Modeling of digital manufacturing of electronics production and product quality assurance

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Abstract. Intensive development of digital production in accordance with the concept of "Industry 4.0" is the most important direction of innovative development. The main elements of the concept are being introduced into the production of electronic products in demand in all spheres of human activity. To create new objects that represent the concept of "Industry 4.0", it is necessary to introduce technological innovations in the electronics industry. This is achieved by solving urgent problems of analyzing the system properties of the means of production and ensuring product quality. Therefore, the purpose of the article is to ensure the quality of electronic products on the basis models and techniques for analyzing the means and processes of electronics production. To achieve the goal, the development of digital production is considered within the framework of a structural, functional and information description. The resulted modeling results of stages a manufacture life cycle have allowed to estimate reached level of production quality at perfection of subsystems of automatic installation of printed-circuit boards.

1. Introduction

The existing technologies for the automatic installation of printed circuit boards are constantly evolving, but the equipment remains composition consistent with the basic structure. Continuous improvement and miniaturization of the electronic component base puts forward new requirements for equipment. Quality assurance is achieved by improving the characteristics of equipment, but the influence the "human factor" and the lack of consideration the mutual influence of the parts the production line remain factors of uncertainty in the production process.

Intellectual solutions in the field of inter-machine communications (M2M) play a special role in the development of IoT. This is the largest segment of the IoT market, connected with the integration of Internet things and "small" ad hoc IoT with larger systems. Introducing the elements of the "Industry 4.0" concept has opened new opportunities for ensuring the quality of electronic products both on the basis of more and more complete "digitization" of production, and at transition to a full digital life cycle of production.

In article on the basis of world tendencies and own experience it is offered to introduce elements of the concept "Industry 4.0" step by step, on the basis of the analysis of means and processes of electronics production within the framework of structural, functional and information description. Solving the problems of system analysis and developing models for improving production efficiency and modeling processes created the necessary methodological basis for ensuring the quality of products.

2. Structures of the technological line of automatic assembly of printed circuit boards

The necessary functional organization and the possibility of its building up with technological innovations are the basis for choosing the option of the structure of the automatic circuit board assembly line, presented as a system. Technical re-equipment is a key factor for the formation of more competitive production. It is aimed at improving the consumer properties of the produced products that make up its quality, as well as increasing the technological flexibility of the production process. The process of re-equipment of production is continuous, and therefore, after analyzing the results of introducing technological innovation, a transition to the stage of monitoring the state of production takes place. Thus, the process of technical re-equipment is cyclical, beginning with the discovery of a discrepancy between the actual parameters of the facility (fixed productive assets), new requirements and norms, technical conditions and quality indicators determined by the market, and ending with the decision to develop and implement a specific technical re-equipment project.

Here it is appropriate to use the idea of creating a new product on the basis structure that is not new and is reduced to the tasks of forming options and choosing the optimal ones. In [1], the intuitive "structural" approach to creating a new product is presented as the selection of some basic minimum set of tools for the subsequent enhancement of functionality in order to perform increasingly complex tasks.

The basic structures are functionally necessary (FNS) and functionally-sufficient (FSS) structures.

Definition [1]. The structure of the SFS is designated as a functionally necessary structure (SFN), designed to perform a defined class of the same purposes, functions, tasks, in which there is no kind of redundancy, and the minimum values of quality indicators from a given set forming an integral quality criterion (IQC) are achieved:

$$IQC:= \{Q_i\}, S_{FNS} \in \{S\}; \{Q_{iFNS}\}=\{Q_{iFNS}: \forall i, Q_{iFNS} \leq Qi\}.$$

Functionally-sufficient structures (FDS) are characterized by the presence of some redundancy, which is permissible within the limits of given constraints, in this connection, the study of structures based on the coefficients of significance of its constituent elements, presented in [1], acquires great importance.

The [2] standards and other known examples [3] use a line that meets the requirements of IPC and SMEMA for electrical and mechanical compatibility as a functionally necessary structure.

Modern industrial technologies require the creation of a competitive basic hardware structure, which is an integration platform for the Internet of things and ensures the acquisition, storage, processing, visualization of data and their integration at all levels of the enterprise. The M2M platform of the electronics manufacturing enterprise will contain universal device drivers on all production facilities of the enterprise, allowing to connect any industrial or custom Iot device under the encoded connection of "foggy computing". The use of low-bandwidth channels will ensure the security of the transmission of commercial secrets of the enterprise.

To create an integration platform for the Internet of things, it is necessary to build an ontology of the enterprise and databases, which are the detailing of work at all stages of the enterprise's life cycle from the stage of purchasing components to shipping to customers, and using the Design for Manufacturing (DFM) concept to take a set of measures to define possible risks and problematic parts that could adversely affect the production process. Using the tools of the DFM will allow to ensure the elimination of inconsistencies in accordance with the requirements of IPC standards during the implementation of the phase. One of the most important tasks for detailing processes and creating knowledge bases of an enterprise is the disclosure of uncertainties. However, the correctly executed modeling process does not remove the uncertainty, but contributes to the understanding and management of complex risks, as well as the analysis of their consequences.

Figure 1. Electronics production line.

The introduction of technological innovations provides new functional and information support provided by the concept "Industry 4.0" using the elements of the concept of M2M, DFM, BOM, ID-identifiers. Examples of functional and information support of technological innovations are given in table 1.

Table 1. Examples of functional and information support of technological innovations.

Technological innovation	Functional provision	Information Support	Quality assurance
M2M	Parametric model of the process, means of storage and processing of large data, accessible user interface.	Device Drivers, Internet of Things.	Correction of technologies based on quality control.
Database Solder Paste Inspection (SPI)	Provides both two-dimensional and three-dimensional control of paste application.	3D-inspection is realized due to the proven method of projecting strips, as a result of which a three-dimensional image is formed. Recognition of three-dimensional images occurs with further mathematical processing.	Correction of materials and finalization of products of technologies based on quality control.
Database Automated Optical Inspection (AOI)	Provides the storage of models of standards, the process of identifying defects and minimizing the number of false failures. Allows you to store all found defects and confirm them before changing the work program. If there are conflicting monitoring results, the disputable parameters are displayed on the screen.	Digital model of the standard.	Ensures compliance with quality standards.
Integrated database	The knowledge base integrates databases, data on technological operations and materials, allows finding the necessary information. Contains a systematic list of defects for different stages of production, an interface for entering new data by the user.	Means for presenting specific and fuzzy knowledge in a given domain, ontology.	Continuous quality improvement based on a parametric model, fuzzy descriptions or under uncertainty.

The structures of the subsystems, including M2M and the knowledge base, are shown in fig. Presented basic structure of interaction of elements of the concept "Industry 4.0".

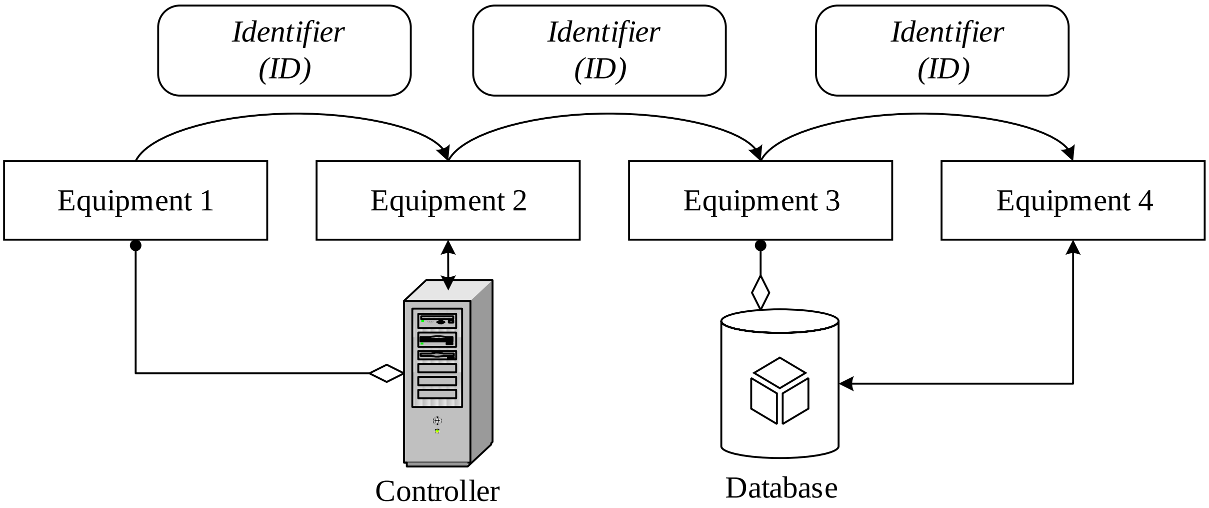

Figure 2. Functional support of the production process.

The questions of the formalized description of the given quality indicators and the integral quality criterion are considered in [1] and other works and are not presented here. Features of the construction of models, methods and criteria applied to the introduction of technological innovation require special study. This is due to the fundamental uncertainty of innovation processes. Thus, the solution of the quality assurance problem in this case involves the use models and methods for uncovering uncertainties.

However, an analysis the uncertainties associated with the risks of quality reduction can be supplemented by models and methods for analyzing new opportunities. Such opportunities arise when introducing technological innovations, and their effectiveness can be estimated quantitatively.

3. Functional description and mathematical model of the basic production structure

Technical re-equipment is a key factor for the formation more competitive production. It is aimed at improving the consumer properties of the produced products, which make up its quality, and also to increase the technological flexibility of the production process.

For the phased introduction of technological processes in digital electronics production, it is necessary to create databases for Solder Paste Inspection (SPI), Automated Optical Inspection (AOI) and an integrated database of all production processes. To create an intellectual software system, it is required to write computer programs based on fuzzy logic and allow the machine to make a decision on its own, which increases the productivity of the manufacturing process for the manufacture of electronic products. When developing the model of the production process, it is required to perform the operational detailing of the technological process. Using databases, it is easier to find and select the necessary production design tools for the phased development of electronic products. The creation of such software is determined by the insufficient degree of elaboration of the questions of modeling the production process in the framework of the creation of innovative technological systems implemented within the framework of the "Industry 4.0" concept.

The urgency of production of innovative electronics, its miniaturization and import substitution leads to the need to develop a process production model, as well as new methods for modeling technological processors to improve their quality.

The mathematical model of processes based on Markov chains was proposed in [4]. To model the processes in this paper we use the Kolmogorov equations. On the basis of this model are all the probabilities of states as a function of time, the volume of the batch produced and the intensity of the equipment loading. In terms of quality, these probabilities determine the estimates of non-conforming products when performing individual operations and final marriage. For a detailed presentation of the production process and subsequent interpretation of operations in a formalized form, modeling is used in the iThink program.

On the basis of the state graph of the production process are all the probabilities of states as a function of time. To this end, Kolmogorov's equations are formulated and solved, the differential equations in which the unknown probabilities are the probabilities of states.

The production process for the serial production of the electronics batch consists seven steps, shown in figure 3.

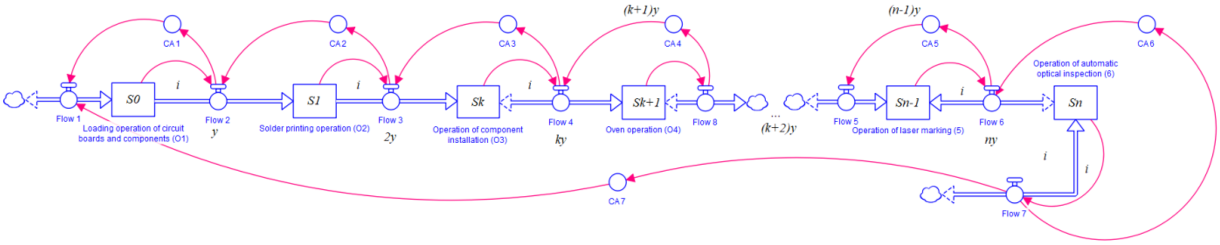

Figure3. Production process of batch production of electronics.

$$i = \mu \tag{1}$$

The batch at the initial stage *i* transfers the entire system from any state $S_k(k=\overline{1,n-1})$ in the subsequent state S_{k+1} the transition probability is the same and is equal to *i*.

To determine single-channel final probabilities, the Kolmogorov system of equations is used:

$$\begin{cases} -\lambda p_0 + yp_1 = 0 \\ \text{L} \\ \lambda p_{k-1} - (\lambda + ky) p_k + (k+1) yp_{k+1} = 0, k = \overline{2,n-1} \\ \text{L} \\ \lambda p_{n-1} - nyp_n = 0 \end{cases} \tag{2}$$

The normalization equation for the system is:

$$p_0 + p_1 + ... + p_n = 1 \tag{3}$$

Solution of the system

$$p_0 = \frac{1}{\sum_{\lambda=0}^{n} \frac{a^{\lambda}}{\lambda!}}, p_k = p_0 \frac{\alpha^k}{k!}, k = \overline{1,n} \tag{4}$$

where

$$\alpha = \frac{\lambda}{y} \tag{5}$$

- this is the volume of the produced batch (or this can be the intensity of the loading of equipment)

$$p_{f7} = p_n = p_0 \frac{\alpha^n}{n!} \tag{6}$$

where p_{f7} - the probability of inconsistency at the end of the production process (for single-channel final probabilities).

According to the formulated equation, the probability of a marriage is equal to the probability p_n Kolmogorov's system of equations for multichannel total probabilities:

$$
\begin{cases}
-\lambda p_0 + yp_1 = 0 \\
\quad \cdots \\
\lambda p_{k-1} - (\lambda + ky)\, p_k + (k+1)\, yp_{k+1} = 0, k = \overline{2, n-1} \\
\quad \cdots \\
\lambda p_{n-1} - (i + ny)\, p_n + nyp_{n+1} = 0 \\
\quad \cdots \\
\lambda p_{n+k-1} - (\lambda + ny)\, p_{n+k} + nyp_{n+k+1} = 0, k = \overline{1, m-1} \\
\quad \cdots \\
\lambda p_{n+m-1} - nyp_{n+m} = 0
\end{cases} \tag{7}
$$

The normalization equation for the system is:

$$\sum_{k=0}^{n+m} p_k = 1 \tag{8}$$

To solve the equation, it is necessary to introduce an additional coefficient β. The coefficient will be a measure of the load per stage.

$$\beta = \frac{\alpha}{n} = \frac{\lambda}{ny} \tag{9}$$

The solution of the Kolmogorov system of equations is expressed in terms of the probability of system downtime p_0.

$$
p_0 = \begin{cases}
\left(\sum_{k=0}^{n} \frac{n^k}{k!} \beta^k + \frac{n^n}{n!} * \frac{\beta^{n+1}(1-\beta^m)}{1-\beta} \right)^{-1} \\
\left(\sum_{k=0}^{n} \frac{n^k}{k!} + \frac{n^n}{n!} * m \right)^{-1}, \beta = 1
\end{cases} \tag{10}
$$

$$
p_0 = \begin{cases}
\left(\frac{n^k}{k!} \right) \beta^k p_0, k = \overline{1, n} \\
\left(\frac{n^n}{n!} \right) \beta^k p_0, k = \overline{n+1, n+m}
\end{cases} \tag{11}
$$

Probability of marriage is the probability that the system is in a state S_{n+m}

$$P_{fail} = p_{n+m} = p_0 \beta^{n+m} \frac{n^n}{n!} \tag{12}$$

- the probability of inconsistency at the end of the production process (for multi-channel final probabilities).

Thus, on the basis of modeling, the proposed universal model makes it possible to determine the probability of the appearance of defective products at the end of the production process and all the probabilities of states as a function of time.

For the gradual introduction of technological innovations in the model, it is possible to introduce the stages and values of parameters for a particular production.

For definiteness, as an example, consider a model that describes the limiting probabilities of all states of stages on the basis of a detailed description of the interaction of production process links.

The model consists of seven elements of the production process, namely:

1. loading operation of circuit boards and components,
2. solder printing operation,
3. solder paste inspection,
4. operation of component placement,
5. oven operation,

6. operation of lasermarking,
7. operation of automatic optical inspection.

Managed manufacturing process of manufacturing electronics in the package of structural mathematical modeling is presented in figure 4.

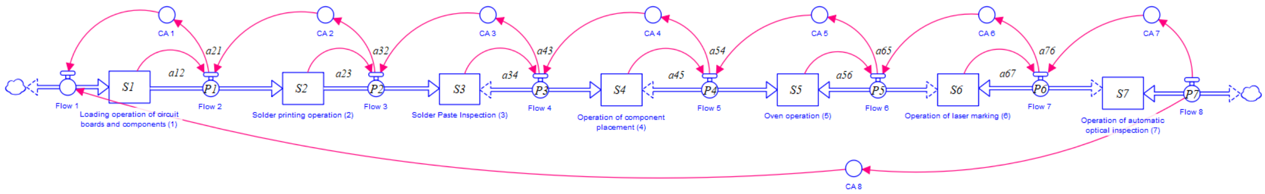

Figure4. The production process, consisting of 7 stages.

Consider the ordered set of states of production of electronics S_1, S_2, S_3, S_4, S_5, S_6, S_7.

Transitions can only be carried out sequentially, i.e. from the state 1 and 2 and vice versa in the event of a marriage. All transient flows translate the production process along the arrows with the corresponding intensities: $a_{k,k+1}$ or $a_{k+1,k}$.

In accordance with the model constructed in iThink, algebraic equations for limiting probabilities of states of the production process are compiled and solved (the equations are made up of the possibility of transition from each previous state to the next).

When solving Kolmogorov's differential equations, the probabilities of states are:

For S_1 $\quad \alpha_{12}p_1 = \alpha_{21}p_2$ (13)

For S_2 $\quad (\alpha_{23}+\alpha_{21})p_2 = \alpha_{12}p_1 + \alpha_{32}p_3$ (14)

The reduced view for S_2 $\quad \alpha_{23}p_2 = \alpha_{32}p_3$ (15)

For S_3 $\quad (\alpha_{34}+\alpha_{32})p_3 = \alpha_{23}p_2 + \alpha_{43}p_4$ (16)

The reduced view for S_3 $\quad \alpha_{34}p_3 = \alpha_{43}p_4$ (17)

For S_4 $\quad (\alpha_{45}+\alpha_{43})p_4 = \alpha_{34}p_3 + \alpha_{54}p_5$ (18)

The reduced view for S_4 $\quad \alpha_{45}p_4 = \alpha_{54}p_5$ (19)

For S_5 $\quad (\alpha_{56}+\alpha_{54})p_5 = \alpha_{45}p_4 + \alpha_{65}p_6$ (20)

The reduced view for S_5 $\quad \alpha_{56}p_5 = \alpha_{65}p_6$ (21)

For S_6 $\quad (\alpha_{67}+\alpha_{65})p_6 = \alpha_{56}p_5 + \alpha_{76}p_7$ (22)

The reduced view for S_6 $\quad \alpha_{67}p_6 = \alpha_{76}p_7$ (23)

For S_7 $\quad \alpha_{76}p_7 = \alpha_{67}p_6$ (24)

As a result of the formulation of the equations for the limiting probabilities of all states, the following system of equations is obtained:

$$\begin{cases} \alpha_{12}p_1 = \alpha_{21}p_2 \\ \alpha_{23}p_2 = \alpha_{32}p_3 \\ i\alpha_{34}p_3 = \alpha_{43}p_4 \\ \alpha_{45}p_4 = \alpha_{54}p_5 \\ \alpha_{56}p_5 = \alpha_{65}p_6 \\ \alpha_{67}p_6 = \alpha_{76}p_7 \\ \alpha_{76}p_7 = \alpha_{67}p_6 \end{cases} \qquad (25)$$

The normalization equation for the system has the form:

$$p_1 + p_2 + p_3 + p_4 + p_5 + p_6 + p_7 = 1 \qquad (26)$$

When analyzing the yield of suitable products, the state of the production stage is S_k, transition of the system from the previous state S_k in the following has the form S_{k+1}, transition S_k into a state of inappropriate production is S_{k-1}.

The solution of the system of equations has the form:

$$p_1 = (1+\frac{\alpha_{12}}{\alpha_{21}}+\frac{\alpha_{23}\alpha_{12}}{\alpha_{32}\alpha_{21}}+\frac{\alpha_{34}\alpha_{23}}{\alpha_{43}\alpha_{32}}+\frac{\alpha_{45}\alpha_{34}}{\alpha_{54}\alpha_{43}}+\frac{\alpha_{56}\alpha_{45}}{\alpha_{65}\alpha_{54}}+\frac{\alpha_{67}\alpha_{56}}{\alpha_{76}\alpha_{65}})^{-1} \quad (27)$$

$$p_2 = \frac{\alpha_{12}}{\alpha_{21}} p_1 \quad (28)$$

$$p_3 = \frac{\alpha_{23}\alpha_{12}}{\alpha_{32}\alpha_{21}} p_1 \quad (29)$$

$$p_4 = \frac{\alpha_{34}\alpha_{23}}{\alpha_{43}\alpha_{32}} p_1 \quad (30)$$

$$p_5 = \frac{\alpha_{45}\alpha_{34}}{\alpha_{54}\alpha_{43}} p_1 \quad (31)$$

$$p_6 = \frac{\alpha_{56}\alpha_{45}}{\alpha_{65}\alpha_{54}} p_1 \quad (32)$$

$$p_7 = \frac{\alpha_{67}\alpha_{56}}{\alpha_{76}\alpha_{65}} p_1 \quad (33)$$

Thus, the obtained values of the probabilities are refined in comparison with the general model, since they take into account the features of the interaction of the links representing the stages of production.

4. Mathematical model of production with introduction of technological innovations

As the initial model, we will examine the stages of the production process, using the control effect, the human factor presented in Figure 4. The model is a further development (figure 3) and differs by the justified introduction of direct and the elimination of unrealized feedbacks for the subsequent introduction of technological innovations. For certainty, the operations (CA3, CA7) performed by a person are presented. This state corresponds to the standard [2].

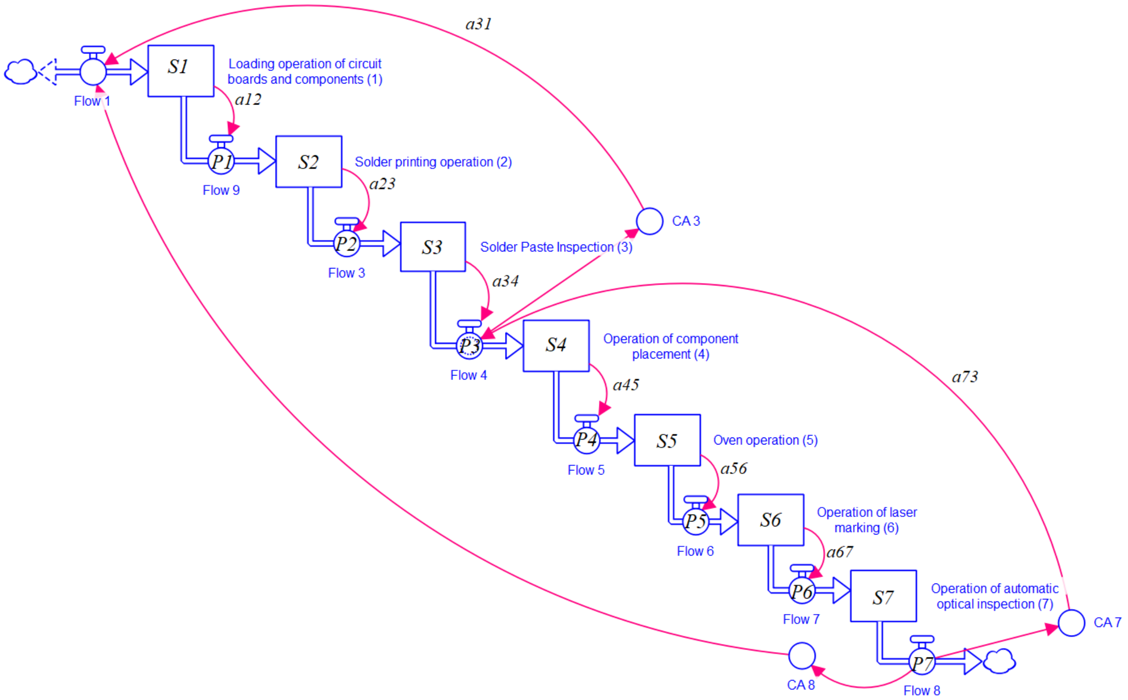

Figure 4. The stages of the production process, using the control action (control action), the human factor (person).

The introduction of technological innovations is carried out by replacing successive interoperational links with the enlarged operators presented by CA3, CA7. During the implementation of CA3, CA7 replaced with M2M and M2M SPI-OAI (figure 5). These operators correspond to the basic structure (figure 2).

The management of the production process is replaced by an intelligent control system. The intellectual system is a fuzzy controller with the ability to introduce or exclude the necessary conditions for the operation of the production process.

The operation of the systems is the inter-machine interaction.

The intellectual self-learning system is implemented in two stages:

- checking the solder paste,
- automatic optical inspection operation.

One of the elements of assessing the quality of products at the stage "testing solder paste" can be:

- coating the area with solder paste;
- filling the volume of the stencil;
- compliance with the shape of the hole;
- the presence of jumpers.

In the event that one of the indicators deviates from the predetermined satisfying limits, the system transfers the mounted PCB to the nonconformity state and independently decides on taking corrective actions to eliminate the nonconformity.

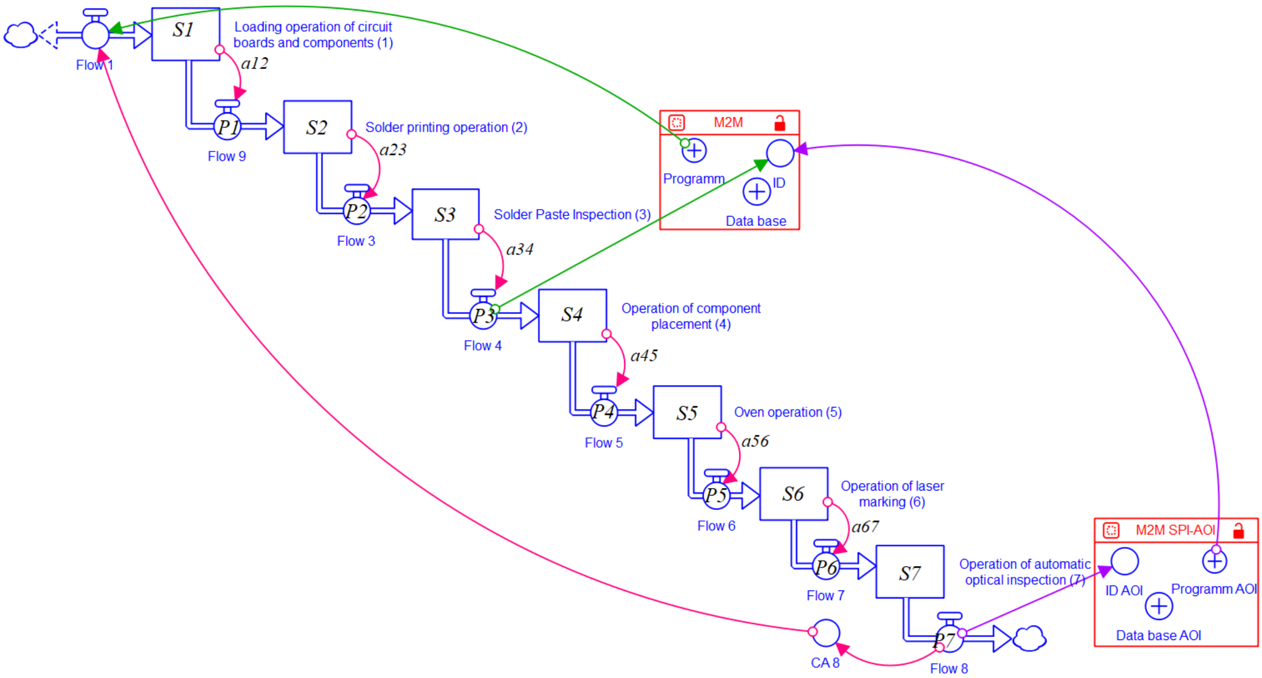

Figure 5. Stages of the production process, using the intelligent self-learning system of inter-machine interaction, built on the basis of the apparatus of fuzzy logic.

Creation of a detailed process model of the manufacturing process (figure 5) of the electronics manufacture, which has an open architecture that allows it to expand to solve new problems and use a single intellectual, self-learning information support built on the basis of the fuzzy logic apparatus, forming the "knowledge base" of the enterprise in which the all results and knowledge obtained as a result of the enterprise's activities will reduce the possible production risks associated with human skim factor and reduce the number of defective products.

5. Conclusion

The new models proposed in the article provide a description of the simple structures of the production process and the transition to technological innovations introduced in these systems. Innovations M2M and M2M SPI-OAI are elements of the concept "Industry 4.0", allowing to reduce the possible production risks associated with the human factor and reduce the amount of defective products. When developing models, the mathematical apparatus of the Kolmogorov equations was used to determine the limiting probabilities as a function of time and the means of structural mathematical modeling iThink.

These models allow to estimate the proportion of nonconforming products and final marriage and to provide ever higher quality in the implementation of technological innovations. The accumulation of experimental data in databases and the subsequent creation of a knowledge base creates the conditions for uncovering uncertainties, assessing risks and opportunities identified [6 -11]. For this it is supposed to use soft calculations and fuzzy logics in the ontological knowledge base with a frame structure. Compliance with quality requirements is initially described in fuzzy categories using piecewise linear membership functions in the tolerance field, the type of which is specified in the learning process. Integration of information from elements of digital production and operational knowledge in the knowledge base will ensure the quality of electronics products and minimize the human factor.

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