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THE IMPACT OF THE AVAILABILITY OF RESOURCES, THE ALLOCATION OF BUFFERS AND NUMBER OF WORKERS ON THE EFFECTIVENESS OF AN ASSEMBLY MANUFACTURING SYSTEM

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Abstract

This paper proposes the application of computer simulation methods in order to analyse the availability of resources, buffers and the impact of the allocation of workers on the throughput and *work-in-progress* of a manufacturing system. The simulation model of the production system is based on an existing example of a manufacturing company in the automotive industry. The manufacturing system includes both machining and assembly operations. Simulation experiments were conducted *vis-à-vis* the availability of the different manufacturing resources, the various allocations of buffer capacities and the number of employees. The production system consists of three manufacturing cells – *each cell including two CNC machines* – and two assembly stations. The parts produced by the manufacturing cells are stored in buffers and transferred to the assembly stations. Workers are allocated to the manufacturing cells and assembly stations, but the number of workers may be less than number of workplaces and are thus termed '*multi-workstations'*. Using computer simulation methods, the impact of the availability of resources, the number of employees and of the allocation of buffer capacity on the throughput and *work-in-progress* of the manufacturing system is analysed. The results of the research are used to improve the effectiveness of manufacturing systems using a decision support system and the proper control of resources. Literature analysis shows that the study of the impact of buffer capacities, availability of resources and the number of employees on assembly manufacturing system performance have not been carried out so far.

Keywords

computer simulation, availability of resources, buffer allocation, throughput analysis, work-in-progress.

Introduction

The effectiveness of a production system is often a very important aspect in deciding the competiveness of manufacturing enterprises. The automotive sector, in particular, requires high throughput and quality from its parts suppliers. Relatively low profit margins limit the technological possibility for small and medium companies, which produce many hundreds of thousands of parts monthly, to increase their effectiveness. However, many manufacturing enterprises have huge potential to effectively improve their production planning and control by the implementation of new methods and re-tooling. Increases in throughput in a manufacturing system can be reached by the proper allocation of buffer capacities, employees and by improving the availability of resources.

Because of the variety of manufacturing system structures and the different assumptions and limitations concerned with manufacturing orders, it is very difficult to find optimal solution using mathematical models. Most of the combinatorial optimisation problems are NP-hard. Therefore, the implementation of computer simulation methods to analyse the behavior of individual systems enables interesting results to be obtained over a relatively short period of time. Of course simulation does not guarantee finding any optimal solution but on the basis of a relatively small number of experiments, sufficient solutions can be found.

Simulation is a very important research method used for the modelling, analysis and development of manufacturing systems. Many scientific papers include the application of computer simulation in the general design of manufacturing systems and in the analysis of the operational, production planning and scheduling of manufacturing systems [1]. Jahangirian *et al.,* report the results of a review of the application of simulations, published within peer-reviewed literature, between 1997 and 2006 and the analysis of the role of simulation techniques within manufacturing and business [2]. Jagstam and Klingstam use discrete event simulation as an aid to conceptual design and the pre-study of manufacturing systems through developing a virtual factory. They propose a simulation handbook to fully integrate simulation as a tool in engineering processes. They also identify the problems associated with integration into the design of manufacturing systems of discrete event simulation [3]. Simulation methods are often used to design and analyse the effectiveness of automated, guided vehicles in manufacturing plants. Lim *et al.* used the total travel time, including the waiting and interference out of service breakdown time of vehicles, as the deciding simulation factor for determining the direction of path segments on uni-directional guide path layouts [4]. Um *et al.* present the simulation design and analysis of a Flexible Manufacturing System (FMS) with an Automated Guided Vehicle system (AGVs). To maximise the operating performance of FMS with AGVs, many parameters were considered, including the number, velocity, and dispatching rule of AGV, part-types, scheduling, and buffer sizes [5]. Vasudevan *et al.* describe the application of simulation with bottleneck analysis, work measurement, floor space requirements and facility layout analysis, in order to improve the efficiency, and hence the reliability and profitability, of steel-mill manufacturing [6]. Jithavech and Krishnan present a simulation-based method in order to develop an efficient layout design facility, however with uncertainty as to the demand for the product. The validation of the simulation approach, against analytical procedures, was detailed firstly and the methodology for a simulation based approach was then provided. Results from case studies showed that this procedure results in a reduction of risk of as high as 80% [7]. Yang *et al.* propose the use of simulation and a digital factory to construct a virtual plant environment in order to implement integration between process planning and manufacturing [8]. Reeb *et al.* examine how 11 part-families were developed and then selected, using discrete event simulation for cell manufacture and subsequent exclusion from the current manufacturing system of a value-added, wood products company. Using simulation and management input, two of the 11 part-families, representing 51 different part types, were chosen for exclusion from the traditional job shop floor. This exclusion resulted in an average total *work-in-process* reduction of 112 parts which represented a 17% reduction [9]. 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 [10]. Azadeh *et al.* present a decision-making model for optimisation of operator allocation in a Cellular Manufacturing System (CMS) using the computer simulation method and a genetic algorithm. They determine the number of cross-trained operators and optimum operator layouts with respect to the cellular condition in a CMS using an integrated approach [11].

Hsueh proposes a new design for a bi-directional automated guided vehicle (AGV) system, using simulation, in which two AGVs could exchange their loads, their scheduled transportation tasks and even their vehicle numbers when they move in opposite directions [12].

The problem of maximising the throughput of production lines, by changing buffer sizes, or locations, using simulation methods was studied by Vidalis *et al.* [13]. The critical literature overview in the area of buffer allocation and production line performance was done by Battini, Persona and Regattieri [14] while 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 [15]. Stanley and Kim presented the results of simulation experiments carried out for buffer allocations in closed, series-production lines [16].

In this article, computer simulation methods are used to analyse the impact of the availability of resources, buffer capacities and the allocation of users in the production system and on throughput and *work-in-progress.* The research was performed on a production system which included 3 manufacturing cells, including 2 CNC machines, and 2 assembly stations. The material flow was directed to the individual machines on the basis of the *round robin* dispatching rule. The processing time of the machines is determined by uniform distribution, to model random numbers that are located between the interval bounds *Start and Stop*. In the model of the system presented, production of three various products is simulated. Each product is manufactured using different batch sizes; when changing production batches, set-up times must be taken into consideration.

Generally, the main research problem can be formulated as follows:

Given that a manufacturing system includes machining and assembly operations, and that between individual operations, intermediate buffers are allocated, how, then, do different numbers of workers, buffer capacities and available resources impact on the system's throughput and the average lifespan of the products?

To solve this problem, a set of simulation experiments was conducted in which the input values were the varying capacities of the intermediate buffers, different numbers of workers and variations in the availability of manufacturing resources and where the output values were the throughput of the system and the average lifespan of the products. The motivation of authors is finding general relations among the resources, buffer allocation and effectiveness of the assembly manufacturing system using simulation methods. Solving of the research problem enable to propose algorithms of buffer and resources allocation to obtain determined performance of manufacturing system. The simulation research was performed using *Tecnomatix Plant Simulation* software. In the next chapter, the simulation model of the production system is described.

A simulation model of a manufacturing system

The model of the production system was prepared on the basis of an existing example of a manufacturing system, dedicated to the production of metal parts for the automotive sector. The model and simulation experiments were implemented using *Tecnomatix Plant Simulation* software, version 11.0.0, and are presented in Fig. 1.

The manufacturing system studied included machining operations realised in three production cells, at two CNC machines per cell, and two assembly operations. The machines are marked as ST11, ST12, ST21, ST22, ST31, ST32 and the assembly stations as AS01 and AS02. Intermediate buffers are allocated between the production cells and the assembly stations. A buffer is also allocated between the two assembly stations. The processing times of the resources are defined on the basis of uniform statistical distribution. Uniform distribution may be used to model a random number that is located between the interval bounds, ***Start and Stop***.

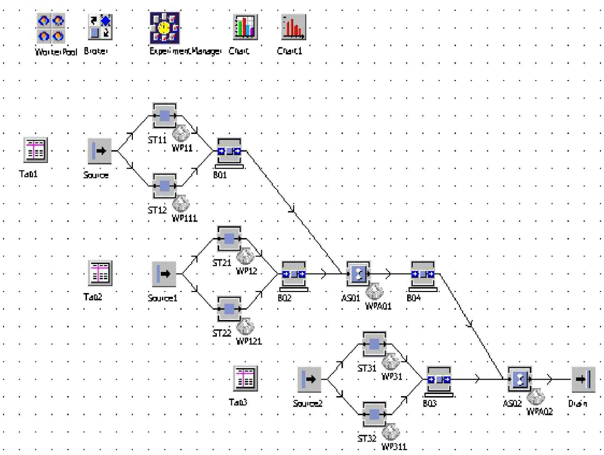


Fig. 1. A simulation model of the manufacturing system.

Uniform distribution can be used when not much is known about the random numbers, that is, the processing times. The probable density function of the uniform distribution for $start < x < stop$ is:

$$f(x) = \frac{1}{(\text{stop} - \text{start})}. \tag{1}$$

The mean is:

$$\mu = \frac{\text{start} + \text{stop}}{2} \tag{2}$$

and the variance is

$$\sigma^2 = \frac{(\text{stop} - \text{start})^2}{2}. \tag{3}$$

An example of the density function of uniform distribution is presented in Fig. 2.

The processing times in CNC machines is characterised by a discrepancy of about 10 minutes being the difference between ***Start and Stop***. The set-up time for all workstations is determined by uniform distribution where $start = 10$ and $stop = 20$. The values of processing times for CNC machines are presented in the Table 1.

The results in Table 1 show that assembly operations are much shorter than machining operations. In the system, three batches of products are processed cyclically, where batch sizes are 100, 50 and 300 pieces respectively. In the system, 30 simulation experiments are prepared for the capability of different resources and the capacity of the buffers. The experiments are conducted for different numbers of employees. In the next chapter, the results of the simulation experiments are presented.

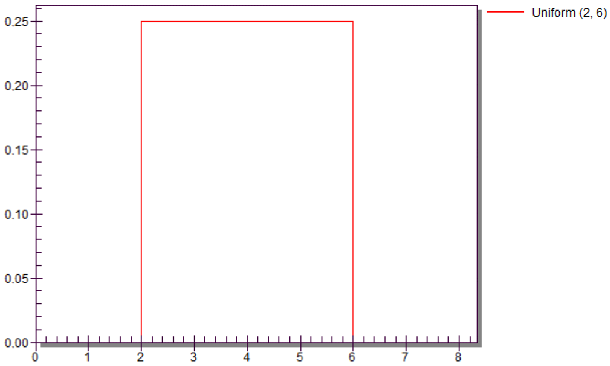


Fig. 2. Density function of uniform distribution for *start* = 2 and *stop* = 6 [17].

Table 1
Processing times for the production resources.

Station	***Start***	***Stop***
ST11	5:00	1:00
ST12	5:00	1:00
ST21	5:00	1:00
ST22	5:00	1:00
ST31	5:00	1:00
ST32	5:00	1:00
AS01	1:00	5:00
AS02	1:00	5:00

The outcome of computer simulation experiments

Figure 3 presents the proposed methodology for the simulation research. Research hypotheses are formulated for the activity of the manufacturing system. In the first step of the procedure, the following hypotheses are formulated:

1. An increase in intermediate buffer capacity results in an increase in the throughput of the system.
2. An increase in the availability of manufacturing resources results in an increase in the throughput of the system if buffer capacity is properly allocated.
3. There is an optimal number of workers and buffer capacity allocation which will guarantee maximum throughput of the system.
4. The average lifespan of the products depends on the allocation of buffer capacity, the number of workers and the availability of resources.

The proposed methodology of scientific research include:

- describing of the assembly manufacturing system and execution of a simulated model.
- preparation of the simulation experiments (allocation of the buffer capacity, and resources (CNC machines) availability.
- conducting of the simulation experiments.
- repeat experiments for different numbers of employees.

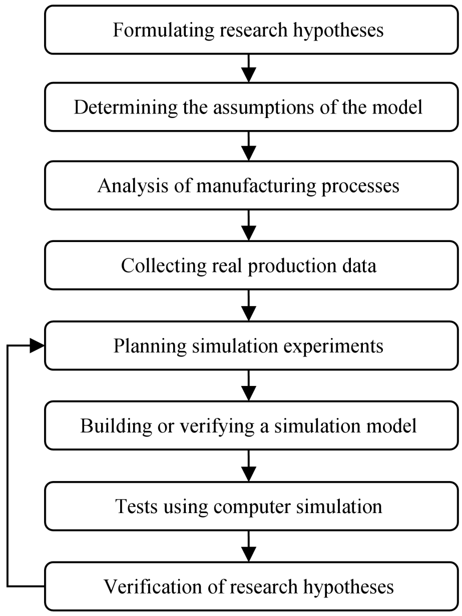


Fig. 3. The procedure for conducting simulation studies

A simulation model is created on the basis of an analysis of an existing manufacturing system; *q.v.* Fig. 1. Processing and set-up times are defined using statistical distribution selected on the basis of real time measurement. Simulation experiments are carried out in order to verify formulated hypotheses. Input values for the experiments are presented in Table 2.

Variables AS01 and AS02 determines the availability of assembly stations. Variables ST11, ST12, ..., ST32 determines the availability of workstation (CNC machines) and variables B01, B02, ..., B04 buffer capacities. Input values for the experiments include the availability of production resources, which changes from 95% to 99% and buffer capacity, which changes from 1 to 20. The combination of the parameters provide 30 experiments. The experiments are conducted for 3, 5 and 6 workers. What is interesting is that no additional increase in the number of workers has any impact on improving system throughput.

The first set of experiments is conducted for 3 workers although, as a general rule, there are 8 workplaces in the system. The results of the experiments *viz.* the throughput and the average product lifespan are presented in Figs. 4a and 4b respectively.

Table 2
Input values defined for experiments.

	ST11	ST12	ST21	ST22	ST31	ST32	AS01	AS02	B01	B02	B03	B04
Ex01	95	95	95	95	95	95	95	95	1	1	1	1
Ex02	96	96	96	96	96	96	96	96	1	1	1	1
Ex03	97	97	97	97	97	97	97	97	1	1	1	1
Ex04	98	98	98	98	98	98	98	98	1	1	1	1
Ex05	99	99	99	99	99	99	99	99	1	1	1	1
Ex06	95	95	95	95	95	95	95	95	2	2	2	1
Ex07	96	96	96	96	96	96	96	96	2	2	2	2
Ex08	97	97	97	97	97	97	97	97	2	2	2	2
Ex09	98	98	98	98	98	98	98	98	2	2	2	2
Ex10	99	99	99	99	99	99	99	99	2	2	2	2
Ex11	95	95	95	95	95	95	95	95	4	4	4	4
Ex12	96	96	96	96	96	96	96	96	4	4	4	4
Ex13	97	97	97	97	97	97	97	97	4	4	4	4
Ex14	98	98	98	98	98	98	98	98	4	4	4	4
Ex15	99	99	99	99	99	99	99	99	4	4	4	4
Ex16	95	95	95	95	95	95	95	95	5	5	5	5
Ex17	96	96	96	96	96	96	96	96	5	5	5	5
Ex18	97	97	97	97	97	97	97	97	5	5	5	5
Ex19	98	98	98	98	98	98	98	98	5	5	5	5
Ex20	99	99	99	99	99	99	99	99	5	5	5	5
Ex21	95	95	95	95	95	95	95	95	10	10	10	10
Ex22	96	96	96	96	96	96	96	96	10	10	10	10
Ex23	97	97	97	97	97	97	97	97	10	10	10	10
Ex24	98	98	98	98	98	98	98	98	10	10	10	10
Ex25	99	99	99	99	99	99	99	99	10	10	10	10
Ex26	95	95	95	95	95	95	95	95	20	20	20	20
Ex27	96	96	96	96	96	96	96	96	20	20	20	20
Ex28	97	97	97	97	97	97	97	97	20	20	20	20
Ex29	98	98	98	98	98	98	98	98	20	20	20	20
Ex30	99	99	99	99	99	99	99	99	20	20	20	20

a) b)

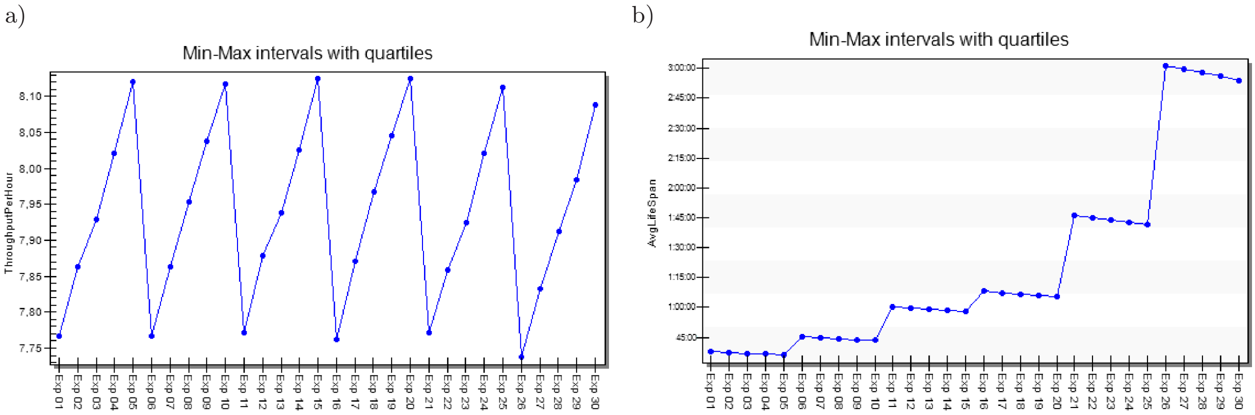


Fig. 4. a) Throughput of the system when serviced by 3 workers, b) average lifespan of products in the system with 3 workers

If the manufacturing system is serviced by 3 workers only, the maximum throughput of the system is reached if the availability of resources is 99%; however, the allocation of buffer capacity does not matter; in fact, the throughput, at maximum buffer capacity, is smaller.

Maximum throughput of the system equals 8 to 12 products per hour and is achieved with smaller buffer capacities. An increase in buffer capacity impacts on the lifespan of the average product. Fig. 4b shows a time increase in the average residence time of the workpieces in the system from 37 minutes to 2 hours and 53 minutes. The throughput of the system is almost without change.

The resource statistics are presented in Fig. 5. The CNC machines ST11 and St12 are blocked because of the lack of human resources, that is, the lack of staff which blocks the whole system. Generally, resources are used at the rate of 50%. The resources statistics chart, given below, is for the last experiment, that is, Exp 30.

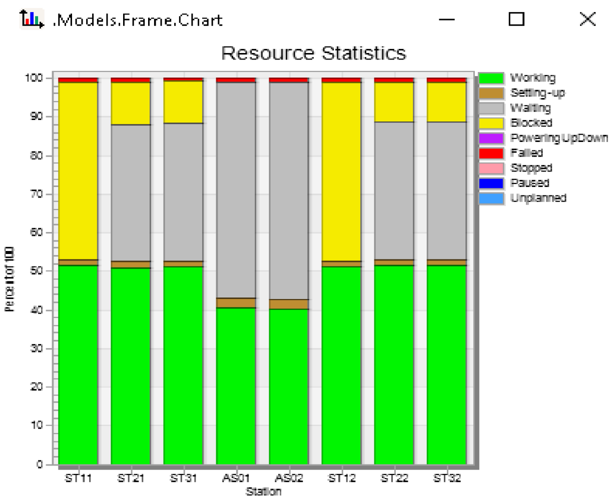


Fig. 5. Resource utilisation for 3 workers.

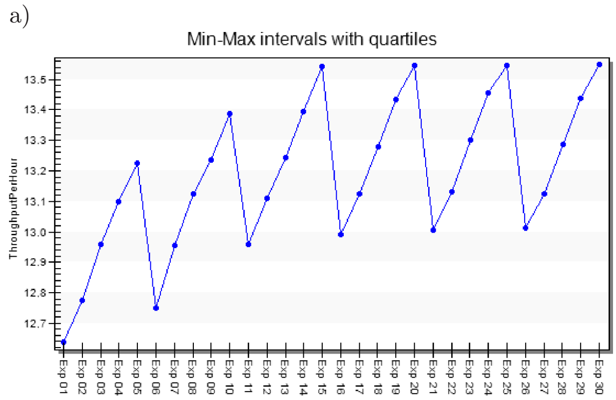
If the number of workers is increased to 5, the maximum throughput of the system is increased to 13.55 products per hour. An increase in intermediate buffers has little impact on the throughput; in buffer capacities 1 and 2, the maximum throughput of the system is 13, 23 and 13.38 respectively. The values of the throughput are presented in Fig. 6a.

Generally, small buffer capacities result from a small throughput within the system; however for buffer capacities greater than 2, the throughput is solely dependent on the availability of resources.

The average product lifespan (Fig. 6b) is significantly increased where buffer capacities equal 20 and the availability of resources equals 96%, the average lifespan of the product being 1 hour and 24 minutes. Increasing the availability of resources does not always result in any reduction in the average lifespan of the product; – *q.v.* and compare- the average product lifespan values for experiments 29 and 30.

The percentage of filled buffers for the last experiment is presented in Fig. 7. The buffers are filled relatively evenly; only buffer B01 is almost filled with 20 products.

a)



b)

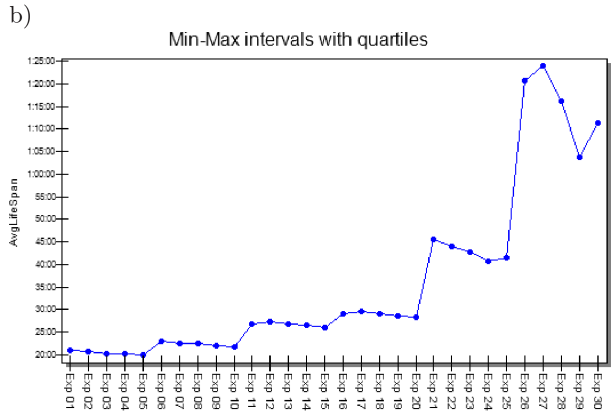


Fig. 6. a) Throughput of the system when serviced by 5 workers, b) average lifespan of products in the system with 5 workers.

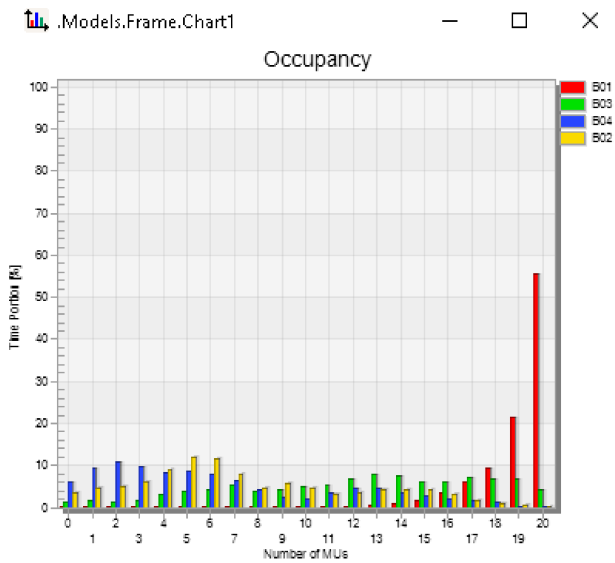
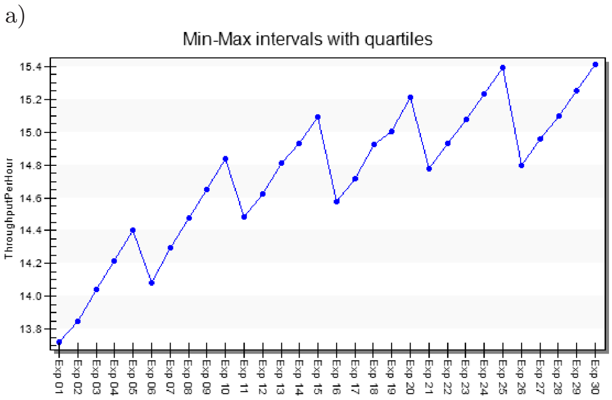


Fig. 7. The buffer occupancy of the system serviced by 5 workers.

Buffer B04 is almost filled with 3–6 products and buffer B02, with 5 or 6 products. Buffer B03 is usually filled with 16–18 products. In the next step of the research, the number of workers increases to 6 persons. The results of the throughput and average lifespan are presented in Figs. 8a and 8b. In the system with 6 workers, the impact of the intermediate buffers is significant.

a)



b)

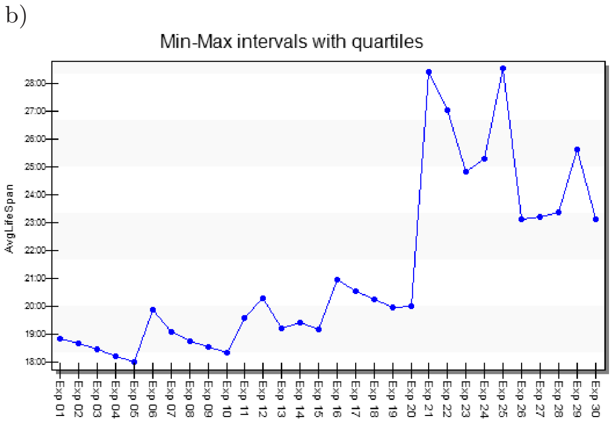


Fig. 8. a) Throughput of the system when serviced by 6 workers, b) average lifespan of products in the system with 6 workers.

The best value of the throughput is reached with buffer capacities of 10 and 20 which are practically the same values as for the analogical values of the availability of resources. As can be seen from the chart presented in fig. 8a, the results obtained for the various combinations of the availability of resources and buffer capacities, indicate that the same level of throughput can be reached. For example, in the system with an availability of resources of 99% and buffer capacities of 2, the same throughput can be reached as for the system with an availability of resources of 96% and buffer capacities of 4, with their respective throughputs being 14,65 and 14,62 products per hour. The average lifespan of products for the system with 6 workers is presented in Fig. 8b.

The significantly shorter stay of products within the system results in a smaller number of *works-in-progress*.

The greatest value for the average lifespan of products, that is, more than 28 minutes, is reached with a buffer capacity of 10 and a resources availability of 95% and 99%. For the final experiments, all resources without assembly stations are utilised maximally, see Fig. 9, which means that by using 6 workers, the system obtains maximum effectiveness of production. The occupancy chart for intermediate buffers for 6 workers and Exp 30 is presented in Fig. 10.

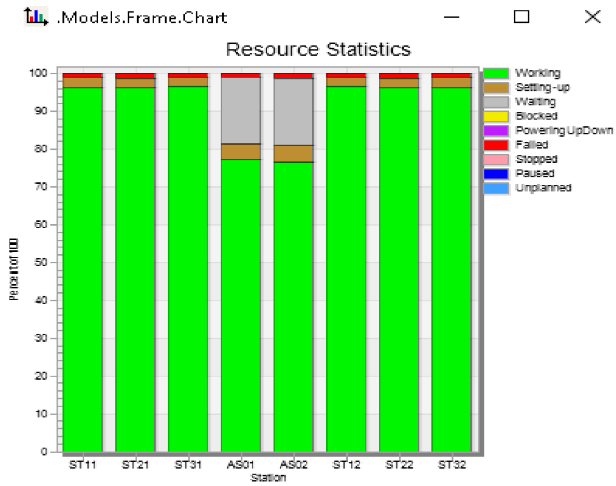


Fig. 9. Resource utilisation for 6 workers.

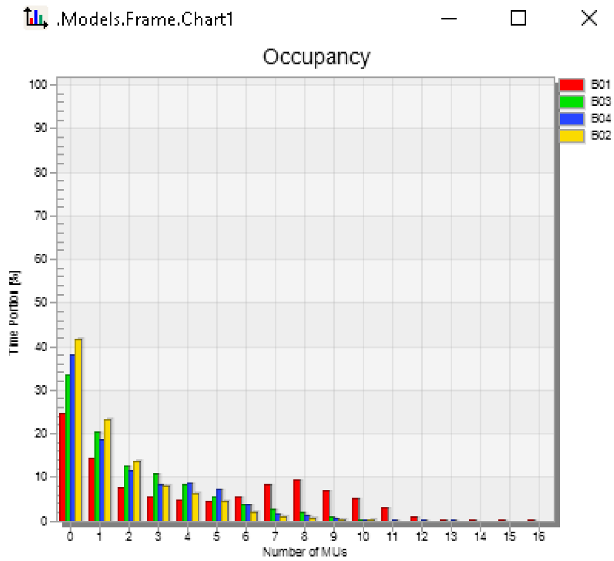


Fig. 10. Buffer occupancy of the system serviced by 6 workers.

Buffers primarily hold from 0 to 5 products with only buffer B01 including more products (0–10). Further increases in the number of workers has no impact on the throughput of the system or on the average lifespan of the products. From the analysis of the experiments, it can be seen that the maximum throughput of the production system, *viz.* more than 15 products per hour, can be obtained with the maximum availability of resources and with the maximum number of users and with an intermediate buffer capacity greater than 10.

Increasing the capacity of intermediate buffers, however, results in an increase in *work-in-progress*, that is, in the average lifespan of the products. The greater the availability of manufacturing resources, then the greater is the requirement to use new CNC machinery and assembly stations.

To evaluate the objective impact of the selected parameters on the efficiency of the system, a new efficiency index γ is proposed, *q.v.*

$$\gamma = \frac{\mathrm{E}}{\alpha \cdot \varphi \cdot \upsilon} \cdot 100, \tag{4}$$

where E – throughput of the system, α – average resources availability, φ – number of workers, υ – average lifespan of products.

The efficiency index γ is proposed to present in simple form, algebraic relation among throughput, number of workers, resources availability and lifespan (buffer capacity).

The index can be used to evaluate generally behavior of the system. If some parameters are more important, weight values can be used. The values of the efficiency index for experiments are presented in Table 3 and Fig. 11.

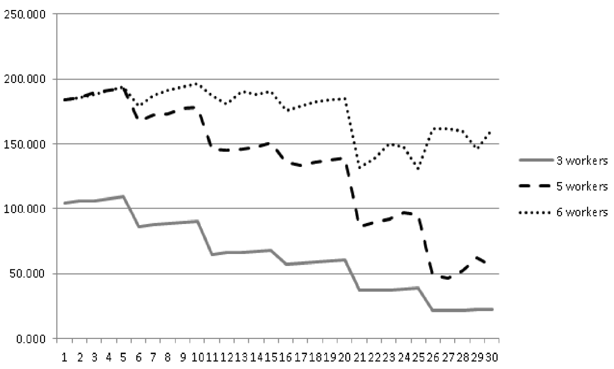


Fig. 11. Values for efficiency index γ for the experiments.

In the table, efficiency indices greater than 190 are marked. The greatest values are obtained for experiment 05 for 5 and 6 workers and experiments 09 and 10 for 6 workers.

Generally, increasing intermediate buffer capacity results in an increase in the average lifespan of products or *work-in-progress*. In the next chapter, the final conclusions and directions for further research are presented.

Table 3
Resource utilisation for 6 workers.

	3 workers	5 workers	6 workers
Exp 01	104,358	183,817	184,145
Exp 02	105,765	185,864	185,505
Exp 03	106,316	189,477	188,477
Exp 04	107,661	**191,354**	**191,375**
Exp 05	109,269	**193,368**	**194,188**
Exp 06	86,644	167,375	178,999
Exp 07	87,880	172,184	187,449
Exp 08	89,028	173,493	**191,297**
Exp 09	89,887	177,506	**193,765**
Exp 10	90,742	178,549	**196,228**
Exp 11	64,898	146,228	187,075
Exp 12	65,990	144,795	180,399
Exp 13	66,317	146,184	**190,881**
Exp 14	66,964	147,721	188,518
Exp 15	67,925	150,959	**190,897**
Exp 16	57,472	135,689	175,974
Exp 17	58,466	133,357	179,036
Exp 18	59,250	135,917	182,585
Exp 19	59,732	137,831	184,200
Exp 20	60,388	139,000	184,569
Exp 21	37,015	86,495	131,388
Exp 22	37,456	89,441	138,119
Exp 23	37,719	92,406	150,376
Exp 24	38,236	97,327	147,501
Exp 25	38,680	94,959	130,755
Exp 26	21,550	48,881	161,699
Exp 27	21,812	46,835	161,263
Exp 28	22,010	51,862	159,994
Exp 29	22,208	61,882	145,838
Exp 30	22,537	55,178	161,736

Conclusions

In this paper, an analysis of the throughput and life-span of a manufacturing system, using computer simulation, is presented. Simulation experiments were conducted for different capacities of intermediate buffers, different numbers of workers and for the different availability of manufacturing resources [18, 19]. A model of a manufacturing system was prepared using ***Tecnomatix Plant Simulation*** software on the basis of an actual manufacturing system [20]. The processing times were defined using uniform, statistical distribution. Three sets of experiments were prepared for 3, 5 and 6 workers. The research hypotheses are formulated and confirmed by the simulation research.

To evaluate the research experiments, an efficiency system was defined. The index enables the relationship between the throughput, the availability of resources, the number of workers and the average lifetime of the products to be analysed. Using the index from all the experiments and the allocation of intermediate buffers, the availability of resources within the system is selected which guarantees the optimum efficiency of the system.

The results of the simulation research has facilitated the formulation of the following conclusions for the model of the manufacturing system investigated:

- the capacity of intermediate buffers can significantly impact on the throughput of the manufacturing system,
- to evaluate the general efficiency of the throughput of a manufacturing system, *the-work-in-progress,* the number of workers and the availability of resources should all be taken into account,
- to obtain maximum throughput within a system, one worker should be allocated to a specific manufacturing resource, that is, 8 resources with only 6 workers,
- the same system throughput can be obtained for different combinations of the availability of resources, buffer capacities and numbers of workers.

The results presented in the paper could be implemented in industrial practice by allocation of personnel for assembly manufacturing system and allocation of buffer capacity when the availability of manufacturing resources are known. Further research will focus on finding a formal relationship between the throughput of the system, the average lifespan of the products, the buffer capacities, the number of workers and the availability of resources.

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