its own information about the product ($I_0$). A part of this redundant information is caused by the need to ensure the noise immunity, and the other part, providing for RPS management, is caused by a multi-stage and multi-phase process of raw material information transmission, as well as raw material preparation for information perception. For example, the information contained in the part assembly drawing, during assembly is "supplemented" with information on position of parts prior to assembly, about the path of the robot gripper movement, etc. [6].

Therefore, to assess the RPS performance, it is advisable to introduce the value (factor) of production perfection ($\Psi_c$), reflecting the ratio of the amount of information contained in the products versus the total amount of information ($I_\Sigma$) converted by RPS during production of these products:

$$\Psi_c = \frac{I_0}{I_\Sigma} = \frac{I_0}{I_0 + I_{nn}} \leq 1.$$ 

(8)

where $I_{nn}$ is the volume of information identified by a specific technology and specific production process.

For example, for the RPS implementing the cutting methods:

$$I_{ip} = I_{fm} + I_{tm} + I_s + I_{org} + I_n + ...$$ 

(9)

where $I_{fm}$ is the information required to ensure operation of the shape forming modules (machine tools), including coordination working movements, tool orientation, etc.;

$I_{tm}$ is the information required for operation of the tool management subsystem (tool selection, change, replacement, recovery, etc.);

$I_s$ is the information required for the transport subsystem operation;

$I_{org}$ is the information required for the production organization;

$I_n$ is the information required to ensure the RPS reliability.

In general $\Psi_c$ is closer to unity when the process discreteness and the number of RPS auxiliary and supporting operations are smaller. The production perfection factor is a
criterion similar (by importance) to the machine and process efficiency. Its use can significantly increase the degree of objective assessment of technical solutions quality both during the macro-design and RPS development prediction, in particular, the production means in general.

4 Conclusion

The above RPS performance (quality) indicators are general in nature and do not depend on a particular purpose of the system, which is especially important to determine the appropriate standard (reference) values. The time required for their calculation (including $T_R, T_c$) is determined in the usual manner on the basis of known techniques (taking into account, for example, parallelism and the degree of time-overlapping of various transitions). It should also be emphasized that the proposed approach ensures unambiguous semantic definition of a generic flexibility, mobility and performance, while strictly enough linking the listed indicators. [7, 8]

The terms such as "organizational", "structural" and "parametric" flexibility found in various sources [9] reflect only a way to ensure flexibility and are of no greater value than, e.g., "organizational performance." Also, the flexibility as an opportunity to change internal ties or elements of the system to ensure reliability and survivability should not be identified with RPS. Certainly, the diversity of the inflow of orders or system reactions can be assessed using any other methods, but the information theory apparatus is preferred because the conversion of information about the product (using the matter and energy values) is the primary entity and content of any technological system.

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