UDC 658.51.012.2:004.94:621.9.01

COMPARATIVE SIMULATIONS OF THE HEAVY MACHINING PRODUCTION SYSTEM

Igor STANKOVIĆ – Zlatan CAR – Branimir BARIŠIĆ

Abstract: *The purpose of this research is to focus on the solution of the resource sizing problem for the real production system. The resource sizing problem is tackled by usage of the mathematical makespan minimization method and comparative simulations of the two different production models. Only two production model simulations were realized due to specificities of the handled production system. Simulation results were presented, compared and discussed. This paper presents an approach which allows studying the heavy machine sizing problem realistically, through the use of simulation tools. The approach used would be of great help in making a decision on whether two new heavy machines should be introduced into an existing production system or not.*

Keywords:
– simulation
– optimization
– machining
– production planning
– production line design
– *Job shop* system

1. INTRODUCTION

A significant part of different scientific areas, especially the technical ones, is characterized by the search for adequate computer models and the most suitable computer simulation software. Without numerous scientific experiments, mathematical methods and modern computer applications which enable the modelling and simulation of previous, existing and future production processes, it would be impossible to develop new technologies, materials and tools that are used in various production environments, [1-9]. *Discrete Event Simulation* has long been a popular technique for studying industrial processes, but it is also widely used for planning purposes–especially for evaluating different design alternatives in a production process [10,11]. Discrete event simulation's methodology is based on the notion that, once properly validated, we can use *models* to help us in answering difficult questions about complex systems. A good simulation model can significantly improve our understanding of a system's behavior. In many dynamic processes, particularlyin industrial contexts like manufacturing, transportation and inventory management, system states change at discrete points in time (i.e. events), rather than through continuous state fluctuations. Queues in front of a group of machines or other manufacturing facilities are an example, since their lengths (number of items queuing for service) only changes when items arrive or depart. Such *queuing networks* typically consist of discrete components, such as machines and workpieces whose behaviors cause state changes through discrete events, which will be dispersed randomly along a model's timeline. In such discrete event simulations, it is often desirable or even necessary to treat many model components as individuals, each with their own properties and processing history. [12] offers a concise introduction and summary of discrete event simulation foundations. As per [10], "Carefully planned simulation studies can yield valuable information without an undue amount of computational effort or (more importantly) your time." [10-13].

This article aims to explore the benefits of using the simulation software agent to support resource sizing of the actual heavy machining production system. There are several specificities that distinguish observed heavy machining production system from the other usual machining production systems. The process plan of each component that should be machined has to be strictly followed so there are no possibilities for a makespan minimization in terms of machining operations rescheduling. The two most important machines in the production system are the portal milling machine and the horizontal lathe, which are the only appropriate machines for the machining of several crucial ship engine components. The next specificity of the observed machining system is that the crucial components of the engine cannot be machined anywhere within a radius of 200 miles. This is an important fact from an economical point of view.

Simulation software was used in order to build two computer models of the mentioned production system. The first model represents the actual production system with a real machines layout plan, real setting and processing times, real time losses (included times needed for the components' crane transportation, machine breakdowns, etc.), and the second model will simulate the same production system with two of the most important additional machines. The results will help to project possible components machining times in the case of significant increase in job orders.

Before the simulations of the heavy machining production system, the shifting bottleneck heuristic method for the *job shop* system will be applied on Model 1, since the real production system properties completely match the theoretical *job shop* system, [14]. The purpose of utilizing the shifting bottleneck heuristic method is the possibility of production system optimization through the investigation of bottleneck machines.

2. COMPUTER MODEL DESCRIPTION AND ANALYSIS

In order to conduct a successful analysis of simulation results, it is necessary to describe all computer model construction elements as well as components that will be processed in the model. Heavy machining production system is comprised of seven machines:

- vertical lathe *Schiess*,
- horizontal lathe *Heyligenstaedt*,
- horizontal lathe *Waldrich Siegen*,
- portal milling machine *Waldrich Siegen*,
- horizontal drilling machine *Union Web*,
- horizontal drilling machine *Union,*
- radial drilling machine *Csepel*.

The machines listed above are inserted into the computer model from the material flow objects' database. Each working station is then appointed with a name which is further used in all programming codes. Machines are used for the machining of the following ship engine components:

- bedplate,
- crankshaft,
- flywheel,
- tuning wheel,
- monoblock column,
- connecting rod,
- cylinder jacket,
- cylinder liners,
- scavenge air receiver,
- fixed support,
- piston rods,
- exhaust manifold,
- cylinder cover platform.

Another additional component is the rudder. It is not listed above because it is not a component of the ship engine. Each of the mentioned components has its own process plan which defines all machining operations that should be performed. Machining technology also includes set up and machining times for each operation. These real production system parameters are further used in computer modelling and simulation.

As previously mentioned in the introduction, crucial components which, due to their size and complexity can be machined only on the portal milling machine and horizontal lathe are the bedplate, cylinder jacket and cylinder liners.

Figure 1 shows the computer model of the actual heavy machining production system, Model 1, constructed with computer simulation software *Tecnomatix Plant Simulation 9*.

Besides the work stations, several objects are shown in Figure 1. The objects named *Buffer* and *Shipping_buffer* are used as components buffers. Components that are waiting to be machined are buffered until the workstation is finished with the machining of the previous component. The capacity of the mentioned buffers is unlimited. Due to simplification, Figure 1 shows machines with indexes which are labelled in Table 1. Except for the seven machines mentioned, there is one more object which is presented like a working station and it is called the marking platform, so there will be a total number of eight workstations. Figure 1 also shows the following objects; different types of *Methods*, the *EventController*, the *Source*, the *Drain,* the *ShiftCalendar* and the *Statictic_Charts* objects. All listed objects and their function will be presented in the third chapter.

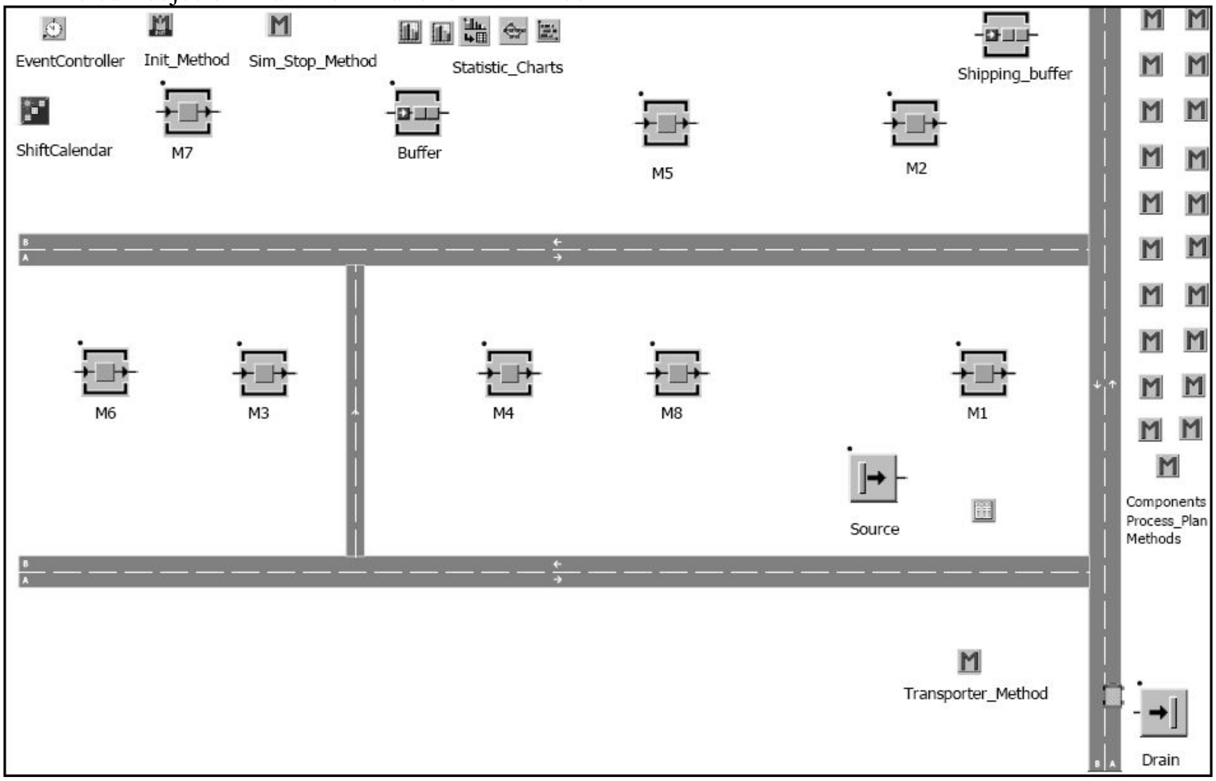

Figure 1. Computer model of the heavy machining production system, Model 1. See Table 1 for the indexation of the machines

2.1. Shifting bottleneck heuristic method analysis

The shifting bottleneck heuristic is a procedure intended to minimize the time it takes to do work, or specifically, the makespan in a *job shop*. The makespan is defined as the amount of time, from the start to finish, to complete a set of multi-machine jobs where a machine order is pre-set for each job. The shifting bottleneck heuristic is used in manufacturing and service industries that include job shops with constraints in the order that the machines are used for each job, [14]. As mentioned before, Model 1 is comprised of 8 workstations and 21 components that need to be machined. Due to problem simplification reasons, the component rudder will be left out since it has relatively short and insignificant machining time.

Furthermore, eight cylinder liners are transformed into one component because of eight identical process plans. Total machining time represents the sum of all single cylinder liner machining times so the production effect is unchanged. Therefore, the calculation is conducted for thirteen different components. Table 1 shows machine indexes that are going to be used in further calculations. Table 2 shows the components' processing plans with their machining times indicated in hours. As mentioned in the introduction, and in accordance with [14,15], the described Model 1 matches a *job shop* system with recirculation. Recirculation means that some components need to be machined on the same machine more than ones. Since recirculation occurs and in order to properly imply the heuristic method, process plans of recirculation components need to be reconfigured. Table 3 indicates reconfigured process plans.

Table 1. Indexation of the machines

Machines	
M1	Marking platform
M2	Vertical lathe Schiess
M3	Horizontal lathe Heyligenstaedt
M4	Horizontal lathe Waldrich
M5	Portal milling machine Waldrich
M6	Horizontal drilling machine Union Web
M7	Horizontal drilling machine Union
M8	Radial drilling machine Csepel

Table 2. Process plans with machining times

Component	Index	Process plan	Machining times [h]
Bedplate	J1	M1, M5, M1, M8, M5, M7, M8, M5	p11=17, p51=50, p11*=6, p81=28, p51*=99, p71=56, p81*=19, p51**=21
Crankshaft	J2	M7	p72=27
Flywheel	J3	M2, M1, M5, M8	p23=26, p13=8, p53=13, p83=2
Tuning wheel	J4	M2, M1, M7	p24=18, p14=3, p74=22
Monoblock column	J5	M1	p15=37
Connecting rod	J6	M5	p56=84
Cylinder jacket	J7	M7, M1, M5, M7, M8	p77=10, p17=19, p57=148, p77*=132, p87=60
Cylinder liners	J8	M4, M2, M6, M4	p48=284, p28=235, p68=307, p48*=300
Scavenge air receiver	J9	M1, M5, M7, M1, M5	p19=12, p59=24, p79=80, p19*=2, p59*=3
Fixed support	J10	M1, M6	p1-10=2, p6-10=26
Piston rods	J11	M3, M6, M3	p3-11=173, p6-11=114, p3-11*=213
Exhaust manifold	J12	M1, M5, M7, M1, M5	p1-12=7, p5-12=24, p7-12=2, p1-12*=5, p5-12*=8
Cylinder cover platform	J13	M1, M8, M5	p1-13=16, p8-13=4, p5-13=24

It is important to mention that, according to [6], *job shop* problem is considered as a single machine problem. The machining schedule is configured as the sum of due dates of job j on the machine i (d_{ij}) and release dates of job j on the machine i (r_{ij}). The job with the minimum value of the mentioned sum is processed first, in accordance with the process plan limitations. Values of the parameter d_{ij} are calculated in the following way:

$$d_{ij} = C_{\max} - p_{ij*} + p_{ij} . \qquad (1)$$

$C_{\max}$ is makespan of the system and it has a constant value, $C_{\max} = 1126$ h. p_{ij} is the processing time of job j on machine i and p_{ij*} represents the time difference between two operations. The first iteration for the machine M1 is carried out in order to get the value of $L_{\max}$.

Table 3. Table with included components' recirculation, machining operations are divided into several steps

Component	Index	Process plan	Machining times [h]
Bedplate	J1	M1, M5, M1, M8, M5, M7, M8, M5	p11=17, p51=50, p11*=6, p81=28, p51*=99, p71=56, p81*=19, p51**=21
	J1a	M1, M5	
	J1b	M1, M8, M5, M7	
	J1c	M8, M5	
Crankshaft	J2	M7	p72=27
Flywheel	J3	M2, M1, M5, M8	p23=26, p13=8, p53=13, p83=2
Tuning wheel	J4	M2, M1, M7	p24=18, p14=3, p74=22
Monoblock column	J5	M1	p15=37
Connecting rod	J6	M5	p56=84
Cylinder jacket	J7	M7, M1, M5, M7, M8	p77=10, p17=19, p57=148, p77*=132, p87=60
	J7a	M7, M1, M5	
	J7b	M7, M8	
Cylinder liners	J8	M4, M2, M6, M4	p48=284, p28=235, p68=307, p48*=300
	J8a	M4, M2, M6	
	J8b	M4	
Scavenge air receiver	J9	M1, M5, M7, M1, M5	p19=12, p59=24, p79=80, p19*=2, p59*=3
	J9a	M1, M5, M7	
	J9b	M1, M5	
Fixed support	J10	M1, M6	p1-10=2, p6-10=26
Piston rods	J11	M3, M6, M3	p3-11=173, p6-11=114, p3-11*=213
	J11a	M3, M6	
	J11b	M3	
Exhaust manifold	J12	M1, M5, M7, M1, M5	p1-12=7, p5-12=24, p7-12=2, p1-12*=5, p5-12*=8
	J12a	M1, M5, M7	
	J12b	M1, M5	
Cylinder cover platform	J13	M1, M8, M5	p1-13=16, p8-13=4, p5-13=24

Table 4 shows the values of parameters p_{1j}, r_{1j} and d_{1j} for the jobs processed on the machine M1. Furthermore, Table 4 indicates the values of lateness L_{1j} for the jobs j processed on the machine M1. L_{1j} is calculated as the difference between the due dates of job j on the machine M1 and completion times of job j on the machine M1.

S_{1j} represents the sum of all processing times of job j up to the machine M1. As indicated in Table 4, the value of the $L_{\max}$ (maximum lateness) for the machine M1 is - 885 h and it is < 0. An identical procedure is conducted for all remaining machines M2, M3, M4, M5, M6, M7 and M8.

Because of the comprehensiveness of the calculation procedure, only the final results will be indicated in this article. The values of the L_{max} for the remaining machines are as follows:

- M2= -540 h,
- M3= -740 h,
- M4= -300 h,
- M5= -586 h,
- M6= -677 h,
- M7= -813 h
- M8= -870 h.

Since the values of L_{max} are all negative, it means that there is no lateness in the system. Therefore, there is no need for further iterations, since there is no bottleneck machine in the system. This means that rescheduling of the job processing order, in accordance with the process plan limitations, would not give any results and there would not be any time savings. In accordance with the aforementioned statement, Model 2 will represent a computer model with changed input parameters, two more machines will be added, and the components' generation times (computer model entrance times) will be changed.

2.2. Differences between Model 1 and Model 2

Model 2 represents the theoretical system which needs to give the answer to the „what if" question. Model 2 is constructed with the purpose of investigating what is happening with Model 1 when one portal milling machine *Waldrich* and one horizontal lathe *Waldrich* are added to the existing production system. Two extra machines are added with the goal of minimizing the processing times of critical components (bedplate, cylinder jacket and cylinder liners). Furthermore, the components' generation times in Model 2 are derived as random variables. This will have an impact on the components' model entrance sequence. In the end, the simulation run for the Model 2 is realized, and the generated results are compared with the results from Model 1. The comments are given in section 3.1.

Figure 2 shows Model 2, the computer model of the theoretical heavy machining production system. Indexes of the Waldrich lathe and Waldrich milling machine have been changed from M4 and M5 to M4a and M5a. The index of the added Waldrich lathe is M4b and that of the added Waldrich milling machine is M5b.

Table 4. Values of the lateness L_{1j} for the jobs which are carried out on the machine M1

Job	p_{1j} [h]	r_{1j} [h]	S_{1j} [h]	C_{1j} [h]	d_{1j} [h]	L_{1j} [h]
7a	19	10	10	29	978	-949
1a	17	0	29	46	931	-885
9a	12	0	46	58	1022	-964
1b	6	67	58	64	1076	-1012
13	16	0	64	80	1098	-1018
10	2	0	80	82	1100	-1018
12a	7	0	82	89	1100	-1011
4	3	18	89	92	1104	-1012
5	37	0	92	129	1126	-997
3	8	26	129	137	1111	-974
12b	5	33	137	142	1121	-979
9b	2	116	142	144	1123	-979

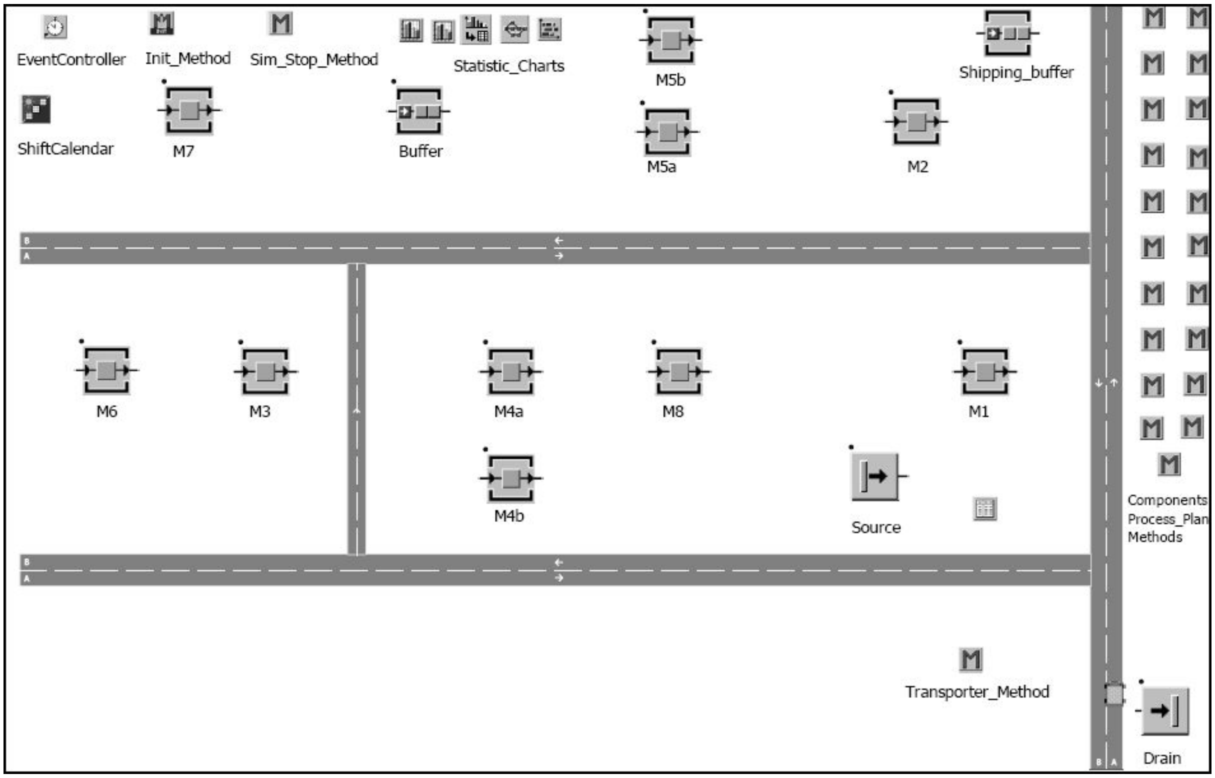

Figure 2. Computer model of the theoretical heavy machining production system, Model 2

3. COMPUTER MODEL SIMULATION

Computer simulation software *Tecnomatix Plant Simulation 9* is used for the construction of heavy machining production systems. Software supports graphical object implementation through the usage of the *drag & drop* method [16, 17]. The graphical database of generic objects is used to construct the computer model of the production system. The mentioned objects are then positioned in the computer model *Frame*. The function of *Frame* is to store all generic objects of the computer simulation model; furthermore, they can be implemented one within the other. This implementation method is called hierarchically modelling [16, 17].
Except for the mentioned *Frames,* there are other generic objects which can be divided into four different categories [16]:

- material flow objects,
- information flow objects,
- movable objects,
- user interface objects.

Objects which are a part of the material flow objects' group, apart from the others, are *Source* (used for the generation of movable objects during a simulation run), *EventController* (it starts and stops simulation, resets, coordinates and synchronizes different events taking place during a simulation run) and *Drain* (removes processed components from the model).
Objects which are a part of the information flow objects group, apart from the others are *Method* (it contains programming codes which describe components' process plans with defined setup and processing times), *DeliveryTable* (used for the different parameters list insertion, it organizes and reads entrance model parameters), *ShiftCalendar* (used for the implementation of working shifts). Apart from the others, *Transporter* (used for the transportation of machined components) is a part of movable objects.
Object *Chart* (used for graphical presentation of simulation run results) is a part of user interface objects.

3.1. Comparison of simulation run results

After completion of Model 1 and Model 2 simulation runs, the generated results show the differences between the two models.

Figure 3 shows the effects of the addition of two extra machines.

In the Model 2, productivity or the production time portion of some components has been increased and the storage time of some components has been decreased.

Of course, this refers to components, which have to be machined on the additional machines.

When the total production times of Model 1 and Model 2 were compared, it is clear that the total production time of Model 2 has been decreased (see Figure 4, *Average lifespan*). On average, the production times have been decreased by nine days. Besides those mentioned, there have been differences between the portions of working, delaying and setup times in Model 1 and Model 2. As can be seen, the working portion and machine setup time portion have been increased in Model 2. Furthermore, the delaying portion has been decreased in Model 2. The mentioned facts are mainly a product of the addition of extra machines, but besides that, the random components' generation times also had an impact on decreased components' production times.

Figure 5 shows the machines' productivity (the employment or usage of the machines).

The machines' productivity for Model 2 has been slightly decreased. The reason for this occurrence is the addition of two extra machines, which decreased productivity of the identical machines.

It should also be mentioned that the specificities of the heavy machining production process, where the process plan of each component needs to be strictly respected, lead inevitably to machine waiting.

Figure 6 shows the total production times (column *LT_Mean*) of each component. Again, for Model 2 the components' production times have been decreased. The main reason for this occurrence is the addition of extra machines, as well as the generation of the random components' entry times.

For some components, the production time has been significantly decreased; up to 16 days (see Figure 5, 16th row, component Flywheel_30711).

It is shown that by usage of additional machines, the critical components' production times have been decreased, as well as the machine productivity.

In order to economically justify the arrangement with two extra machines, new machines have to process more components, which means that an additional job has to be accepted and processed.

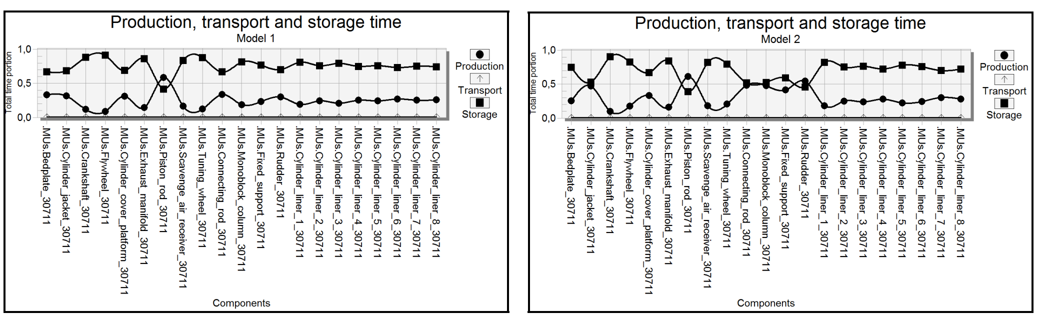

Figure 3. Comparison of components productivity between Model 1 and Model 2

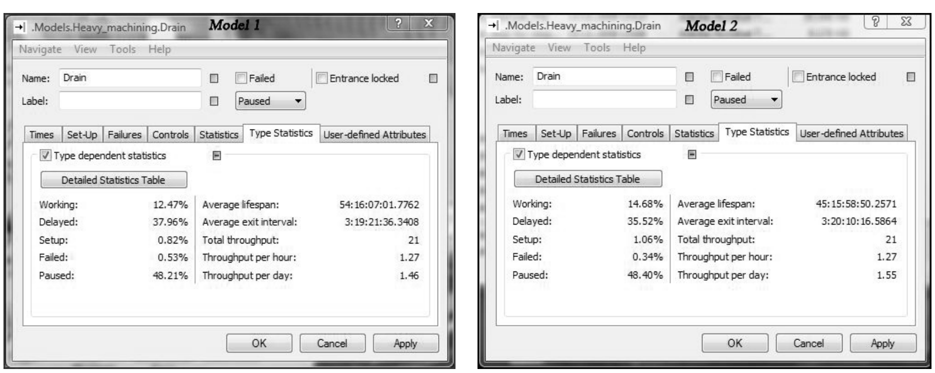

Figure 4. Comparison of components machining statistical data between Model 1 and Model 2

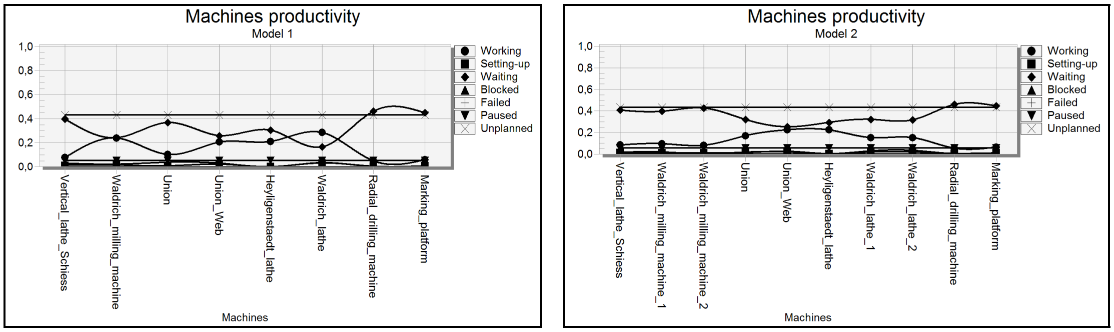

Figure 5. Comparison of the machines' productivity between Model 1 and Model 2

Type Statistics **Model 1**

	Type	Time	LT_Mean
1	Bedplate_30711	95:02:30:21.0	95:01:09:46.2905
2	Connecting_rod_30711	95:02:30:21.0	24:05:44:26.3843
3	Crankshaft_30711	95:02:30:21.0	18:12:19:32.4327
4	Cylinder_cover_platform_30711	95:02:30:21.0	20:00:34:11.4327
5	Cylinder_jacket_30711	95:02:30:21.0	66:19:40:17.4880
6	Cylinder_liner_1_30711	95:02:30:21.0	76:22:41:52.9938
7	Cylinder_liner_2_30711	95:02:30:21.0	81:00:49:30.8134
8	Cylinder_liner_3_30711	95:02:30:21.0	77:00:46:48.1406
9	Cylinder_liner_4_30711	95:02:30:21.0	72:19:12:59.0274
10	Cylinder_liner_5_30711	95:02:30:21.0	71:19:06:59.0975
11	Cylinder_liner_6_30711	95:02:30:21.0	67:23:28:39.0975
12	Cylinder_liner_7_30711	95:02:30:21.0	66:00:05:57.7995
13	Cylinder_liner_8_30711	95:02:30:21.0	62:01:04:02.0424
14	Exhaust_manifold_30711	95:02:30:21.0	55:14:00:01.3431
15	Fixed_support_30711	95:02:30:21.0	23:17:12:07.8129
16	Flywheel_30711	95:02:30:21.0	40:07:46:58.9145
17	Monoblock_column_30711	95:02:30:21.0	16:00:19:18.8421
18	Piston_rod_30711	95:02:30:21.0	85:11:06:49.3848
19	Rudder_30711	95:02:30:21.0	28:08:30:01.3431
20	Scavenge_air_receiver_30711	95:02:30:21.0	58:06:31:49.4644
21	Tuning_wheel_30711	95:02:30:21.0	35:04:30:01.3431

Type Statistics **Model 2**

	Type	Time	LT_Mean
1	Bedplate_30711	89:06:27:43.0	73:21:21:14.3236
2	Connecting_rod_30711	89:06:27:43.0	17:23:26:23.2735
3	Crankshaft_30711	89:06:27:43.0	12:01:06:22.9055
4	Cylinder_cover_platform_30711	89:06:27:43.0	11:22:54:04.7021
5	Cylinder_jacket_30711	89:06:27:43.0	63:15:09:08.2751
6	Cylinder_liner_1_30711	89:06:27:43.0	62:18:33:02.1994
7	Cylinder_liner_2_30711	89:06:27:43.0	72:16:20:46.9429
8	Cylinder_liner_3_30711	89:06:27:43.0	69:05:31:30.5010
9	Cylinder_liner_4_30711	89:06:27:43.0	68:15:54:50.5010
10	Cylinder_liner_5_30711	89:06:27:43.0	65:06:24:50.5010
11	Cylinder_liner_6_30711	89:06:27:43.0	65:19:16:30.5010
12	Cylinder_liner_7_30711	89:06:27:43.0	62:00:23:10.5010
13	Cylinder_liner_8_30711	89:06:27:43.0	59:00:15:07.4626
14	Exhaust_manifold_30711	89:06:27:43.0	46:15:18:11.0081
15	Fixed_support_30711	89:06:27:43.0	17:10:54:04.7021
16	Flywheel_30711	89:06:27:43.0	24:08:30:58.8449
17	Monoblock_column_30711	89:06:27:43.0	10:06:46:09.2857
18	Piston_rod_30711	89:06:27:43.0	77:19:53:05.5143
19	Rudder_30711	89:06:27:43.0	16:01:54:04.7021
20	Scavenge_air_receiver_30711	89:06:27:43.0	56:01:41:07.3413
21	Tuning_wheel_30711	89:06:27:43.0	20:05:11:23.2735

Figure 6. Comparison of the components total machining time (LT_Mean) between Model 1 and Model 2

4. CONCLUSION

Simulations allow the user to quickly analyze and understand the functioning of flexible manufacturing flows, somewhere between theory and practice. Virtual completion of flexible manufacturing systems is an important step towards a higher quality rate of the future “real” technological flow.

Applications of computer simulation software, enables easier production process prediction. Furthermore, generation and analysis of important production parameters are cheaper and more effective, which is important when new upgrading or investment production process activities need to be carried out. It is also easy to answer the "*what if*" question.

This article presents the benefits of using the simulation software. The greatest benefit is a great help in making decision whether or not two new heavy machines should be introduced into an existing production system. It can be concluded that additional machines would definitely decrease machining times of crucial components. From an economical point of view, the two additional machines are very expensive (investment costs approx. 12 million Euros) and their profitability is questionable for the existing amount of work. But for cases of increased job orders, the mentioned investment would be paid off in a five year period.

In addition, the usage of simulation software enables greater *flexibility,* along with the ability to execute the product changeovers rapidly, to mix production of different products, and to return to the production of previously shelved products. Besides flexibility, the usage of simulation software enables greater *responsiveness* with the ability to respond to the customer question about the impact of various production system modifications.

The results provided by the realized comparative simulations proposed in this paper are promising and further research would follow, for example, in terms of production process optimization through the usage of evolutionary algorithms. This is the topic of our current research.

5. LIST OF SYMBOLS

processing time of job *j* on the machine *i*	p_{ij} , h
time difference between two jobs	p_{ij}^* , h
release date of job *j* on the machine *i*	r_{ij} , h
due date of job *j* on the machine *i*	d_{ij} , h
completion time of job *j* on the machine *i*	C_{ij} , h
makespan	$C_{\max}$, h
sum of times of job *j* up to the machine *i*	S_{ij} , h
lateness of job *j* on the machine *i*	L_{ij} , h
maximum lateness	$L_{\max}$, h

REFERENCES

[1] Ziljak, V.: *Simulacija racunalom (Computer simulations)*, Skolska knjiga, Zagreb, 1982.

[2] Jerzy, T.: *Computer Simulation of Discrete-Event Systems,* Kluwer Academic Publishers, Norwell, 1999.

[3] Rubinstein, R.Y., Melamed, B.: *Modern Simulation and Modeling*, Wiley, New York, 1998.

[4] Kibira, D., McLean, C.: *Manufacturing Modeling Methods: Virtual Reality Simulation of a Mechanical Assembly Production Line,* Proceedings of the 34th Conference on Winter Simulation: Exploring New Frontiers, San Diego, 2002, p. 1130-1137.

[5] Mahdavi, I., Shirazi, B., Solimanpur, M.: *Development of a Simulation-Based Decision Support System for Controlling Stochastic Flexible Job Shop Manufacturing Systems,* Simulation Modelling Practice and Theory, Vol. 18 (2010), No. 6, p. 768-786.

[6] Car, Z., Mikac, T.: *Evolutionary approach for solving cell-formation problem in cell manufacturing,* Advanced Engineering Informatics, Vol. 20 (2006), No. 3, p. 227-232.

[7] Ikonic, M., Mikac, T., Car, Z.: *New Method of Choosing the Optimal Organization Structure,* Proceedings of 6th International Workshop on Emergent Synthesis: IWES, Tokyo, University of Tokyo, 2006, p. 25-34.

[8] Car, Z., Barišić, B., Rucki, M.: *Emergent Synthesis Based Multi-Objective Design of the Manufacturing System Shop-Floor*, Strojniški vestnik, Vol. 55 (2009), No. 9, p. 523-530.

[9] Arsham, H., Feuerverger, A., McLeish, D., Kreimer, J., Rubinstein, R.: *Sensitivity Analysis And The What-If Problem in Simulation Analysis,* Mathematical and Computer Modelling, Vol. 12 (1989), No. 1, p. 193-219.

[10] Law, A. M., Kelton, W.D.: *Simulation Modelling and Analysis*, 3rd Edition, Mc Graw-Hill, New York, 2000.

[11] Oakshott, L.: *Business Modelling and Simulation*, Pitman, London, 1997.

[12] Page, B., Kreutzer, W.: *The Java Simulation Handbook – Simulating Discrete Event Systems in UML and Java*, Shaker Publications, Aachen, 2005.

[13] Volker, W., Page, B., Kreutzer, W.: C*ombining Discrete Event Simulation and Material Flow Analysis based a Component-Oriented Approach to Industrial Environmental Protection*, Environmental Modelling & Software, Vol. 21 (2006.), p. 1607-1617.

[14] Pinedo, M. L.: *Scheduling – Theory, Algorithms and Systems*, Springer Science + Business, New York, 1982.

[15] Monch, L., Driesel, R.: *A Distributed Shifting Bottleneck Heuristic for Complex Jobshops,* Computers and Industrial Engineering, Vol. 49 (2005), No. 3, p. 363-380.

[16] Bangsow, S.: *Manufacturing Simulation With Plant Simulation and Simtalk*, Springer, Berlin, 2010.

[17] Tecnomatix Technologies GmbH&Co.: *eM Plant 7.5 User Guide*, Tecnomatix Technologies Ltd., Herzlia, 2000.

Received: 28.02.2011.

Accepted: 16.05.2011.

Original scientific paper

Authors' address
Igor Stanković, B. Sc. Mech.
3. Maj, Engines & Cranes d.d.
Liburnijska 3
51000 Rijeka
CROATIA
Prof. D. Sc. Zlatan Car
Prof. D. Sc. Branimir Barišić
University of Rijeka, Faculty of engineering
Vukovarska 58
51000 Rijeka
CROATIA
igor.stankovic@zg.t-com.hr
zlatan.car@riteh.hr
branimir.barisic@riteh.hr