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# A METHOD DEVELOPMENT FOR MODELING THE TECHNOLOGICAL PROCESS OF PRINTED CIRCUIT BOARD PRODUCTION BASED ON THE Q-SCHEME

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## ABSTRACT

The article considers the development and modeling of the technological process of printed circuit board production based on the Q-scheme as an effective approach to optimizing production processes. A methodology is proposed that allows reducing the number of defects, improving product quality, and shortening the production cycle through digital modeling and automation of key stages. The use of the Q-scheme contributes to increasing productivity and adapting to the requirements of Industry 4.0, ensuring flexibility and efficiency of the technological process. The modeling results are presented, confirming the feasibility of implementing this approach in production practice.

**Keywords:** Printed Circuit Boards, Q-Circuit, Digital Modeling, Production Automation, Process Optimization, Industry 4.0, Electronic Manufacturing, Technological Process.

## INTRODUCTION

The development of the electronics industry and the growing demand for high-quality printed circuit boards (PCBs) necessitate the improvement of technological processes for their production. Modern requirements for electronic devices require increased accuracy, reliability and minimization of production costs, which stimulates the search for new methods and approaches to the manufacture of printed circuit boards [1]-[7]. And here different methods and approaches can be used [8]-[41].

One of the promising areas is the use of the Q-scheme, which allows to increase the efficiency of the technological process by optimizing the structural organization of production, reducing the number of defects and reducing the time for manufacturing products. The implementation of this technique ensures high repeatability of products, which is critically important for the mass production of electronic components. In addition, digital modeling of production processes based on the Q-scheme allows to predict possible errors at the design stage, minimize testing costs and improve the quality of the final product. The relevance of the study is also determined by the need to adapt technological solutions to the conditions of digital transformation of production, which is a key aspect in the development of the Industry 4.0 concept [42]-[48]. The use of modern software tools for modeling printed circuit board production processes contributes to automation, increasing productivity and competitiveness of enterprises in the electronics industry. Thus, the development and modeling of the technological process of printed circuit board production based on the Q-scheme is an important scientific and technical task aimed at improving electronic production and expanding the capabilities of modern production facilities.

## LITERATURE REVIEW

Since the requirements for the quality of printed circuit boards are very high and are increasing, many scientists are dealing with this problem. Many scientific works are devoted to this. Let us consider some of them.

Nassar, H., & Dahiya, R. in [49] propose to use multimaterial 3D printing in electronics. They note that it is expanding due to the ability to realize geometrically complex systems with simplified processes compared with conventional printed circuit board.

The paper [50] was designed to investigate the step-wise glycine leaching of the base and precious metals from waste printed circuit boards (WPCBs) as one of the most dominant and problematic e-wastes in today's world.

Scientists in [51] initiate a new model known as YOLO-v5 to detect defects in PCB. Therefore, there is a huge revolution going on in the manufacturing industry where the object detection method like YOLO-v5 is a game changer for many industries such as electronic industries.

Xie, H., and co-authors in [52] propose a method for detecting surface defects of printed circuit board based on improved YOLOv4. Experimental results showed that compared with other traditional and deep learning object detection models, the improved model has improved detection accuracy and detection rate.

The article [53] note that the pyrolysis mechanism of printed circuit board (PCB) without any electronic components and with a small amount of copper foil is not comprehensive at present. The study [53] found that the pyrolysis of waste printed circuit board (PCB) resin powder can be divided into four stages: evaporation of residual water on the surface or dissipation of other small molecules, oxidation of side chain groups of epoxy resin, decomposition of tetrabromobisphenol A and decomposition of pyrolysis residues.

Bhattacharya, A., & Cloutier, S. G. in [54] report a complete deep-learning framework using a single-step object detection model in order to quickly and accurately detect and classify the types of manufacturing defects present on Printed Circuit Board.

Next, we will present our vision of how to manage the quality of PCB.

## A METHOD DEVELOPMENT FOR MODELING THE TECHNOLOGICAL PROCESS OF PRINTED CIRCUIT BOARD PRODUCTION

Q-scheme for modeling the cyclic technological process (TP) of printed circuit board production is a graphical representation of the technological operations sequence with a cyclic nature, which includes the stages of manufacturing printed circuit boards with regular quality control and the ability to return to previous stages to correct defects. Such a scheme emphasizes quality control of each step and provides flexibility in the production process due to the possibility of repeated cycles to achieve the required product standards.

The following factors justified the choice of Q-scheme for modeling the cyclic technological process of printed circuit board production:

– real-time quality control, the Q-scheme provides for periodic quality checks after each critical operation. This allows for timely detection of defects and repetition of individual stages to correct them without the need to complete the entire process;

– reduction of repair costs, the cyclic process allows you to identify problems at an early stage, minimizing the cost of correcting defects and reducing the number of scrap at the final stages of production;

– resource optimization, with the help of a Q-scheme, material and energy resources can be better managed, providing savings by avoiding reprocessing of the entire product;

– automation integration, in modern printed circuit board production, which uses Industry 4.0 and robotic systems, Q-schemes allow integrating control and production systems into a single continuous process.

A mass service system (MSS) is a production, service, and management system in which homogeneous events are repeated many times, for example, in consumer service enterprises, in information reception, processing and transmission systems, automatic production lines, etc. The main elements of a MSS are objects served in a MSS (requirements or requests) and one or more serving devices with a queue. In an open MSS network, requirements come from outside the network and, after processing, leave it. In a closed MSS network, a certain number of requirements are always in it, moving from one MSS to another, but never leaving the MSS network. Using the MSS theory,

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the developed flexible automated production line of DP based on cyclic TP will have the following graphical representation, as shown in Figure 1

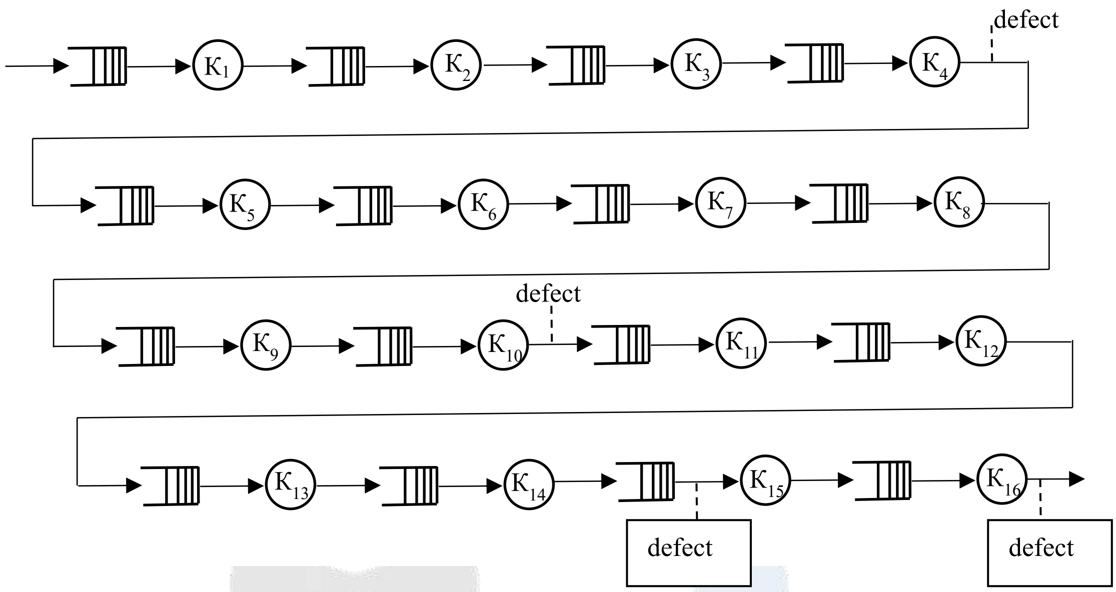


**Figure 1:** Graphical representation of the developed flexible automated production line of printed circuit boards based on cyclic TP in MSS elements

Based on the cyclic technological process of printed circuit board (PCB) production, presented in Figure 1, each stage can be described from the perspective of mass service systems. According to the graphic representation of the developed flexible automated production line of PCB based on cyclic TP in the QMS elements in the diagram, each node $K_i$, where $i$=1,2,3,….,16 is a separate service station. Each station processes a queue of orders or batches of boards and can be described using the QMS model of type *M/M/1*.

MSS models of type *M/M/1* were selected for modeling the cyclic technological process of printed circuit board production according to the following criteria:

– Poisson order flow, since the *M/M/1* model assumes that orders (batch or individual PCBs) enter the system according to a Poisson distribution, which is adequate for modeling random events. In the production of DP, this can be reflected as random delays or unevenness in the receipt of orders at different stages of the cyclical TP;

– Exponential service time, since the service time at each stage of the cycle, as assumed by the *M/M/1* model, is distributed according to an exponential law. This is suitable for modeling processing times at technological stations, such as drilling, coating, soldering or quality control, where the average service time varies;

– Single service station (single-channel system), assumes that each stage of PCB production, according to the *M/M/1* model, is considered as a separate station with a single service channel. This corresponds to the realities of production, where each operation is performed sequentially on one machine or at one workstation;

– an unconstrained queue, i.e. the *M/M/1* model assumes that the service queue can have an arbitrary length. In the cyclic PCB manufacturing process, this helps to model situations where a backlog of orders may occur at a certain stage, for example, when one machine is running slower or is delayed due to maintenance;

Thus, the *M/M/1* model is a reasonable choice for modeling the PCB manufacturing process due to its ability to adequately reflect the process of receiving and processing orders, as well as its ease of use for calculations and optimization.

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Let us introduce the following parameters to describe the process of modeling the cyclic TP of PCB production: $\lambda_i$ – the intensity of the flow of applications (the number of PCBs that arrive for service per unit of time); $\mu_i$– the intensity of service on each piece of equipment (the average execution time of one operation); $n_i$ – the number of PCB blanks in the queue for the equipment.

For each imposition of the cyclic TP of PCB production, the average queue length can be determined as:

$$L_q = \frac{\lambda^2}{\mu(\mu-\lambda)}, \quad (1)$$

$L_q$ – is an average queue length;

$\mu$ – is a service intensity on each piece of equipment (average time to complete one operation);

$\lambda$ – the intensity of the flow of applications (the number of PCBs arriving for service per unit of time).

This expression shows how many batches or individual boards are waiting for service at each stage. It is important to note that the system is considered stable only when $\lambda < \mu$.

Based on (1), we define the waiting time in the queue ($W_q$) as the average waiting time of an order in the queue in front of each piece of equipment, this can be determined by Little's formula as:

$$W_q = \frac{L_q}{\lambda}, \quad (2)$$

$W_q$ – is an average time spent waiting for service;

$L_q$ – is an average queue length;

$\lambda$ – the intensity of the flow of applications (the number of PCBs arriving for service per unit of time).

The probability of equipment occupancy (*P(z)*) can also be calculated as the probability that the equipment is occupied at a time equal to:

$$P(z) = \frac{\lambda}{\mu}, \quad (3)$$

$P(z)$ – is a probability of equipment being busy;

$\lambda$ – is an intensity of the flow of applications (number of DPs received for service per unit of time);

$\mu$ – is a service intensity on each equipment (average execution time of one operation).

In this case, the routing is a single-channel system for the production of printed circuit boards and means that all boards pass sequentially through each technological operation. Since each operation is served by only one piece of equipment, the requests move along the route from one stage to another in a strictly defined order, as shown in Figure 1. This routing can be described as follows:

– sequence of operations, all requests must pass through all stages of the technological process, such as drilling, coating, soldering, quality inspection, etc., in a strictly sequential order;

– limited number of equipment, since each stage is served by only one automated CNC machine or conveyor, each request must wait its turn if another request is already being served on this equipment. This creates a queue before each operation;

– queue system, if there is a queue, requests move along the route only after the completion of the operations. As a result, each PCB passes through all stages sequentially, waiting for its turn at each stage.

Thus, the route of passage in a single-channel system reflects the sequential movement of PCBs through all technological stages without the possibility of parallel service at each stage, which emphasizes the importance of queue management for process optimization.

The development of an algorithm for modeling the technological process of printed circuit board production is a key stage of the research, as it allows creating an effective tool for optimizing complex production operations. Printed circuit boards are the basis of modern electronics, and their production includes a multi-stage cycle with high requirements for accuracy, quality and speed. The general view of the algorithm for modeling the cyclical technological process of printed circuit board production is presented in Figure 2.

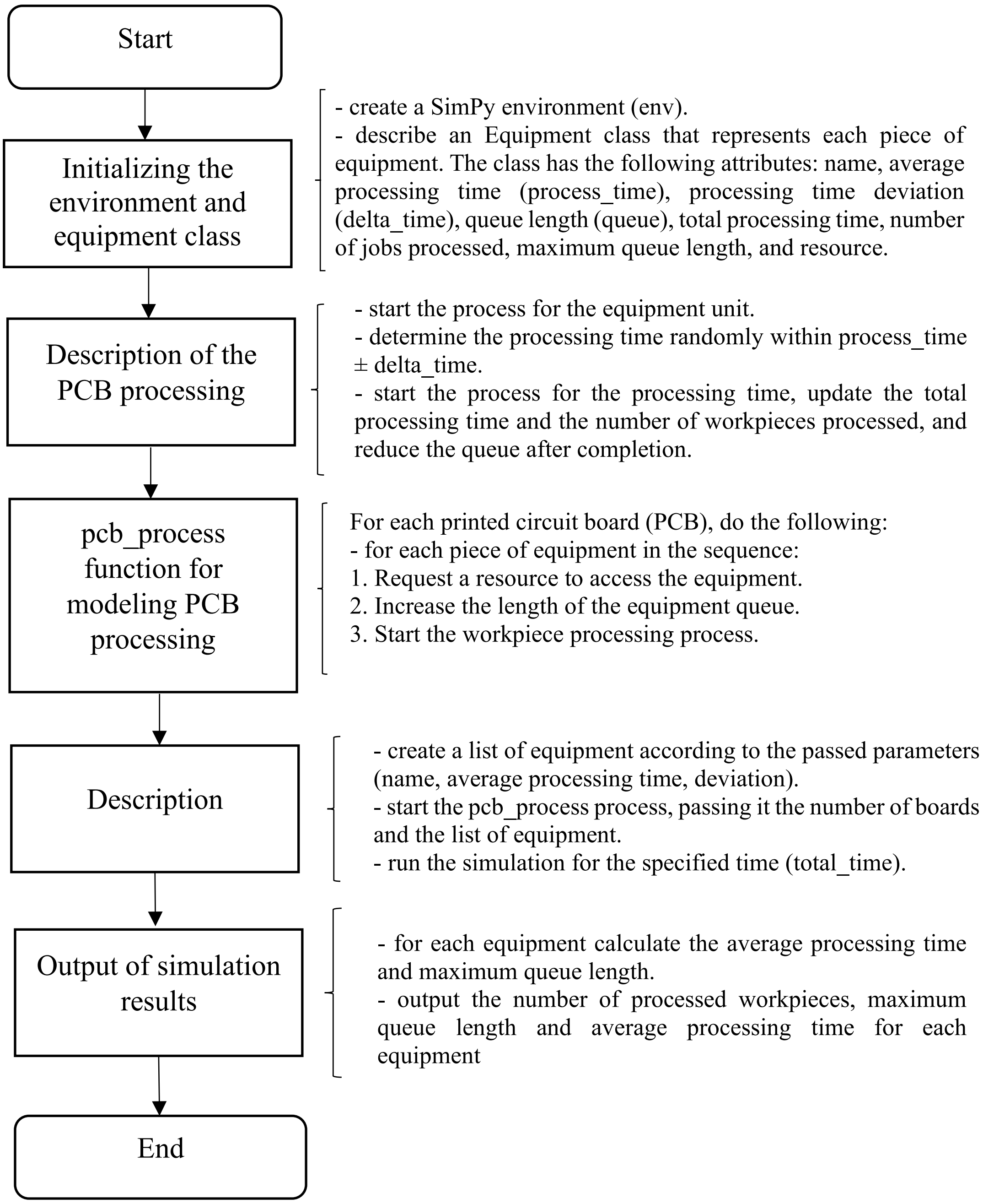


**Figure 2:** General algorithm of the program for modeling the cyclic technological process of printed circuit board production

## CONDUCTING EXPERIMENTS ON MODELING THE TECHNOLOGICAL PROCESS OF PRINTED CIRCUIT BOARD PRODUCTION

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The PCB manufacturing process simulation experiment consists of creating a simulation model that allows analyzing the efficiency of the passage of boards through various production stages. The main goal is to determine the load on individual stages and identify potential bottlenecks that can cause delays. The model simulates processes such as coating, drilling, conveyor movements, and other key operations. The experiment analyzes the number of boards processed over a certain period, the maximum length of queues in front of the equipment, the average time the boards spend in the queue, and the processing time at each stage. The goal is to identify stages where delays occur due to queue accumulation, which affects the overall productivity of the production line. The results of the experiment help optimize the number of equipment or process parameters to increase throughput. Carrying out simulations for different production volumes allows evaluating the efficiency of the process under conditions of variable demand, which is important for flexible planning of production capacities and improving productivity.

This approach allows you to determine at which stages of production delays may occur due to queue accumulation, as well as to assess the overall productivity of the production line. In addition, the results of the experiment will help to determine the optimal amount of equipment or change the parameters of the production process to increase throughput. Conducting a series of simulations for different numbers of boards and simulation times allows you to compare the efficiency of the production process under different conditions, which is especially important for production with high variability in order volumes. The task is also to optimize the time and resource costs at each stage, which provides more effective planning of production capacities and improvement of production productivity indicators.

The first simulation result with the following input data: Results for PCBs: 50, Simulation Time: 200 is presented in Table 1.

**Table 1:** Results obtained from the simulation of the cyclic technological process of printed circuit board production with the following input data: Results for PCBs: 50, Simulation Time: 200

| Equipment | Maximum queue length | Average time in queue | Average processing time for each equipment |
|---|---|---|---|
| Schmoll Maschinen MODUL 200 | 1 | 0 | 10,48 |
| FlexLink Modular Conveyor System | 1 | 0 | 4,93 |
| Orbotech Nuvogo 1000 DI | 1 | 0 | 8,28 |
| Koh Young Zenith Alpha AOI | 1 | 0 | 6,39 |
| Hitachi DR300 PCB Drilling Machine | 1 | 0 | 11,81 |
| Atotech Uniplate InPulse 2 | 1 | 0 | 8,27 |
| MEC Solder Mask Coating Line | 1 | 0 | 8,62 |
| Yamaha YSM20R Pick and Place Machine | 1 | 0 | 16,27 |
| Rehm V8 Reflow Soldering System | 1 | 0 | 10,01 |
| Takaya APT-1400F Flying Probe Tester | 1 | 0 | 11,91 |

The analysis of the results of modeling the cyclic technological process of printed circuit board production indicates the high efficiency of the production process under the given parameters. For each equipment, the maximum queue length was only one board, which indicates the absence of serious delays at any of the production stages. The average queue time is zero, which confirms the

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smooth transition of printed circuit boards between stages without the formation of queues. This indicates that the throughput of each device corresponds to the volume of production and that the equipment is not idle due to excessive load. The average processing time on each equipment varies from 4.93 to 16.07 units of time. Thus, the FlexLink Modular conveyor system showed the shortest processing time, while the Yamaha YSM20R Pick and Place Machine showed the longest, which can be explained by the difference in the complexity of the operations performed. It is also worth noting the relatively high processing time for stages such as drilling, soldering and testing, which is due to longer technological processes that require additional accuracy or quality checks. The results obtained show that, given the processing of 50 boards for 200 units of time, the production line capacity is sufficient to support a continuous production process without delays. For ease of analysis, we present the obtained data in the form of a combined graph, shown in Figure 3.

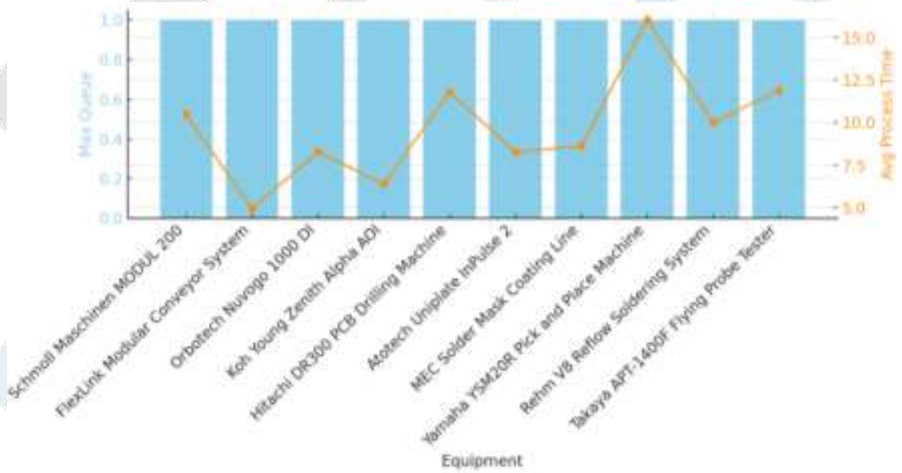


**Figure 3:** Combined graph of the obtained data of the first experiment

The results of the second simulation experiment with the following input data: Results for PCBs: 100, Simulation Time: 400 are given in Table 2.

**Table 2:** Obtained results of simulation of the cyclic technological process of printed circuit board production with the following input data: Results for PCBs: 100, Simulation Time: 400

| Equipment | Maximum queue length | Average time in queue | Average processing time for each equipment |
|---|---|---|---|
| Schmoll Maschinen MODUL 200 | 1 | 0 | 10,43 |
| FlexLink Modular Conveyor System | 1 | 0 | 5,40 |
| Orbotech Nuvogo 1000 DI | 1 | 0 | 8,34 |
| Koh Young Zenith Alpha AOI | 1 | 0 | 6,89 |
| Hitachi DR300 PCB Drilling Machine | 1 | 0 | 12,37 |
| Atotech Uniplate InPulse 2 | 1 | 0 | 10,21 |
| MEC Solder Mask Coating Line | 1 | 0 | 9,01 |
| Yamaha YSM20R Pick and Place Machine | 1 | 0 | 15,71 |
| Rehm V8 Reflow Soldering System | 1 | 0 | 10,73 |
| Takaya APT-1400F Flying Probe Tester | 1 | 0 | 14,13 |

Analysis of the results of modeling the process of printed circuit boards production shows that the maximum queue for each stage is equal to one, which indicates the efficient use of equipment and the absence of significant accumulation of work in front of any of the devices. The average queue time for all stages is zero, which indicates the optimal distribution of the load between the elements

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of the system and a high level of organization of the production process. However, the average processing time on different machines varies, being relatively short for devices such as the FlexLink conveyor system and the Koh Young Zenith Alpha automatic optical inspection module, and longer for more complex processes such as the selection and placement of components on the Yamaha YSM20R and testing using the Takaya APT-1400F. This can be explained by the different complexity of the operations performed at each stage. Such results allow us to conclude that the production line is able to maintain a continuous technological cycle without significant delays, thereby ensuring high productivity. For ease of analysis, we present the obtained data in the form of a combined graph, shown in Figure 4.

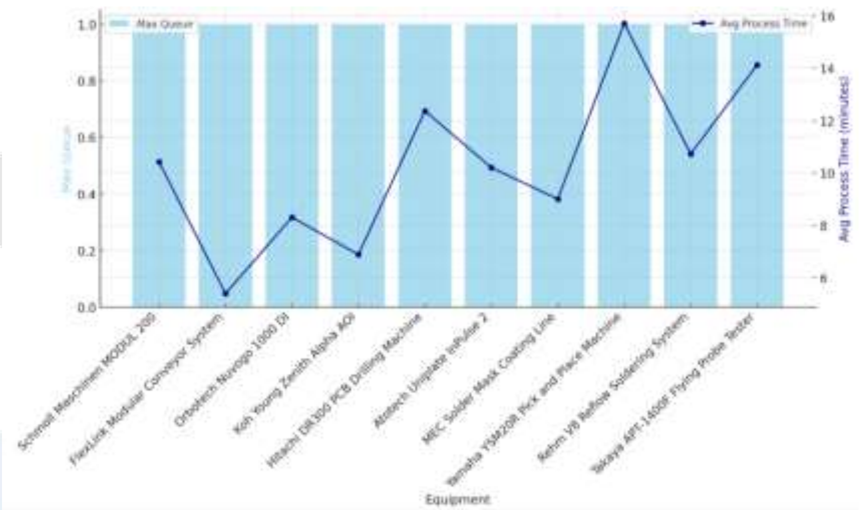


**Figure 4:** Combined graph of the obtained data of the second experiment

The results of the third simulation experiment with the following input data: Results for PCBs: 150, Simulation Time: 600 are given in Table 3.

**Table 3**: Obtained results of simulation of the cyclic technological process of printed circuit board production with the following input data: Results for PCBs: 150, Simulation Time: 600

| Equipment | Maximum queue length | Average time in queue | Average processing time for each equipment |
|---|---|---|---|
| Schmoll Maschinen MODUL 200 | 1 | 0 | 10,35 |
| FlexLink Modular Conveyor System | 1 | 0 | 4,80 |
| Orbotech Nuvogo 1000 DI | 1 | 0 | 8,27 |
| Koh Young Zenith Alpha AOI | 1 | 0 | 6,94 |
| Hitachi DR300 PCB Drilling Machine | 1 | 0 | 12,02 |
| Atotech Uniplate InPulse 2 | 1 | 0 | 10,39 |
| MEC Solder Mask Coating Line | 1 | 0 | 8,97 |
| Yamaha YSM20R Pick and Place Machine | 1 | 0 | 14,66 |
| Rehm V8 Reflow Soldering System | 1 | 0 | 11,18 |
| Takaya APT-1400F Flying Probe Tester | 1 | 0 | 13,30 |

The simulation results of the cyclic technological process of printed circuit board production demonstrate the efficient organization of the process with minimal delays in the queue before the equipment. The maximum queue value is equal to one for all equipment units, which indicates the absence of accumulation of boards before any production stage and ensures a smooth process. The

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average queue time is zero, which emphasizes the high throughput of the system and proper resource allocation. The average processing time for each stage varies depending on the complexity of the technological operation. For example, stages such as component placement (Yamaha YSM20R) and testing (Takaya APT-1400F) have a longer average processing time due to their high accuracy and complexity of the process. At the same time, conveyor systems have a significantly shorter processing time, reflecting their role in quickly moving boards between other stages. Overall, the simulation results confirm the balanced process and optimal use of resources, which avoids downtime and ensures uniform loading of each equipment unit.

For ease of analysis, we present the obtained data in the form of a combined graph, shown in Figure 5.

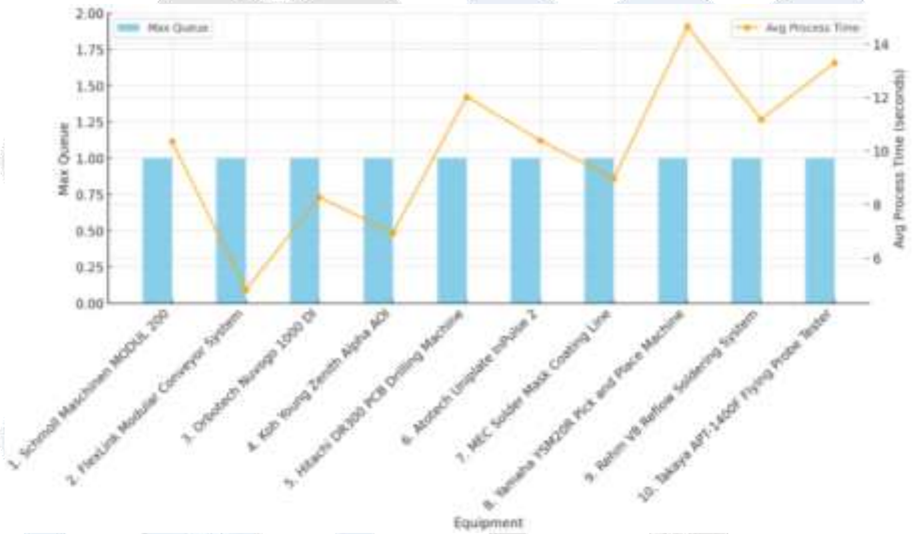


**Figure 5:** Combined graph of the obtained data of the third experiment

## CONCLUSION

The overall findings from the comparative analysis of the data for the three experiments show how increasing the number of printed circuit boards (PCBs) processed affects the processing time and average latency. In each experiment, the maximum queue of the equipment remained constant, indicating the stability of the system in terms of queuing, while the average processing time varied with the increase in the number of boards processed. For all experiments, there is a trend towards an increase in the average processing time for most equipment, which is likely due to the increase in the volume of work with the same infrastructure. In the first experiment, the average processing time ranged from 4.93 seconds for the FlexLink Modular Conveyor system to 16.07 seconds for the Yamaha YSM20R Pick and Place Machine, reflecting significant differences in the efficiency of the different equipment types. In the second experiment, with twice the number of boards, the average processing time on the different devices increased, in particular, for the FlexLink Modular Conveyor this indicator increased to 5.40 seconds and for the Yamaha YSM20R - to 15.71 seconds. This confirms that with a larger workload, even highly efficient equipment can experience some delays. In the third experiment, when processing 150 boards, a further increase in the average processing time is observed for most of the equipment, although in some cases the changes are minimal. For example, the average processing time for the FlexLink Modular Conveyor increased again to 4.80 seconds, and for the Yamaha YSM20R to 14.66 seconds. This result indicates that over time and with increasing workload, the strain on the equipment becomes apparent, which may require optimization to maintain high efficiency. Overall, the results indicate the importance of balancing performance with the ability to process a larger workload without significantly increasing time. Most equipment shows a gradual increase in average processing time in all experiments, indicating the need for potential improvements in the systems to increase their efficiency as production volumes increase.

Therefore, optimizing the performance of each device and the system as a whole is a key task to ensure stable operation under changing conditions.

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