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USING COMPUTER SIMULATION METHOD TO IMPROVE THROUGHPUT OF PRODUCTION SYSTEMS BY BUFFERS AND WORKERS ALLOCATION

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Abstract

This paper proposes the application of computer simulation methods to support decision making regarding intermediate buffer allocations in a series-parallel production line. The simulation model of the production system is based on a real example of a manufacturing company working in the automotive industry. Simulation experiments were conducted for different allocations of buffer capacities and different numbers of employees. The production system consists of three technological operations with intermediate buffers between each operation. The technological operations are carried out using machines and every machine can be operated by one worker. Multi-work in the production system is available (one operator operates several machines). On the basis of the simulation experiments, the relationship between system throughput, buffer allocation and the number of employees is analyzed. Increasing the buffer capacity results in an increase in the average product lifespan. Therefore, in the article a new index is proposed that includes the throughput of the manufacturing system and product life span. Simulation experiments were performed for different configurations of technological operations.

Keywords
computer simulation, series-parallel production line, buffer allocation, throughput analysis, life span of products.

Introduction

The buffer allocation problem is an NP-hard combinatorial optimization problem well known in the research area of industrial engineering [1–3]. On the one hand, the proper allocation of buffer capacities in production lines can result in an increase in the total effectiveness of the production system. On the other hand, in capital-intensive industries, like the automotive one, even a simple redistribution of total existing buffer capacities may lead to significant savings in spending [4, 5]. In this article, computer simulation methods are used to analyze the allocation of buffer capacities in the production system (including three technological operations) and the relationship between the throughput of the system, buffer capacities and the number of workers. The research was performed for a series-parallel production line which included 9 machines and 2 intermediate buffers. The material flow was directed to the individual machines on the basis of the round robin dispatching rule. The machines performed 3 different technological operations and each operation was able to be realized by 3 identical machines simultaneously. In the system, 4 kinds of products are manufactured and the production lot sizes were defined. The simulation model of the system was created on the basis of part of a real manufacturing system designed for the automotive industry. Generally, the main research problem can be formulated as follows:

it is given a flow production system with $N \cdot K$ manufacturing resources and $N-1$ intermediate buffers. How do different numbers of workers and buffer capacities impact the system throughput and the average lifespan of the products.

To solve the problem a set of simulation experiments was conducted in which the input values were different capacities of intermediate buffers and different numbers of workers and the output values were the throughput of the system and average lifespan of the products. The simulation research was performed using Tecnomatix Plant Simulation Software. In the next chapter, the buffer allocation problem is described.

The buffer allocation problem (BAP)

The buffer allocation problem (BAP) is one of the most important questions to face a designer in the field of serial production. It is an NP-hard combinatorial optimization problem in the design of production lines and the issue is studied by many scientists and theorists around the world. The buffer allocation problem is concerned with the allocation of a certain number of buffers P, among the $N-1$ intermediate buffer locations of a production line to achieve a specific objective [2]. A production line consists of machines connected in a series and separated by buffers (Fig. 1) where the machines are denoted as M_1, $M_2, \ldots, M_N$, and the buffers as B_1, $B_2, \ldots, B_{N-1}$.

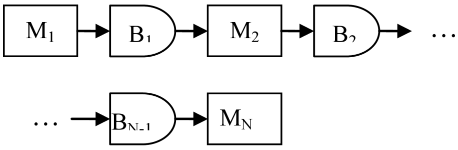

Fig. 1. A production line with N machines and $N-1$ intermediate buffers.

Also, it is obvious that in each station there might be a number of parallel machines that help production and manufacturing systems (Fig. 2). In the literature, several types of production lines are taken into account. The classification of production lines can be based on the blocking type (blocking before or after service), job transfer timing (asynchronous, synchronous, continuous), production control mechanisms (push and pull), types of workstations (reliable and unreliable) and job carrier requirements (open and closed) [6].

The BAP can be formulated in three cases depending on the objective function [2]. In the first case, the main objective is the maximization of the throughput rate for a given fixed number of buffers.

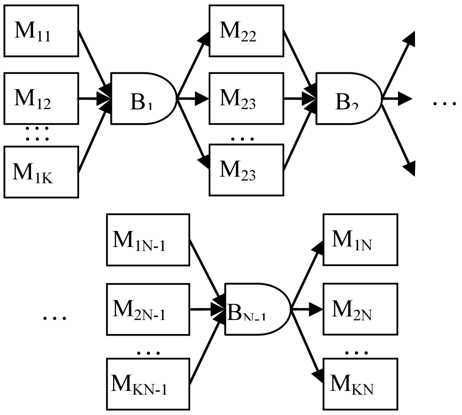

Fig. 2. A series-paralell production line.

The first case of the BAP is formulated as follows:
find

$$B = (B_1, B_2, \ldots, B_{N-1}), \tag{1}$$

so as to

$$\max f(B), \tag{2}$$

subject to

$$\sum_{i=1}^{N-1} B_i = P, \tag{3}$$

where B represents a buffer size vector, and $f(B)$ represents the throughput rate of the production line as a function of the size vector of the buffers, and P is a fixed non-negative integer denoting the total buffer space available in the manufacturing system. The second case of the BAP is formulated as follows:

$$B = (B_1, B_2, \ldots, B_{N-1}), \tag{4}$$

so as to

$$\min \sum_{i=1}^{N-1} B_i, \tag{5}$$

subject to

$$f(B) = f^*, \tag{6}$$

where f^* is desired throughput rate.

The third case of the BAP is formulated as follows:
find

$$B = (B_1, B_2, \ldots, B_{N-1}), \tag{7}$$

so as to

$$\min Q(B), \tag{8}$$

subject to

$$f(B) = f^*, \tag{9}$$

$$\sum_{i=1}^{N-1} B_i \leq P, \tag{10}$$

where $Q(B)$ denotes the average work-in-process inventory as a function of the size vector of the buffers and f^* is the desired throughput rate.

This formulation of the problems expresses the maximization of the throughput rate for a given fixed number of buffers, achieving the desired throughput rate with the minimum total buffer size or the minimization of the average work-in-process inventory which is subject to the total buffer size and the desired throughput rate constraint.

The issue of buffer allocation is the subject of numerous scientific publications. The problem of maximizing the throughput of production lines by changing buffer sizes, or locations, using simulation methods was studied by Vidalis et al. [7]. A critical literature overview in the area of buffer allocation and production line performance was done by Battini, Persona and Regattieri [1]. Demir, Tunali and Eliiyi proposed a classification scheme to review the studies and presented a comprehensive survey on the buffer allocation problem in production systems [2]. Stanley and Kim presented the results of simulation experiments carried out for buffer allocations in closed series-production lines [8]. In a production line, a single buffer space is the room and the associated material handling equipment that is needed to store a single job that is a work-in-process, and buffer allocation is the specific placement of a limited number of buffer spaces in a production line. The authors demonstrated a buffer allocation decomposition result for closed production lines, and also provided evidence that optimal buffer allocations in closed lines are less sensitive to bottleneck severity than in open production lines. The placement of buffers in a production line is an old and well-studied problem in industrial engineering research. Vergara and Kim proposed a new buffer placement method for serial production lines [9]. The method is very efficient and uses information generated in a production line simulation whose conceptual representation of job flow and workstation interaction can be described with a network which aims to place buffers in such a way as to maximize throughput. They compared the results of the new method against a method for buffer placement based on a genetic algorithm. Yamashita and Altiok [10] proposed an algorithm for minimizing the total buffer allocation for desired throughput in production lines with phase-type processing times. They implemented a dynamic programming algorithm that uses a decomposition method to approximate system throughput at every stage. Shi and Gershwin presented an effective algorithm for maximizing profits through buffer size optimization for production lines [11]. They considered both buffer space cost and average inventory cost with distinct cost coefficients for different buffers. To solve the problem, a corresponding unconstrained problem was introduced and a nonlinear programming approach was adopted. Joseph and Sridharan made an evaluation of the routing flexibility of an FMS with the dynamic arrival of part types for processing in the system. A typical FMS configuration was chosen for detailed study and analysis. The system was set to five different levels of routing flexibility. A discrete-event simulation model was developed to describe the operation of the FMS [12].

In the next chapter, a simulation model of a series-parallel production line is presented.

A simulation model of a production system

The model of the series-parallel production line was prepared on the basis of a real example of a manufacturing system dedicated to metal tooling in an automotive company. The model and simulation experiments were implemented using Tecnomatix PLM simulation software. The studied manufacturing system includes three technological operations: turning, milling and grinding. The manufacturing process is divided into three stages by technology and between each two stages an intermediate buffer is allocated. Every stage of the manufacturing system encompasses a determined number of manufacturing resources (three machines in every stage). The simulation model of the manufacturing system was prepared with Tecnomatix Plant Simulation Software version 11.0.0 and is presented in Fig. 3.

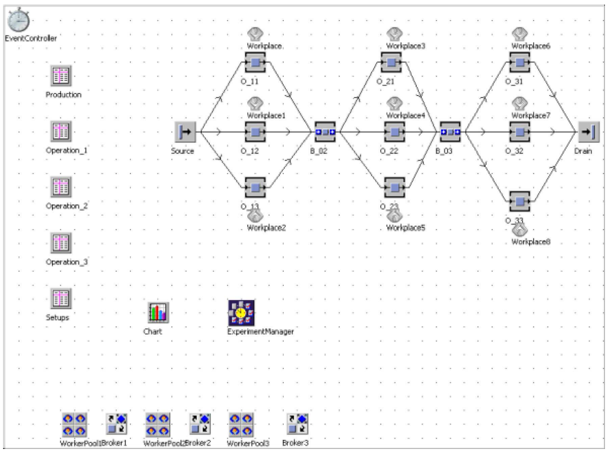

Fig. 3. A simulation model of series-paralell production line.

For the topology of the manufacturing system presented in Fig. 3, the operation times of the technological operations are determined for two different variants. In the first variant, the first operation (turning) is performed with resources O_11, O_12 and O_13, the second operation (milling) is performed with resources O_21, O_22 and O_23 and the last operation (grinding) is done using resources O_31, O_32 and O_33. In the system, four different products are manufactured (A, B, C and D). The first variant of batch sizes and operation times is presented in Table 1.

Table 1
The first variant of batch sizes and operation times.

	Products			
	A	B	C	D
Batch size	20	25	15	10
Turning O_11,O_12, O_13	3:00	3:00	3:00	3:00
Milling O_21,O_22, O_23	6:00	6:00	6:00	6:00
Grinding O_31,O_32, O_33	9:00	9:00	9:00	9:00

In the first variant, the first operation (grinding) is performed with resources O_11, O_12 and O_13, the second operation (milling) is performed with resources O_21, O_22 and O_23 and the last operation (turning) is done using resources O_31, O_32 and O_33. The second variant of batch sizes and operation times is presented in Table 2.

Table 2
The second variant of batch sizes and operation times.

	Products			
	A	B	C	D
Batch size	20	25	15	10
Grinding O_11,O_12, O_13	9:00	9:00	9:00	9:00
Milling O_21,O_22, O_23	6:00	6:00	6:00	6:00
Turning O_31,O_32, O_33	3:00	3:00	3:00	3:00

The changing of a batch requires a setup time. The matrix of setup times is presented in Table 3.

Table 3
The matrix of setup times.

	A	B	C	D
–	30:00	20:00	10:00	30:00
A	30:00	10:00	30:00	15:00
B	30:00	30:00	20:00	30:00
C	40:00	40:00	30:00	20:00
D	20:00	30:00	30:00	30:00

The numbers presented in the set-up time matrix refer to the setup time needed for the changing of a production batch (for example a batch change from product A to product B takes 10 minutes of setup time and from product B to product A 30 minutes). For each machine a workplace is allocated and it is assumed that one workplace is dedicated for one worker. The number of workers is allocated on the basis of the technological operations. It means that one operator can operate more than one machine.

Simulation experiments were prepared for different capacities of buffers and different numbers of workers dedicated to the technological operations. In Table 4, the combination of buffer capacities is presented. Overall, 16 experiments were prepared in which the buffer capacity was increased from 1 to 30 (see Table 4). For each experiment, 3 observations were performed.

Table 4
The different buffers capacities.

Experiment number	B_02	B_03
Exp 1	1	1
Exp 2	2	2
Exp 3	1	2
Exp 4	2	1
Exp 5	3	2
Exp 6	2	3
Exp 7	3	3
Exp 8	5	1
Exp 9	1	5
Exp 10	5	2
Exp 11	2	5
Exp 12	5	3
Exp 13	5	5
Exp 14	10	10
Exp 15	20	20
Exp 16	30	30

The experiments were repeated for different numbers of workers allocated to the technological operations. The number of workers allocated to the technological operations is presented in Table 5. From the table results, it is evident that, for example: in variant V_11 the maximum number of workers is allocated to the technological operations (one machine one worker). The efficiency of operators is equal for all experiments and assumed to be 100%. The machine availability is assumed to be 95% and the mean time to repair is determined to be 1 minute. The simulation experiments were repeated for the different variants of the technological operation orders, different numbers of workers and buffer capacities. In addition to the output values, the throughput of the system and the average lifespan of products is also presented. In the next chapter, the results of the simulation experiments are presented.

Table 5
The allocation of workers for the operations.

Variant 1 – different number of workers				
	V_11	V_12	V_13	V_14
Turning O_11,O_12, O_13	3	2	2	1
Milling O_21,O_22, O_23	3	2	2	1
Grinding O_31,O_32, O_33	3	3	2	2
Variant 2 – different number of workers				
	V_21	V_22	V_23	V_24
Grinding O_11,O_12, O_13	3	3	2	2
Milling O_21,O_22, O_23	3	2	2	1
Turning O_31,O_32, O_33	3	2	2	1

The outcomes of computer simulation experiments

The research methodology is presented in Fig. 4.

The main research hypotheses can be formulated as follows:

1. The proper allocation of buffer capacities enables the obtainment of the same throughput of the system for smaller numbers of workers.
2. The sequence and time of the technological operations have a significant impact on the throughput of the system.
3. Increasing the total buffer capacity in the system does not always result in an increase of the throughput. The crucial factor is a proper allocation of the intermediate buffers.
4. Increasing the total number of workers in the system does not always result in an increase in the throughput. The crucial factor is the proper allocation of workers and buffers.

The assumptions and limitations for the model and the proposed simulation experiments are presented in the last chapter.

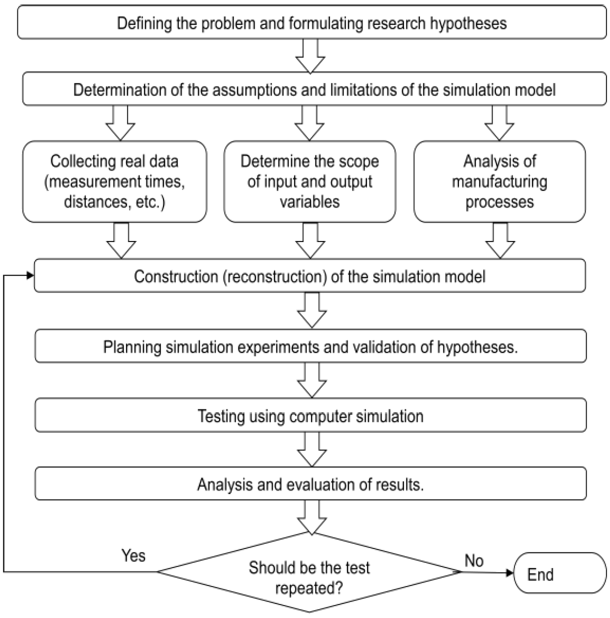

Fig. 4. The procedure for conducting simulation studies.

In Fig. 5a and 5b the results of the simulation experiments for variant V_11 are presented.

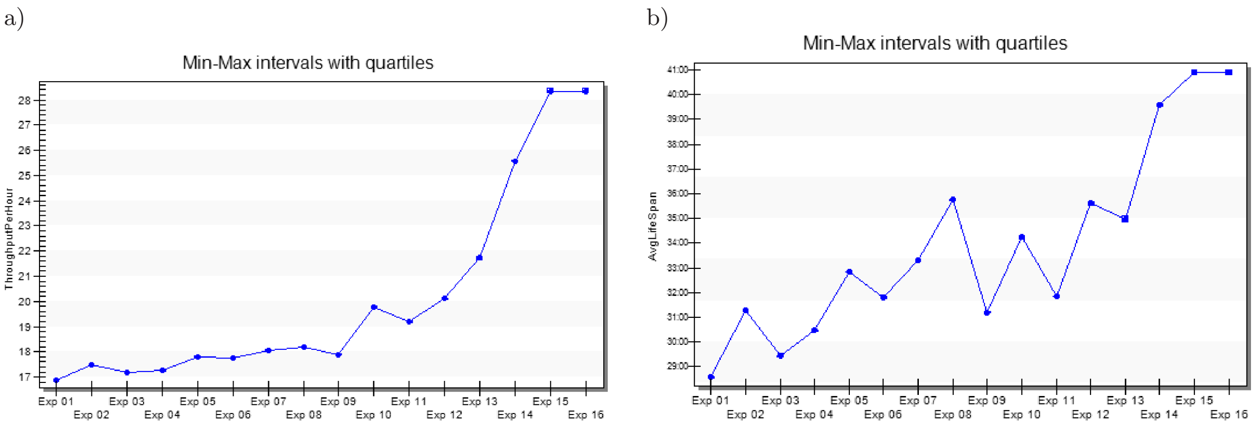

Fig. 5. a) The throughput of the system for the number of workers and operation times defined in V_11; b) the average lifespan of products of the system for the number of workers and operation times defined in V_11.

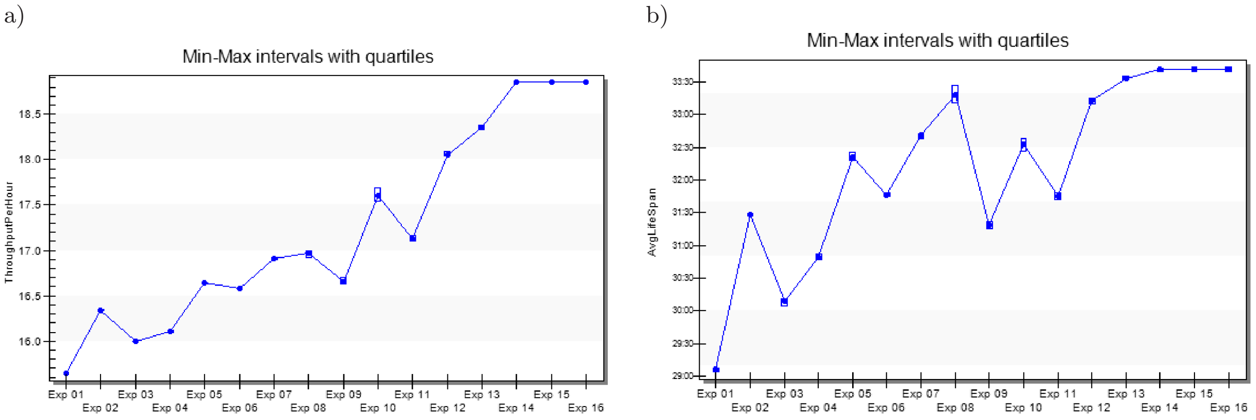

Fig. 6. a) The throughput of the system for the number of workers and operation times defined in V_12; b) the average lifespan of products of the system for the number of workers and operation times defined in V_12.

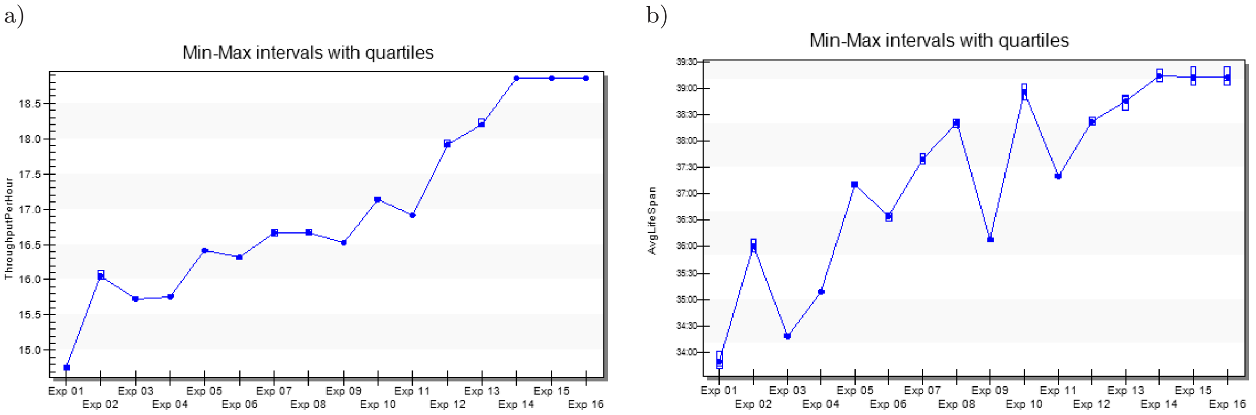

Fig. 7. a) The throughput of the system for the number of workers and operation times defined in V_13; b) the average lifespan of products of the system for the number of workers and operation times defined in V_13.

The maximum throughput of the system (more than 28 parts per hour) is obtained for both buffer capacities (B_02 and B_03) which are greater than 20. The lifespan for the throughput was relatively high (about 41 minutes). The values are obtained for a full staffing of the machines (9 workers). In Figs. 6a and 6b the results of the simulation experiments for variant V_11 are presented.

The maximum throughput of the system (more than 18 parts per hour) is obtained for both buffer capacities (B_02 and B_03) which are greater than 4. The lifespan for the throughput was about 33 minutes. The values are obtained for 7 workers. In Figs. 7a and 7b the results of the simulation experiments for variant V_13 are presented.

The maximum throughput of the system (more than 18 parts per hour) is obtained for the buffer capacities (B_02 and B_03) which are greater than 10.

The lifespan for the throughput was about 39 minutes. The values were obtained for 6 workers (2 workers allocated to each technological operation). In Figs. 8a and 8b the results of the simulation experiments for variant V_14 are presented.

The maximum throughput of the system is about 14 parts per hour and is obtained for both buffer capacities (B_02 and B_03) which are greater than 20. The lifespan for the throughput was about 2 hours and 30 minutes. The values are obtained for 4 workers. In Figs. 9a and 9b the results of the simulation experiments for variant V_21 are presented.

The maximum throughput of the system is about 14 parts per hour and is obtained for both buffer capacities (B_02 and B_03) which are greater than 4. The lifespan for the throughput was about 34 minutes. The values are obtained for a full staffing of the machines (9 workers). This experiment shows that the changing of the operation order can significantly impact the throughput of the system. If the operation times increase (variant V_11), so does the maximum throughput of the production system with a full staffing greater than 28 and a total buffer capacity of 40. If the operation times decrease, the throughput is reduced to 14 parts per hour. In Figs. 10a and 10b the results of the simulation experiments for variant V_22 are presented. The maximum throughput of the system is about 14 parts per hour and is obtained for both buffer capacities (B_02 and B_03) which are greater than 4 (similar to the previous case). The lifespan of the throughput was about 39 minutes. The values are obtained for 7 workers.

a)

b)

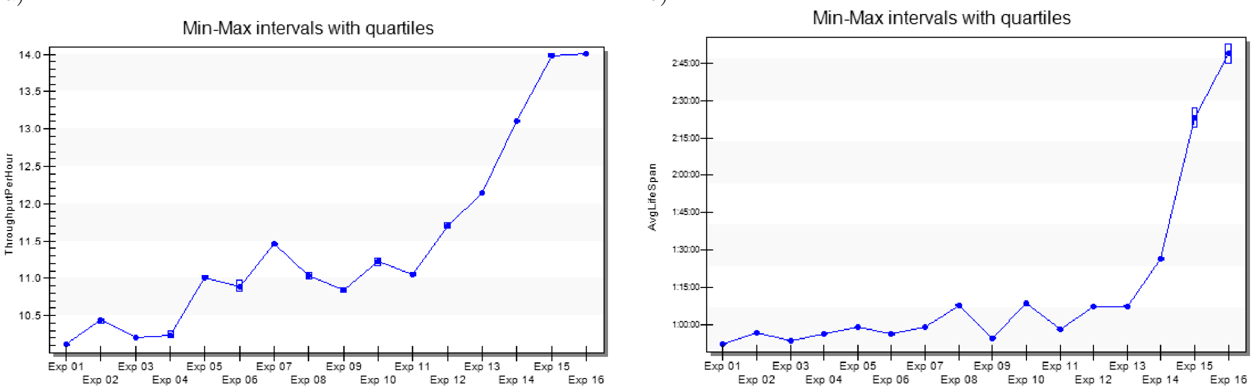

Fig. 8. a) The throughput of the system for the number of workers and operation times defined in V_14; b) the average lifespan of products of the system for the number of workers and operation times defined in V_14.

a)

b)

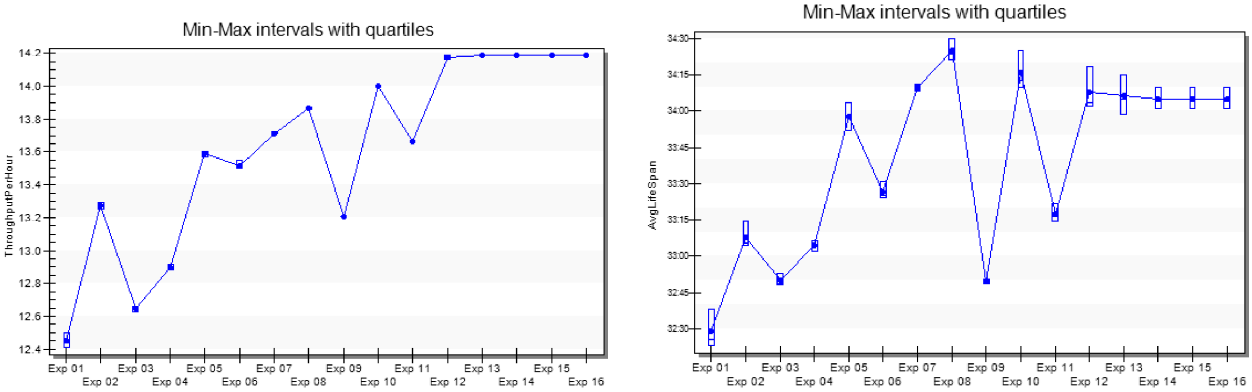

Fig. 9. a) The throughput of the system for the number of workers and operation times defined in V_21; b) the average lifespan of products of the system for the number of workers and operation times defined in V_21.

a)

b)

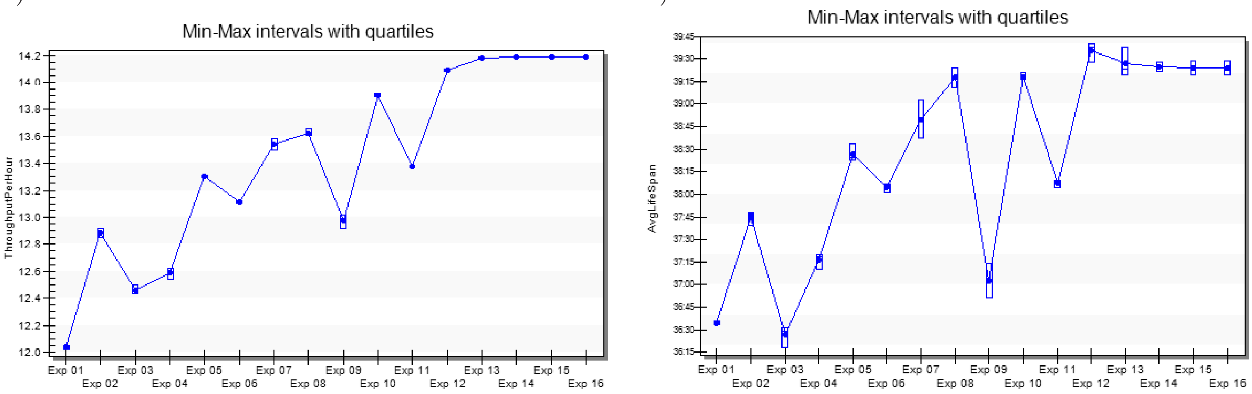

Fig. 10. a) The throughput of the system for the number of workers and operation times defined in V_22; b) the average lifespan of products of the system for the number of workers and operation times defined in V_22.

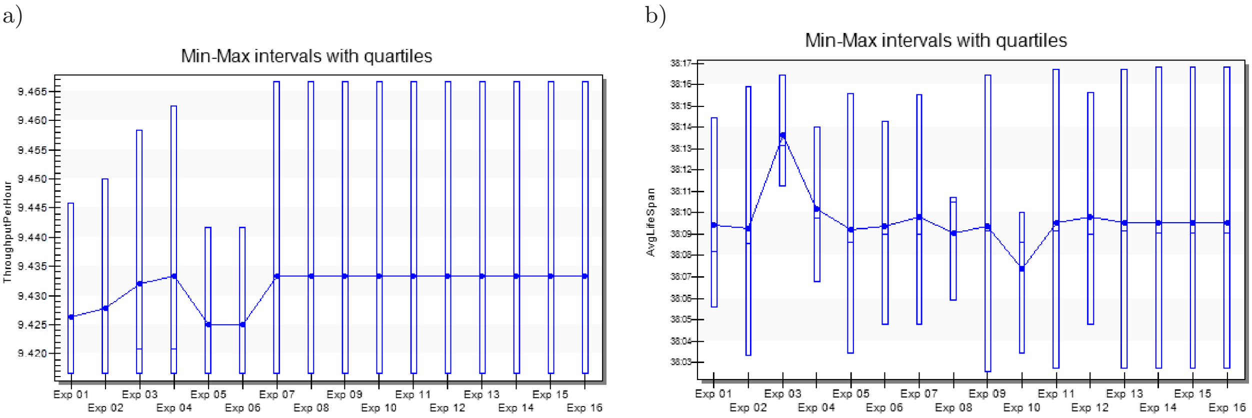
a) b)

Fig. 11. a) The throughput of the system for the number of workers and operation times defined in V_23; b) the average lifespan of products of the system for the number of workers and operation times defined in V_23.

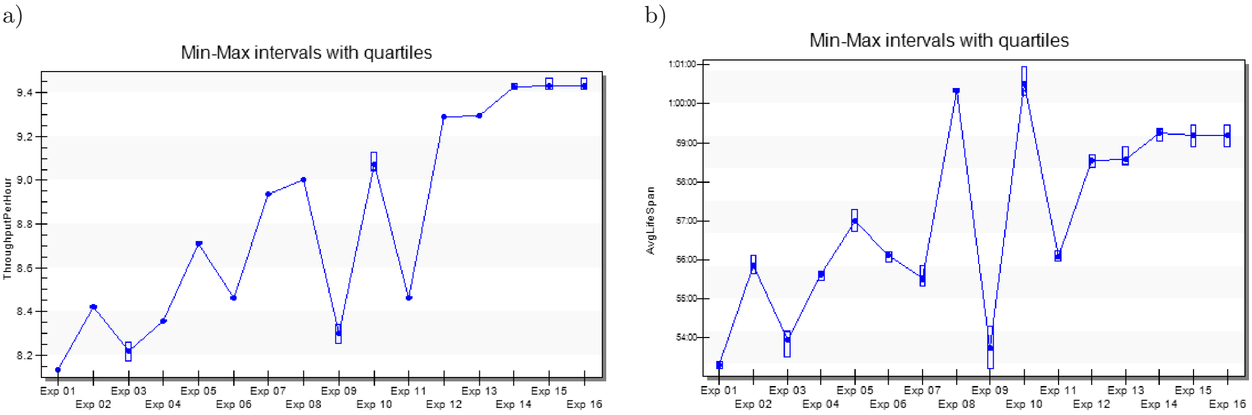
a) b)

Fig. 12. a) The throughput of the system for the number of workers and operation times defined in V_24; b) the average lifespan of products of the system for the number of workers and operation times defined in V_24.

In Figs. 11a and 11b the results of simulation experiments for variant V_23 are presented.

The maximum throughput of the system is about 9 parts per hour and is obtained for all buffer capacities. The lifespan for the throughput was about 39 minutes. The values are obtained for 6 workers. If 2 workers are dedicated to each technological operation, the throughput of the system is constant regardless of the size and allocation of the buffers. That means that for this configuration of operation times and allocation of operators, the buffer allocation does not affect the throughput.

In Figs. 12a and 12b, the results of the simulation experiments for variant V_24 are presented.

The maximum throughput of the system that is obtained is about 9 parts per hour. The lifespan for the throughput was about 1 hour. The values are obtained for 4 workers.

An analysis of the results of the experiments shows that a similar throughput of the system can be obtained through different allocations of buffers and workers. Generally-speaking, an increase in the buffer capacity and the number of workers leads to an increase in the throughput of the system. Of course, if the total buffer capacity is greater; the average lifespan of the products increases and that results in greater costs of production (more work in process). The same problem occurs with increasing the number of workers which results in greater labor costs. To find the best compromise between throughput and average life span; flow index θ is proposed. To calculate the index, the value of the throughput of the system is divided by the average life span and the total number of workers.

$$\theta = \frac{T}{\Lambda \cdot L}, \tag{11}$$

where T denotes throughput, Λ is the average lifespan and, respectively, L is number of workers. In Fig. 13 and in Table 5, the values of the flow index for variants V_11, V_12, V_13 and V_14 are presented.

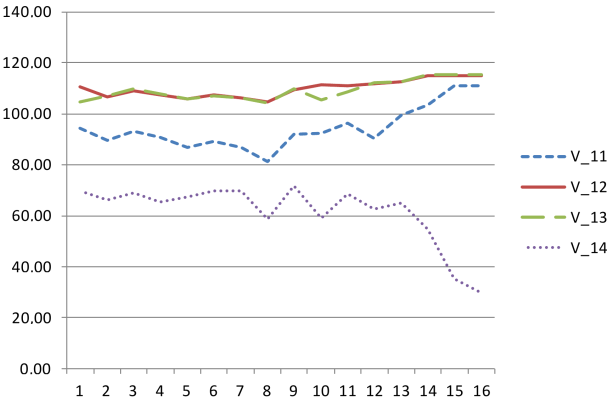

Fig. 13. The values of the flow index for different numbers of workers for variants V_11, V_12, V_13 and V_14.

Table 6
The values of the flow index for different numbers of workers for variants V_11, V_12, V_13 and V_14.

	V_11	V_12	V_13	V_14
Exp 1	94.48	**110.59**	104.77	69.75
Exp 2	89.56	106.80	107.02	66.34
Exp 3	93.31	109.18	**110.00**	68.93
Exp 4	90.65	107.56	107.66	65.57
Exp 5	86.81	105.81	105.95	67.32
Exp 6	89.32	107.35	107.05	69.83
Exp 7	86.68	106.44	106.16	69.77
Exp 8	81.31	104.83	104.31	58.64
Exp 9	91.79	109.40	109.74	71.63
Exp 10	92.48	**111.28**	105.67	59.10
Exp 11	96.43	**110.93**	108.74	68.75
Exp 12	90.37	**111.82**	**112.06**	62.80
Exp 13	99.46	**112.55**	**112.70**	64.95
Exp 14	103.43	**115.13**	**115.33**	54.77
Exp 15	**110.85**	**115.12**	**115.43**	35.13
Exp 16	**110.87**	**115.12**	**115.43**	29.85

The best values of the flow index are obtained for variants V_12 and V_13. The values greater than 110 in Table 6 are marked in bold.

In Fig. 14 and in Table 7, the values of the flow index for variants V_21, V_22, V_23 and V_24 are presented.

The best values of the flow index are obtained for variant V_22. In Table 5, the values greater than 71 are marked in bold. An analysis of the research shows that the best allocation of buffers and workers was obtained for variant V_13 and experiment 3 (total capacity of the buffers: 3, and number of workers: 6).

In the next chapter, the final conclusions and directions for further research are presented.

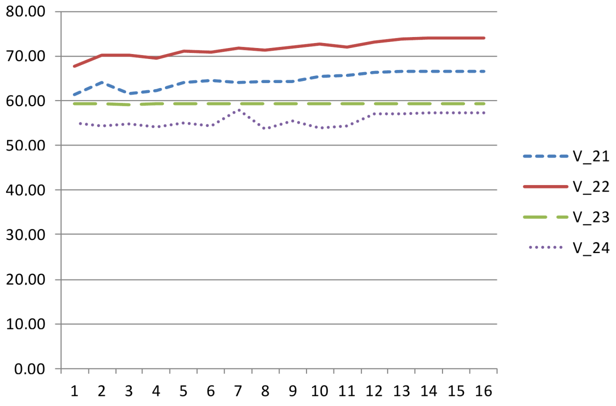

Fig. 14. The values of the flow index for different numbers of workers for variants V_21, V_22, V_23 and V_24.

Table 7
The values of the flow index for different numbers of workers for variants V_21, V_22, V_23 and V_24.

	V_21	V_22	V_23	V_24
Exp 1	61.32	67.71	59.29	54.95
Exp 2	64.09	70.24	59.30	54.28
Exp 3	61.64	70.33	59.22	54.83
Exp 4	62.40	69.49	59.31	54.09
Exp 5	64.02	**71.19**	59.29	55.03
Exp 6	64.66	70.87	59.28	54.28
Exp 7	64.23	**71.76**	59.32	57.95
Exp 8	64.46	**71.31**	59.34	53.70
Exp 9	64.37	**72.06**	59.33	55.61
Exp 10	65.37	**72.77**	59.39	54.01
Exp 11	65.68	**72.16**	59.33	54.35
Exp 12	66.43	**73.23**	59.32	57.15
Exp 13	66.56	**73.96**	59.33	57.12
Exp 14	66.60	**74.06**	59.33	57.27
Exp 15	66.60	**74.08**	59.33	57.38
Exp 16	66.60	**74.08**	59.33	57.38

Conclusions

In this paper, an analysis of the throughput and life span of a series-parallel production line based on a computer simulation is presented. Simulation experiments were conducted for different allocations and capacities of intermediate buffers, different allocations and numbers of workers and for different orders of technological operations (increasing and decreasing operation times). The formulated hypotheses are confirmed by the simulation research. For example: it was demonstrated that in variants V_12 and V_13 a smaller number of workers can obtain the same level of throughput as a higher number of workers. The order of the operation impacts the throughput of the system (hypothesis 2) which results in a comparison of variants V_11 and V21 (overall – the throughput for variants V1x is greater than for variants V2x).

Increasing the total buffer capacity in the system, does not always results in an increase of the throughput (hypothesis 3). Experiment 9 for variants V_21 and V_22 shows that with a smaller total capacity of intermediate buffers, a greater throughput value can be obtained (compare this with experiments 5 and 6).

The last hypothesis formulated in this paper concerned the impact of the total number of workers in the system on the throughput. A comparison of variants V_22 and V_21 shows that the same level of throughput can be obtained by a smaller number of workers.

The results of the simulation research enabled us to formulate the following conclusions for the investigated model of a manufacturing system:

- increasing operation times enable to increase greater throughput values,
- to compare the effectiveness of different variants of a series-parallel production line, a flow index is proposed that includes: throughput, the number of workers and the average lifespan of products,
- the proposed simulation methodology enables the discovery of a satisfactory allocation of buffers and workers that guarantees proper values of the throughput of the system.

Further research will be focused on finding a relationship between the structure of the production orders, setup times and the throughput of the system and the average lifespan of products.

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