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POSSIBILITIES OF INCREASING THE EFFICIENCY OF PRODUCTION SYSTEMS BY USING AN ADDITIONAL CAPACITIVE ELEMENT

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Abstract:
The continuity of the flow of materials needed for correct operation of manufacturing systems can be achieved using different means and control methods. These objectives can be achieved through the use of Total Productive Maintenance (TPM). Specific effects can also be achieved by using additional capacitive elements in device systems (manufacturing lines). In this paper to be considered is a system with a serial structure and an additional capacitive element (the position within the system and the capacity of the element are determined). The capacitive element divides the system into two subsystems: the part delivering the material to the buffer (DP) and the part receiving the material (RP). The time lost due to unplanned interruptions in the operation of the production system equipment is described by the MTTR (Mean Time to Repair) indicator. The analysis of the system's operation used the failure index, which is directly related to the MTTR index. To study the system, a method involving the analysis of states and a digital simulation are used. To assess the system with an additional capacitive, a production performance indicator is used. The obtained results allow for conclusions on the possibilities for improving the effectiveness of manufacturing systems using the proposed method.

Key words: manufacturing effectiveness, serial structure with buffer, system state analysis, system with a capacitive element, simulation research

INTRODUCTION

The diverse nature of manufacturing systems (e.g., the type of business, the scale of production) means that the methods for improving effectiveness which are possible to implement require deep analysis. Any assessment of a manufacturing system is complex. There are many measurable production indicators (KPI – *Key Performance Indicators*) which can be used to assess effectiveness. Among the most often used are:

- performance indicators – which the effectiveness of exploitation of resources,
- quality indicators – which assess the compliance of products with norms (e.g., the costs of bad quality),
- delivery timeliness indicators – which describe the degree to which orders are fulfilled (e.g., delivery timeliness),
- cost indicators – which analyse the costs of production (e.g., costs of materials, costs of downtime),
- downtime indicators – which assess the operation of machines and devices.

One of the most important KPIs used for the assessment of a production system is OEE (*Overall Equipment Effectiveness*), which measures the overall effectiveness of the way in which machines and devices are used [1, 2]. OEE takes into account three main factors: availability (operation time without downtime), performance (production tempo), and quality (number of good products) [3].

It is important to ensure the reliability and up-to-date data on the basis of which the indicators are calculated. This requires the implementation of appropriate systems for collecting and processing production data, such as MES (Manufacturing Execution Systems) or SCADA (Supervisory Control and Data Acquisition).

The aim of the research was to demonstrate that the appropriate use of an additional buffer can improve the efficiency of the production system.

Systems with a complex serial structure are often used in small and medium-sized enterprises (SMEs). The proposed method can be used in these enterprises to improve production indicators.

METHODS OF IMPROVING EFFICIENCY IN LITERATURE

One of the more important tasks in manufacturing systems is the maintenance of a steady flow of materials and information [4]. The main factors which cause unwanted interruptions in the operation of systems are disruptions in the delivery of components and materials to the relevant workstations, and downtime and failures of equipment realising production processes. To minimise such disruptions, many different strategies and methods are used, from lean manufacturing [5], lean maintenance [6], and reliability theory [7, 8]. In terms of technical infrastructure, one important task is to ensure a high degree of reliability of equipment, devices, and entire production lines [9]. The short life cycle of products as well as the introduction of new technologies has led to additional difficulties in the field of ensure appropriate preparedness for task completion and for identifying the causes that reduce reliability levels [10, 11].

Problems related to the assessment of the effectiveness of production systems are of great interest to researchers, who use various methods to solve this problem. An overview of diagnostic and prognostic capabilities, including the analysis of reliability and data management using the PHM (Prognostics and Health Management) system is described in publications [12, 13]. A review of multi-criteria models used to solve maintenance optimization problems is included in the paper [14]. During the review process, 259 publications in the area of MCO (Multi Criteria Optimization) and over 100 commonly used criteria were identified.

On the other hand, a review of the methods for assessing the reliability of production systems is included in the papers [15, 16]. The problems of modelling the reliability of production systems, taking into account the quality of production and reliability of equipment, are described by the authors of the papers [17, 18].

A methodology using a knowledge base to develop models of production processes in terms of Petri nets is presented by the authors of the study [19, 20, 21]. Line balancing methods can be used to increase the efficiency of assembly systems [22, 23].

A proposal to solve the problem using the RL (reinforcement learning) method is presented in the paper [24]. An innovative approach based on machine learning is included in the publication [25]. Problems related to the appropriate fitting of machine learning models to the reliability estimation function are presented in the papers [26, 27].

The process of selecting the structure of the production system in terms of the possibility of maintaining the stability of the production process along with the change in the degree of reliability of the technological machines included in the system is presented in the papers [28, 29]. Original models of reliability and productivity maintenance are described in the papers [30]. A description of the evolution in the area of system reliability optimization is included in the paper [31].

The issue of allocation is one of the leading in terms of linking the efficiency of the production system with reliability. Issues of allocation optimization to improve reliability, taking into account correlation errors and risk uncertainty, are described in the papers [32, 33]. The reliability allocation method taking into account the reduction of quality control costs is described in the publication [34]. A frequently used method to improve the reliability of a production system is to allocate buffers in these systems [35, 36]. The impact of the allocation of buffers and production resources on the efficiency of manufacturing systems is described in the papers [37, 38]. In theory, the buffer allocation problem is in itself a difficult NP-hard combinatorial optimization problem. The use of dynamic programming to optimize buffer allocation in flow-shop production systems is presented in the publication [39]. An innovative solution for reliability allocation for series-parallel systems is proposed by the authors of the study [40, 41].

The literature review conducted shows that the purpose of assessing the reliability of any system operating in industry is to ensure continuous operation without failure and to restore the system's capability as quickly as possible in the event of a failure. If the reliability of the system remains high, then total production costs and downtime can be kept to a minimum. Reliability assessment can be performed using qualitative and quantitative methods. Qualitative methods involve the use of models, diagrams, or other visual representations to analyse and understand the reliability of a manufacturing system and its components. Quantitative methods, on the other hand, involve the use of mathematical and statistical tools to assess the reliability of the system and its components. This analysis typically involves using system performance data, as well as other data that describes system reliability (among others, failure rates and mean time between failures) to quantify the probability of failure over time.

Described methods are listed in Table 1.

Table 1

List of improvement methods (authors as described)

Improvement methods	Authors
Lean manufacturing, lean maintenance	[1], [2], [3], [4], [5], [6], [9], [10], [11]
Reliability and maintenance optimization	[7], [8], [12], [13], [14], [15], [16], [17], [18], [28], [29], [30], [31]
Petri nets and balancing of line	[19], [20], [21], [22], [23]
Machine learning	[24], [25], [26], [27]
Allocation of reliability and buffers	[32], [33], [34], [35], [36], [37], [38], [39], [40], [41]

A research gap was identified in the area of low-cost methods enabling the quantitative assessment of the implementation of a production task with the existing resources of the enterprise. This is especially true for achieving performance that is greater than the capabilities of the existing system.

METHODOLOGY

The article proposes method of improving the efficiency of production systems with a serial structure. To study the system, a method involving the analysis of states and a digital simulation are used. To assess the system with an additional capacitive, a production performance indicator is used.

Analysis of the operation of a system with added capacitive element

For the analysis, a serial N-device system was adopted, which can be a typical series system of single devices, as well as a reduced mixed system consisting of series and parallel elements.

Figure 1 shows the scheme of the considered serial structure of system.

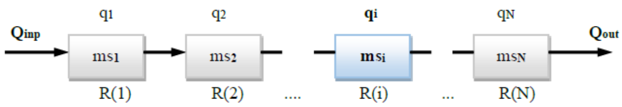


Fig. 1 Scheme of the considered serial structure

Markings on the scheme:

ms_i – machining station number *i*, i = 1, 2...*N*, R(i) – reliability of *i* station, q_i – efficiency of *i* station, Q_{inp} – efficiency (flow rate) of the input stream, Q_{out} – efficiency of the output stream.

The mean efficiency of the system is:

$$Q_{av} = min\ q_i \cdot R_s(t); i = 1,2 \ldots N. \tag{1}$$

While the reliability of the serial system is:

$$R_s(t) = \prod_{i=1}^{N} R(i). \tag{2}$$

Additionally, when $Q_{inp} < \min q_i$, then the mean efficiency of the output is:

$$Q_{out} = Q_{inp} \cdot R_s(t). \tag{3}$$

The main problems to be solved when using a capacitive element are (Fig. 2):

- determination of the capacity of the buffer,
- determination of the best position for the buffer in the system,
- determination of the number of buffers.

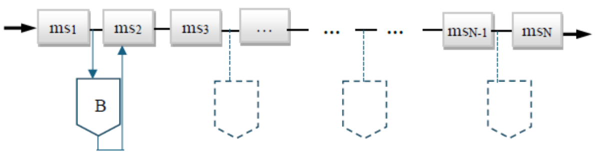


Fig. 2 Scheme of a serial structure with a capacitive element

To analyse the impact of the capacitive element on the performance achieved by the system, a serial system with one buffer was adopted. The capacitive element divides the system into two subsystems:

- the part delivering the material to the buffer (DP),
- the part receiving the material (RP).

Figure 3 shows the division of the system into the delivering part (DP) and receiving part (RP).

The time lost due to unplanned interruptions in the operation of the production system equipment is described by the MTTR (Mean Time to Repair) indicator. The analysis of the system's operation used the failure index κ, which is directly related to the MTTR index.

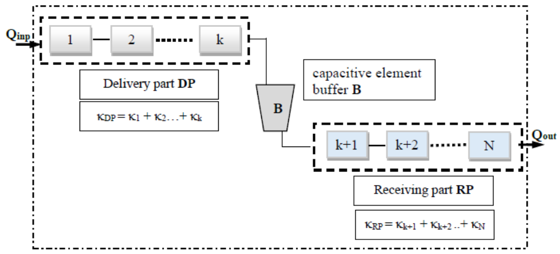


Fig. 3 Scheme of the division of a system with buffer

It is assumed that the fault rate of a single ms_i device can be described by the relationship:

$$\kappa(ms_i) = \frac{t_{us}}{t_w} = \frac{unplanned\ downtime\ (damage)}{working\ time}. \tag{4}$$

In addition, it was assumed that there is a relationship between the failure rate and the probability of reliability of the *i*-th device:

$$R(i) = \frac{1}{1 + \kappa_i} \tag{5}$$

Therefore, the damage indicator of the system with a capacitive element (Fig. 3) is:

- κ_{DP} for the delivering part DP

$$\kappa_{DP} = \sum_{i=1}^{k} \kappa_i, \tag{6}$$

- κ_{RP} for the receiving part RP

$$\kappa_{RP} = \sum_{k+1}^{N} \kappa_i, \tag{7}$$

and thus the total damage indicator κ_T of the system is:

$$\kappa_T = \kappa_{DP} + \kappa_{RP}. \tag{8}$$

The probability of reliability of a system without a storage device is:

$$R(t) = \frac{1}{1 + \kappa_T}. \tag{9}$$

The probability of reliability of a system with a storage device is:

- for the delivering part DP

$$R_{DP}(k) = \frac{1}{1 + \kappa_{DP}}, \tag{10}$$

- for the receiving part RP

$$R_{RP}(N-k) = \frac{1}{1 + \kappa_{RP}}. \tag{11}$$

The probability of failure of a system with a storage device is:

- for the delivering part DP

$$F_{DP}(k) = F(DP) = \frac{\kappa_{DP}}{1 + \kappa_{DP}}, \tag{12}$$

- for the receiving part RP

$$F_{RP}(N-k) = F(RP) = \frac{\kappa_{RP}}{1 + \kappa_{RP}}. \tag{13}$$

The analysed system can function in four states:

State I – correct operation of the DP part and RP part – material flows through the buffer

State II – downtime of the DP part and correct operation of the RP part – material received from the buffer

State III – correct operation of the DP part and downtime of the RP part – material delivered to the buffer

State IV – downtime of both parts (DP and RP) – no flow.

The probabilities at which states I – IV occur are, respectively:

State I: $$P(I) = R_{DP}(k) \cdot R_{RP}(N-k), \tag{14}$$

State II: $$P(II) = F_{DP}(k) \cdot R_{RP}(N-k), \tag{15}$$

State III: $$P(III) = R_{DP}(k) \cdot F_{RP}(N-k), \tag{16}$$

State IV: $$P(IV) = F_{DP}(k) \cdot F_{RP}(N-k). \tag{17}$$

Taking into account the possible system states, it can be assumed that the average system performance is:

$$Q_{av} = Q_{RP} \cdot [P(I) + P(II)] = Q_{RP} \cdot \left[\frac{1}{1+\kappa_{DP}} \cdot \frac{1}{1+\kappa_{RP}} + \frac{\kappa_{DP}}{1+\kappa_{DP}} \cdot \frac{1}{1+\kappa_{RP}}\right]. \quad (18)$$

Analysis of states in systems with a capacitive element

The serial system was reduced to an equivalent system (Fig. 3). For analysis, it was assumed that the delivering part DP and the receiving part RP may be in the following states:

W – working (operational), F – failure (damaged), S – working, in a state of forced stop.

State S, forced stop, occurs when the equipment is in a state of readiness but due to failures in other equipment, it cannot perform its tasks.

On the other hand, the capacitive element – buffer B can take one of the following three states:

1 – empty, 2 – partially filled, 3 – full.

Hence, the number of possible states in which the system can be is: 3n = 33 = 27 states.

The adoption of simplifying assumptions (states and momentary transitions) made it possible to reduce the number of states to eight, which are collected in Table 2 (along with possible transitions between them).

Examples of temporary states and transitions:

F2W → F1W → F1S,   W2F → W3F → S3F

Table 2

Possible system states with transitions between states

Previous state	No	Current state	Next state
4	**1**	**W1W**	4,6
5,6	**2**	**W2W**	5,6
8	**3**	**W3W**	5,8
1,5	**4**	**F1S**	1
2,3,7	**5**	**F2W**	2,7,4
1,2,7	**6**	**W2F**	7,2,8
5,6	**7**	**F2F**	6,5
3,6	**8**	**S3F**	3

A graph of states and possible transitions between states is shown in Figure 4.

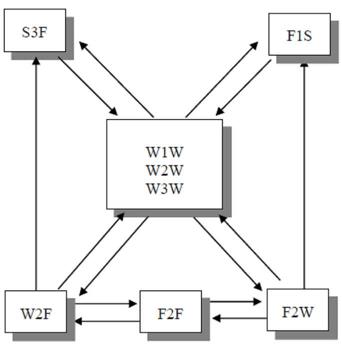


Fig. 4 Graph of states and transitions for the studied system

The above analyses were the basis for simulation tests. The decision variables in the analysis are:

- capacity of the element,
- the position of the capacitive element in the structure of the devices.

In order to check the effects that can be obtained by using a capacitive element, a calculation algorithm was prepared and a computer program (in C++) was written that allows the operation of a serial system with one capacitive element to be simulated. Eight basic states of the system were simulated: W1W, W2W, W3W, F2W, W2F, F2F, S3F and F1S.

Algorithm of simulation calculation

In the calculations, it was assumed that the operation of the devices of the delivery and receiving parts is described by the time of operation to damage and the duration of repair. Both uptime and repair time are random variables described by an exponential distribution.

The following parameters were adopted as input data (according to Figure 6):

- damage indicator for each individual device: κ_i; $i = 1,2 \ldots N$;
- capacity of the storage element: $V = \{V_1, V_2 \ldots V_i \ldots V_k\}$;
- mean working time of each device: B(I), B(II);
- mean repair time of each device: E(I), E(II): $E(I) = B(I)\kappa_I$; $E(II) = B(II)\kappa_{II}$;
- simulation time: *TSYM.*

Actual state durations (working, repair) are calculated from the exponential distribution density function:

$$f(t) = \lambda e^{-\lambda t} \text{ thus: } t = -\lambda \ln C. \quad (19)$$

Figure 5 shows a block diagram of simulation calculations enabling the study of the influence of the buffer position and its capacity on the obtained effect of increased system effectiveness (for the structure according to Fig. 3).

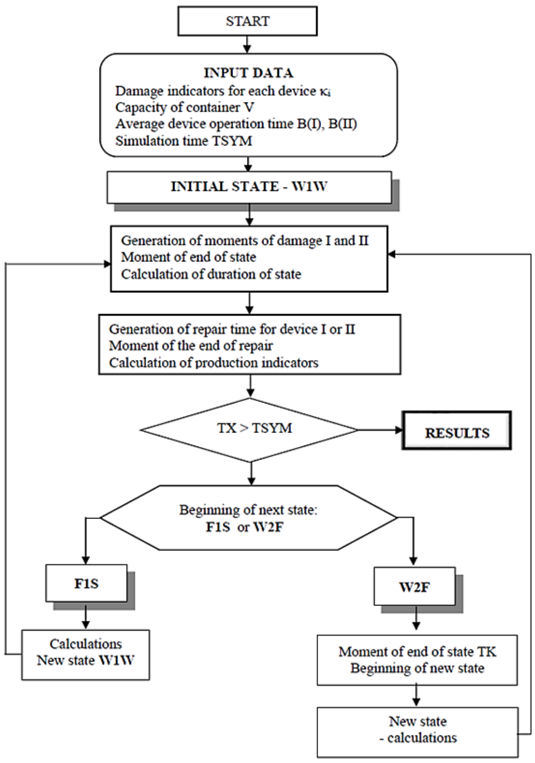


Fig. 5 Block diagram of simulation calculations

Results of system operation simulation

The structure of system under investigation shows Figure 6.

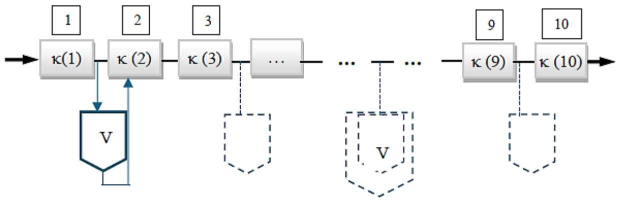


Fig. 6 Diagram of the tested system

Four variants of the system consisting of 10 elements were developed for exemplification (Tab. 3).

Table 3
Simulation variants

Variable	Variant 1	Variant 2	Variant 3	Variant 4
Capacity of the buffer V [relative unit]	V = {0, 1, 2, 4}	V = 4	V = 4	V = 4
Damage indicator κ [-]	0.01 for i = 1...10	0.01 for i = 1, 3, 5, 7, 9 0.02 for i = 2, 4, 6, 8, 10	0.01 for i = 1,2, 3, 4, 5 0.01 for i = 6, 7, 8, 9, 10	0.01 for i = 1, 2, 3, 4, 5 0.01 for i = 6, 7, 8, 9, 10

Variant 1 (Fig. 7)

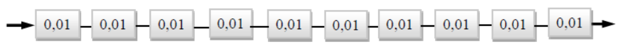


Fig. 7 Damage indicators for variant 1

1. The damage indicator for each *i*-th element ms_i is:
$\kappa_i = 0.01$ for i = 1,2 ...10 ➔ $\kappa_T = 0,10$
2. The capacity of buffer V is: V ∈ {0, 1, 2, 4} relative units
3. Simulation time: TSYM = 4000 h
Some results of the simulation calculations for variant 1 are shown in Table 4.

Table 4
Simulation results – variant 1

$W_{V/J}$	κ = 0,01; V = {1, 2, 4}, J = {1, 2, ...9}								
	V_I	J	P	CP_{DP}	CP_{RP}	CN_{DP}	CN_{RP}	κ_{DP}	κ_{RP}	Q
$W_{1/1}$	1	1	3677,9	3969,1	3682,3	39,5	330,1	0,01	0,0896	0,9195
...	...	...	...	...	...	...	...	...	...	...
$W_{1/5}$	1	5	3818,2	3827,3	3827,3	188,6	187,2	0,0493	0,0489	**0,9545**
...	...	...	...	...	...	...	...	...	...	...
$W_{1/9}$	1	9	3643,2	3643,2	3643,2	327,9	35,6	0,09	0,0097	0,9108
$W_{2/1}$	2	1	3670,9	3693,5	3676,3	39,5	329,2	0,01	0,0895	0,9177
...	...	...	...	...	...	...	...	...	...	...
$W_{2/5}$	2	5	3823,5	3866,3	3866,3	185,4	181,5	0,0489	0,0495	**0,9559**
...	...	...	...	...	...	...	...	...	...	...
$W_{2/9}$	2	9	3679,9	3694,4	3694,4	332,5	27,7	0,09	0,094	0,9200
$W_{4/1}$	4	1	3692,5	4001,1	3679,8	39,6	329,9	0,0099	0,0897	0,9231
...	...	...	...	...	...	...	...	...	...	...
$W_{4/5}$	4	5	3889,1	3930,1	3982,1	186,2	178,4	0,0484	0,0488	**0,9724**
...	...	...	...	...	...	...	...	...	...	...
$W_{4/9}$	4	9	3684,8	3685,3	3634,8	327,1	35,8	0,0888	0,0099	0,9212

where: $W_{V/J}$ – is the variant in which the buffer has a capacity of V and is positioned after the J-th device

When operating without a capacitive element (V = 0), the average relative performance is:

$$Q_{av}(V=0) = \frac{1}{1+\kappa_T} \cdot 1 = 0,909$$

A graphic representation of the results of variant 1 is presented in Figure 8.

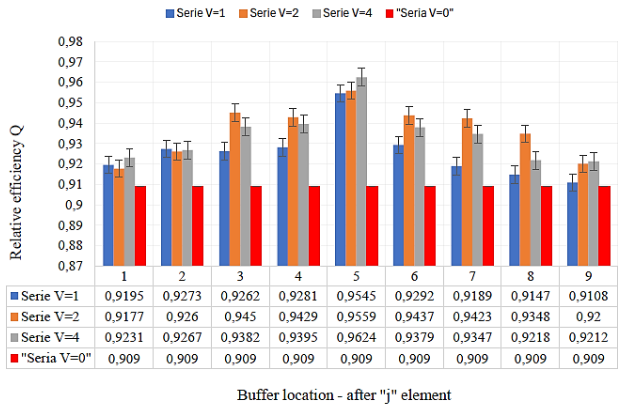


Fig. 8 Results of the simulation for variant 1

The system adopted for consideration is characterized by the same failure indicators of all elements, hence the greatest increase in performance should occur for the middle position of the capacitive element (after the 5th element). The results from Table 4 and the graph in Figure 8 confirm this regularity, hence it can be concluded that the simulation model is correct.
The following conclusions can be drawn from the analysis of the results of the different capacity variants:

1. The performance gain for an element with a relative capacity of V = 1 is 4.55%
2. The performance gain for an element with a relative capacitance of V = 2 is 4.69%
3. The performance gain for an element with a relative capacity of V = 4 is 6.34%

This means that even for a capacity of V = 1 (relative to the flow rate), the performance gain is significant. At the same time, it is also evident that successive capacity increases improve performance, but disproportionately to the capacity being increased.
In subsequent simulations, three variants of the system with a damage indicator of $\kappa_T = 0.15$ and a capacity of V = 4 are considered. The damage indicators of individual elements are selected in such a way as to show that the location of the capacitive element significantly depends on the damage in the part supplying and receiving the material for production (according to the data in Table 3).
Similar simulations were performed for variants 2 to 4.
Performance of the system without the capacitive element:

$$Q_{av}(V=0) = \frac{1}{1+\kappa_T} \cdot 1 = 0,8695$$

Variant 2 (Fig. 9)

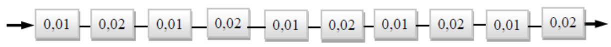


Fig. 9 Damage indicators for variant 2

The damage indicator for each i-th element ms_i is:
$\kappa_i = 0.01$ for i = 1, 3, 5, 7, 9 and $\kappa_i = 0.02$ for i = 2, 4, 6, 8, 10 ➔ $\kappa_T = 0{,}15$

Variant 3 (Fig. 10)

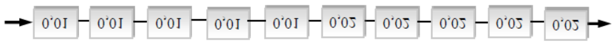


Fig. 10 Damage indicators for variant 3

The damage indicator for each i-th element ms_i is:
$\kappa_i = 0.01$ for i = 1, 2, 3, 4, 5 and $\kappa_i = 0.02$ for i = 6, 7, 8, 9, 10 ➔ $\kappa_T = 0{,}15$

Variant 4 (Fig. 11)

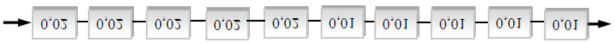
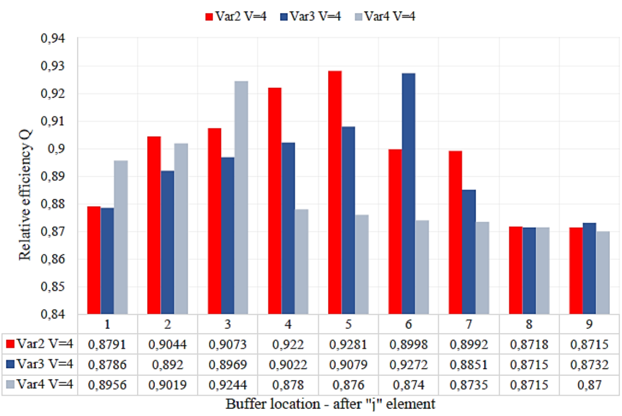


Fig. 11 Damage indicators for variant 4

The damage indicator for each i-th element ms_i is:
$\kappa_i = 0.02$ for i = 1, 2, 3, 4, 5 and $\kappa_i = 0.01$ for i = 6, 7, 8, 9, 10 ➔ $\kappa_2 = 0{,}15$
A graphic representation of the results for variants 2 - 4 is shown in Figure 12.



	1	2	3	4	5	6	7	8	9
Var2 V=4	0,8791	0,9044	0,9073	0,922	0,9281	0,8998	0,8992	0,8718	0,8715
Var3 V=4	0,8786	0,892	0,8969	0,9022	0,9079	0,9272	0,8851	0,8715	0,8732
Var4 V=4	0,8956	0,9019	0,9244	0,878	0,876	0,874	0,8735	0,8715	0,87

Fig. 12 Results of the simulation of variants 2-4

Conclusions from the analysis

1. Performance gain for variant 2 (damage indicators symmetrically distributed in the system)
2. is 5.86 %, the capacitive element V = 4 should be located after the 5th element.
3. The performance gain for variant 3 (damage rates higher after the 5th element) is 5.76%, and the capacitive element V = 4 should be located after the 6th element.
4. The performance gain for variant 4 (damage rates higher after 1 element) is 5.49%, and the capacitive element V = 4 should be located after the 3rd element.

The simulation results confirm the logical regularity that the additional capacitive element should be located in places with higher damage indicators.
The results confirm the reliability of the adopted model and can be used for testing serial systems in which the failure rates of individual elements are different.

CONCLUSIONS

This paper presents method for the improvement of the effectiveness of manufacturing systems with a serial structure (the elements of this structure can have a parallel structure). Such structures occur very frequently in product manufacturing systems with an organised, serial type of production technology.
In the research used the analysis of system states in which an additional capacitive element has been added (a warehouse, a buffer).
The algorithm proposed makes it possible to indicate the capacity of the element and its place in the system. The capacitive element divides the system into two subsystems, the subsystem delivering components to the buffer and the subsystem receiving components from the buffer. The indicator for the effectiveness of the system was its performance (one of the most important KPIs).
For a damage indicator of $\kappa_T = 0{,}10$ the possible performance increase was: 4,55% for buffer capacity V = 1, 4.69% for V = 2 and 6.34% for capacity V = 4. Meanwhile, the system efficiency increases from 0.909 to 0.9624 conventional units.
Both the increase in performance and the position of the capacitive element depend to a large extent on indicators of damage to individual elements of the system. Depending on the variant (V2-V4) - a performance increase of 0.8695 to 0.9272 is possible.
The simulations conducted during the study indicated that depending on the capacity of the element, it is possible to achieve an improvement in performance at the level of 4-5 percent.
This method makes it possible to undertake decisions regarding the choice of optimal solution while bearing in mind the financial resources of the business entity.

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