A SIMULATION APPROACH TO PRODUCTION LINE BOTTLENECK ANALYSIS

Michal Leporis and Zdenka Králová

Slovak University of Technology
Faculty of Electrical Engineering and Information Technology
Ilkovičova 3, 812 19 Bratislava, Slovak Republic
Phone: +421 2 60291539 Fax: +421 2 65429521
e-mail: michal.leporis@stuba.sk; zdenka.kralova@stuba.sk

Abstract: The paper presents a comparison of several methods for production line bottleneck analysis using discrete event simulation approach and the simulation software WITNESS. An experimental environment has been created for processing and comparison of results obtained from the WITNESS simulation experiments. The advantages and constraints of the cited methods are discussed.

Keywords: production system, bottleneck detection, simulation, WITNESS

1 INTRODUCTION

The term "bottleneck" is used to describe a point of congestion in any system from computer networks to a factory assembly line. In such a system, there is always some process, task, machine, etc. that is the limiting factor preventing a greater throughput and thus determines the capacity of the entire system. Knowing the bottleneck allows increasing the flow by improving just one process in the system rather than all its remaining parts. Vice versa, if there is a bottleneck, nothing done elsewhere in the value stream can improve the throughput (Goldratt, Cox, 1984).

Both theory and practice of production management pay great attention to the bottleneck analysis in order to increase throughput of a production system, i.e. the rate at which the system generates money through sales of its products.

The bottleneck in production system occurs when workloads arrive at a given point more quickly than that point can handle them. The bottleneck situation causes unneeded inventory and prolongs manufacturing lead times. In a wider sense of the word, any element of a production system (machine, conveyor, AGV, buffer, labor etc.) can turn to a bottleneck.

As a result of the bottleneck analysis, particular recommendations can be drawn to improve the production system in the most effective way, significantly increasing its throughput and capacity.

2 BOTTLENECK DETECTION METHODS

Detecting a bottleneck in a production system is not a trivial task. Current bottleneck detection methods can be separated into two categories: analytical and simulation-based. A special conception of bottleneck detection has been developed based on evaluation of the real-time data from the manufacturing system (Li et al., 2007).

For analytical methods, the system performance is assumed to be described by a statistical distribution. Although an analytical model is suitable for long term prediction, this type of model is not adequate for solving problems of short term bottleneck detection.

For real production processes with complex structure and dynamics the analytical approach is practically inapplicable; in such a case, simulation-based methods seem to be more useful. Although creation of an adequate simulation model of a system is time-consuming, results of simulation experiments provide sufficient information enabling to detect a bottleneck. Advanced simulation tools offer complete statistics about the average utilization, waiting, blocking, breakdown etc. for each element of the model as results of the experiments. Other useful data can be obtained using special procedures. Furthermore, a simulation model can help identify the possibilities for system improvements and verify their impact on the overall system performance.

Leading companies, especially those operating in the automotive industry, have developed their own software tools for the manufacturing system bottleneck analysis and identification based on simulation models; e.g. General Motors Corporation created an internal throughput-analysis tool called C-MORE, which is a combination of decomposition-based analytical methods and customized discrete-event-simulation solvers. TOYOTA Central Research and Development Laboratories implemented their bottleneck detection methods into the software tool GAROPS Analyzer (Roser et al., 2001).

Bottleneck analysis algorithmization requires definition of an explicit criterion for bottleneck detection and a suitable method for transformation the obtained set of simulation results into a particular indicator. This provides a possibility to unify approaches to the bottleneck analysis for various types of production systems.

Simulation methods for bottleneck detection differ with respect to the criterion and the way of transformation of the simulation results to the values of the criterion.

This paper deals with four bottleneck detection methods developed over the last decade:

- Active period method (Roser et al., 2001)
- Turning point method (Li et al., 2007),
- Arrow-based method (Biller et al., 2008),
- Criticality indicators based method (Králová, Bielak, 2004).

Active period method

The active period method developed by (Roser et al., 2001) at Toyota Central Research and Development Laboratories is based on the analysis of machine status information determining periods during which a machine is active without interruption (Figure 1). Five distinct states are recognized for each machine: Working, Waiting, Blocked, Tool Change and Under Repair. For analysis, Waiting and Blocked are considered inactive. Active periods are occasionally interrupted by inactive periods during which the machine is waiting for the arrival of parts (Waiting) or for their removal (Blocked). The term “Machine” includes any element performing activity, e.g. machine, conveyor, AGV, etc.
The machine with the longest average active period is considered to be a bottleneck, as this machine is least likely to be interrupted by other machines, and in turn is most likely to dictate the overall system throughput.

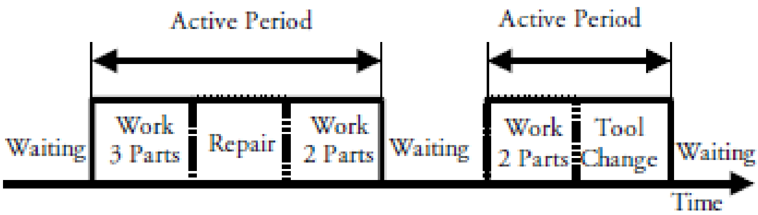

Figure 1. Illustration of the active periods of machine during the simulation run

This method does not use the summary statistics obtained as a result of a simulation experiment, but is based on the analysis of the log file recording the relevant data about the events occurred during the simulation run (start and finish of the operation, repair, tool change, etc.).

Turning point method

A data driven bottleneck detection method proposed in (Li, et al., 2007) detects bottlenecks using the term "turning point". A turning point is defined to be the machine where the trend of blockage and starvation changes from blockage being higher than starvation to starvation being higher than blockage. Furthermore, the sum of a "turning point" machine's blockage and starvation is smaller than for its neighboring machines. Thus, the "turning point" machine has the highest percentage of the sum of operating time and downtime compared to other machines in the segment.

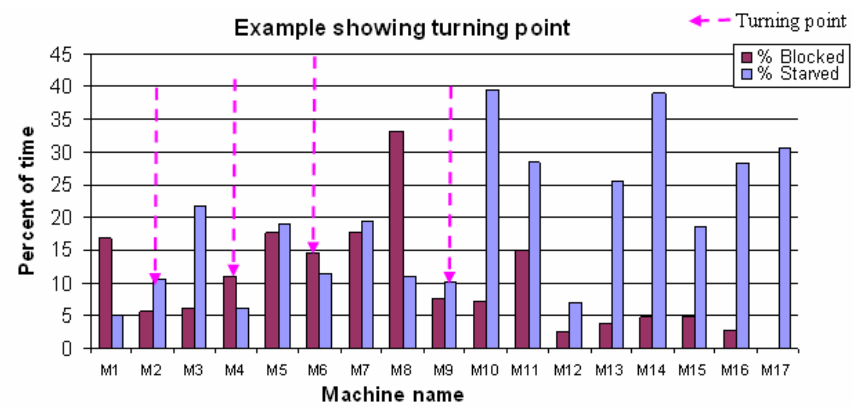

Figure 2. Example of turning points determination

The j-th machine is the turning point in a n-machine segment with finite buffers if

$$(TB_i - TS_i) > 0 : i \in [1, \dots, j-1], \; j \neq 1, j \neq n$$

$$(TB_i - TS_i) < 0 : i \in [j+1, \dots, n], \; j \neq 1, j \neq n$$

$$TB_j + TS_j < TB_{j-1} + TS_{j-1}, \; j \neq 1, j \neq n$$

$$TB_j + TS_j < TB_{j+1} + TS_{j+1}, \; j \neq 1, j \neq n$$

If $j = 1$: $(TB_1 - TS_1) > 0$ & $(TB_2 - TS_2) < 0$ & $TB_1 + TS_1 < TB_2 + TS_2$

If $j = n$: $(TB_{n-1} - TS_{n-1}) > 0$ & $(TB_n - TS_n) < 0$ & $TB_n + TS_n < TB_{n-1} + TS_{n-1}$

where TB_j is the blockage time for the j-th machine;
TS_j is the starvation time for the j-th machine;
j-1 is the index of the nearest upstream machine and
j+1 is the index of the nearest downstream machine.

According to (Li et al., 2007) both the analytical and the simulation-based verification was carried out. It has been proved that the turning point method can provide quick bottleneck identification.

Arrow-based method

The method described in (Biller et al., 2008) is built on the concept of (Kuo et al., 1996, 2008) who proposed an indirect method of bottlenecks identification for open serial lines. The Arrow-based method detects the bottlenecks in longer lines arranging the probabilities of starvations (ST_i) and blockages (BL_i) for each machine as shown in Figure 3 and placing arrows directed from one machine to another according to the following rules:

if $BL_i > ST_{i+1}$, assign the arrow pointing from m_i to m_{i+1}
if $BL_i < ST_{i+1}$, assign the arrow pointing from m_{i+1} to m_i

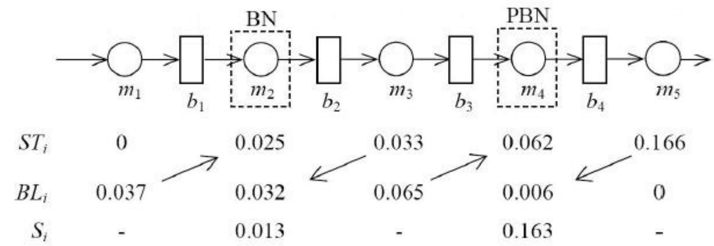

Figure 3. Example of the bottleneck identification in the open serial line

A single machine with no emanating arrows is the bottleneck. If there are multiple machines with no emanating arrows (as in Figure 3), the one with the largest severity is the primary bottleneck.

The severity of the bottleneck is defined as

$$S_1 = |ST_2 - BL_1| \qquad (1)$$

$$S_i = |ST_{i+1} - BL_i| + |ST_i - BL_{i-1}| \quad \text{pre } i = 2,...,M-1 \qquad (2)$$

$$S_M = |ST_M - BL_{M-1}| \qquad (3)$$

This method was modified by (Biller, et al., 2008) as a two-stage procedure for serial lines with rework loops.

Criticality indicators based method

The approach described in (Králová, Bielak, 2004) is based on the evaluation of the so-called “criticality indicator” for each workplace and comparison of the indicator values to detect the critical place. The way of the indicator evaluation allows finding the critical places, including the bottlenecks needing the capacity expansion, as well as ”the reserves” – workplaces allowing a better utilization.

For the i-th workplace KR_i, the criticality indicator is calculated from the simulation statistics considering the differences of the individual rates for this workplace (the average rates of utilization, starvation, blocking, waiting for labor) with respect to the whole-system average of this rate.

The integrated approach to the evaluation of criticality is based on aggregating the indicators of all related indices into one value. The particular criticality indicator for each workplace is created by summing deviations of statistical indicators for the workplaces from the mean values of indicators for all workplaces in the system. The aggregated indicator is a function of the rates: busy, blocking, waiting for parts and waiting for labor. A graphical presentation in MS Excel provides a summary of system bottlenecks and reserves and their relationships as well.

KR_i is calculated by the formula:

$$KR_i = \left(\frac{\sum_{i=1}^{n} B_i}{n} - B_i \right) + \left(I_i - \frac{\sum_{i=1}^{n} I_i}{n} \right) + \left(Bl_i - \frac{\sum_{i=1}^{n} Bl_i}{n} \right) + \left(L_i - \frac{\sum_{i=1}^{n} L_i}{n} \right)$$

where:

KR_i – the criticality indicator for the i-th workplace [%]
B_i – the average utilization rate for the i-th machine (Busy) [%]
I_i – the average starvation rate for the i-th machine (Idle) [%]
B_{li} – the average blocking rate for the i-th machine (Blocked) [%]
L_i – the average waiting rate for labor for the i-th machine (Labor) [%]

The workplace with the minimal value of KR_i is regarded as a bottleneck, the workplace with the maximal value of KR_i as a maximal capacity reserve.

3 WITNESS SIMULATION SOFTWARE

WITNESS is a comprehensive discrete event and continuous process simulator. It is designed to model dynamics of complex systems. It is an established simulation tool for analysis and validation of business process to achieve a desired process performance or to support continuous process improvement activities used by thousands of companies worldwide (Markt, Mayer, 1999).

WITNESS provides a graphical environment to build simulation models. It enables to represent a real world process in a dynamic animated computer model and allows automating simulation experiments, optimizing material flow across the facility and generating animated models. A simulation model allows incorporating all the variability of real life experience (variable reliability, process times, resource efficiency etc.).

The WITNESS simulation package is capable of modeling a variety of discrete (e.g., part-based) and continuous (e.g. fluids and high-volume fast-moving goods) elements. Depending on the type of element, each can be in any of a number of states; these states can be idle (waiting), busy (processing), blocked, in-setup, broken down, waiting labor (cycle/setup/repair) etc.

Complex routing and control logic is achieved with numerous input and output rules as well as special actions using functions. The format for using actions is similar to that of a simple programming language.

Results of simulation can be viewed on the screen either in tabular or graphic format. In addition, several graphical elements are available for summarizing statistics from a model. Pie charts, time-series and histograms provide a meaningful, easy-to-read format for data from a simulation run. Reports allow user to examine the performance of elements in the model and provide him with relevant information about their interaction, details and status. Reports can help to identify areas where the model's operation can be improved.

WITNESS Optimizer provides a plug-in module which can intelligently test different combinations of changes within a model and carry out the desired experimentation

4 COMPARISON OF BOTTLENECK DETECTION METHODS

An experimental environment for processing the results obtained from WITNESS simulation experiments allows comparing effectiveness and limitations of the cited methods. The environment consists of the discrete event simulation model in WITNESS and the MS Excel user interface allowing setup of input data of the model and viewing analysis results for each method according to its criterion. The analysis is based on the simulation statistics about the resource utilization, starvation, blocking, waiting for labor, set-up and breakdown characteristics and on the evaluation of the relationships between the downstream and upstream activities. Serial recording of the important events such as operation start and finish, machine repair, tool change, etc. is assured via procedures in the input/output rules in the WITNESS model.

The basic experimental model represents a serial production line with thirty workplaces with buffers. Other variants of the model differ from the basic one by material flow branching and connection (Figure 4) and by rework loops. The simulation models were extended by the element "Labor" to enable verifying the capability to detect a labor as a bottleneck Values of the relevant parameters, such as machine cycle times, breakdown frequency, repair and setup times, etc. can be initiated through the MS Excel user interface.

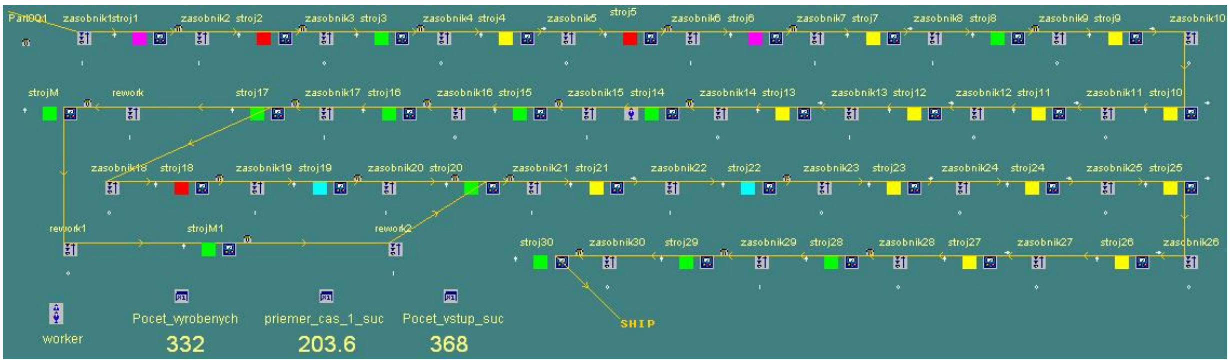

Figure 4. View of the WITNESS model of the experimental production line

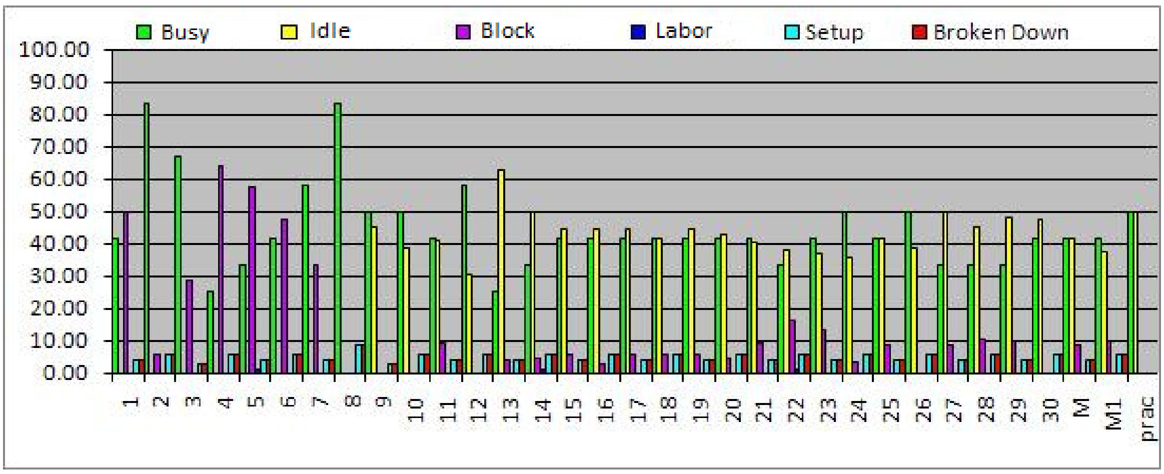

Figure 5. Illustration of the WITNESS simulation statistics obtained by a procedure in MS Excel

At first, a simulation model of a fully synchronized production line was used to evaluate the maximum capacity of the system. Afterwards, various combinations of the values of cycle times, times between failures, repair times, set-up times, etc. have been prepared for the experiment. Numerous series of experiments have been carried out for several types of production systems in order to study the ability of the particular methods to detect a bottleneck.

Next samples illustrate the graphical output of the analysis results for the particular methods.

	1	2	3	4	5	6
count interval activity	481	160	521	561	479	480
length interval activity	3600	6750	5160	2600	2996	3800
average length interval activity	7.4844	42.188	9.904	4.6346	6.2547	7.9167

Figure 6. Illustration of the calculation for the Active period method

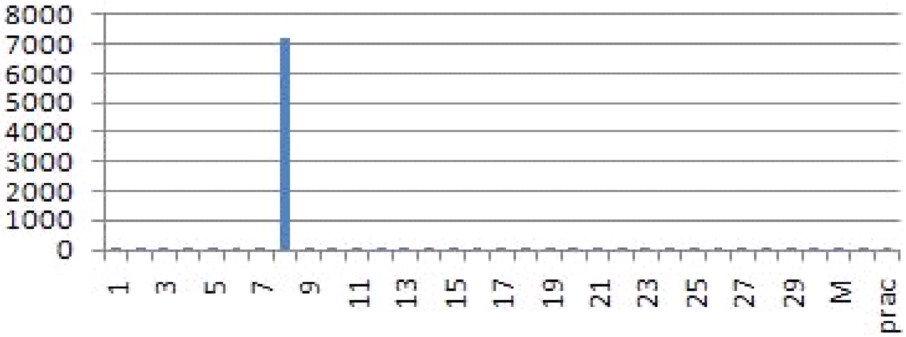

Figure 7. Result of the bottleneck analysis using the Active period method

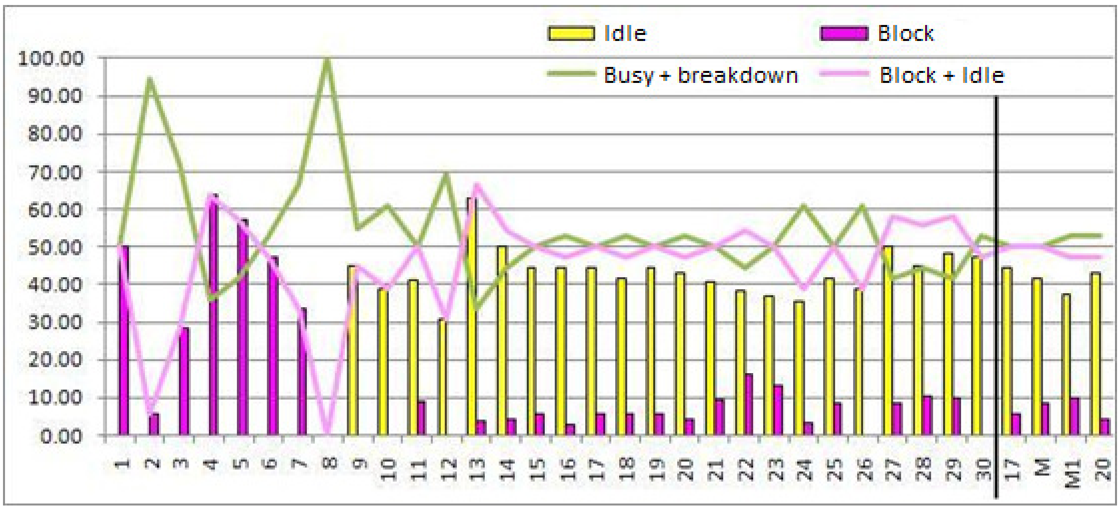

Figure 8. Result of the bottleneck analysis using the Turning point method

	Stroj1		Stroj2		Stroj3		Stroj4		Stroj5		Stroj6		Stroj7		Stroj8		Stroj9		Stroj10	
idle	0,00		0,00		0,00		0,00		0,00		0,00		0,00		0,00		45,00		38,89	
		>		>		>		>		>		>		>		<		<		<
block	50,00		5,56		28,33		63,89		57,22		47,22		33,33		0,00		0,00		0,00	
weight BN	s1		s2		s3		s4		s5		s6		s7		s8		s9		s10	
	50		55,56		33,89		92,22		121,11		104,44		80,55		78,33		83,89		80	
Nepracuje	Stroj11		Stroj12		Stroj13		Stroj14		Stroj15		Stroj16		Stroj17		Stroj18		Stroj19		Stroj20	
	41,11		30,56		62,78		50,00		44,44		44,44		44,44		41,67		44,44		42,78	
block		<		<		<		<		<		<		<		<		<		<
	8,89		0,00		3,89		4,44		5,56		2,78		5,56		5,56		5,56		4,44	
weight BN	s11		s12		s13		s14		s15		s16		s17		s18		s19		s20	
	62,78		84,45		108,89		86,11		78,88		80,54		77,77		74,99		76,1		73,34	
	Stroj21		Stroj22		Stroj23		Stroj24		Stroj25		Stroj26		Stroj27		Stroj28		Stroj29		Stroj30	
idle	40,56		38,33		36,67		35,56		41,67		38,89		50,00		45,00		48,33		47,22	
		<		<		<		<		<		<		<		<		<		
block	9,44		16,11		13,33		3,33		8,33		0,00		8,33		10,56		10,00		0,00	
weight BN	s21		s22		s23		s24		s25		s26		s27		s28		s29		s30	
	65,01		49,45		42,79		60,57		68,9		80,56		86,67		74,44		74,99		37,22	
	Stroj17		StrojM		StrojM1		Stroj20													
idle	44,44		41,67		37,22		42,78													
		<		<		<														
block	5,56		8,33		10,00		4,44													
weight BN	sS17		ssM		ssM1		ss20													
	37,23		73,34		68,89		32,78													

Figure 9. Sample of the results for the first stage of the Arrow-based method
Primary bottleneck is the workstation number 8 with the value $S_8 = 78.333$

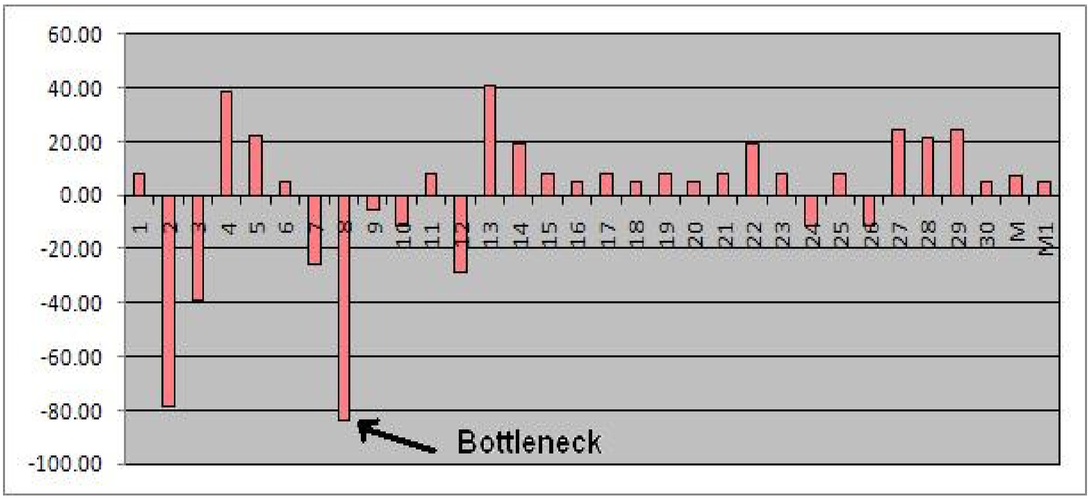

Figure 10. Results of the bottleneck analysis using the Criticality indicator based method

The advantages of *the Active period method* are:

- simple and reliable bottleneck evaluation,
- the likelihood of being the bottleneck is reliably identified for all machines and AGV's, conveyors or labors
- indicators are computed for each workplace separately, thus the method can be implemented independently of the production system structure (the workplace order, branching of the process, rework loops, etc.) .

The experiments revealed the drawbacks of this method in case when several bottlenecks of the same severity occurred; in such a case only one of the bottlenecks was marked and therefore after extending the capacity of this workplace the throughput didn't increase.

*The Turning point method yield*s good results; nevertheless, it has several disadvantages:

- direct evaluation of the global bottleneck from several local bottlenecks is not possible,
- labor is not considered as a potential bottleneck.

The Arrow-based method based on comparison of the simulation statistics of the starvation and blocking of the neighboring workplaces is able to evaluate multiple bottlenecks. The bottleneck of the largest severity is the workplace with the maximum value of the specific index. A disadvantage of this method is its low reliability to find a bottleneck if it is located at the beginning or at the end of production line.

The Criticality indicators based method allows a direct quantitative identification of the bottleneck workplace, considering machines and labor. The element of the workplace causing congestion is discovered in the second stage after the analysis of statistics. Compared with other methods, this one determines not only the bottlenecks and their severity but also the reserves in the production system (workplaces with unused capacity). This is a good starting point for the automation of the process synchronization when the throughput maximization can be achieved by synchronization of all production process elements to ensure the continuous flow of material.

Comparison of the values of the partial indicators allows detecting bottlenecks without knowledge of the production system structure which makes the algorithm applicable for various types of production processes.

5 CONCLUSION

The main objective of this paper was to compare several bottleneck detection methods developed in the last decade and to explore the advantages and disadvantages of each approach. The results of the study showed that the Criticality indicators based method gives good results compared with other methods and is prospective to be used for automated synchronization of the production line.

ACKNOWLEDGEMENT

The work has been supported by the Scientific Grant Agency of the Ministry of Education of the Slovak Republic and the Slovak Academy of Sciences under Grant No. 1/0544/09.

REFERENCES

BILLER, S., LI, J., MARIN, S.P., MEERKOV, S. M., ZHANG, L. (2008): Bottlenecks in Production Lines with Rework: A System Approach. In: *Proceedings of the 17th World Congress the Int. Federation of Automatic Control*, Seoul, Korea, July 6-11, 2008, pp.14888-14893

CHIANG S.-Y., KUO C.-T. AND MEERKOV S.M. (2000): c-Bottlenecks in serial production lines: Identification and application, In: *Mathematical Problems in Engineering* 7 (2000), pp. 543–578

GOLDRATT, E.M. AND J. COX (1984): *The Goal. Excellence in Manufacturing.* North River Press, Croton-on-Hudson, N.Y 1984

KRÁLOVÁ, Z., BIELAK, M. (2004): Production process synchronization using simulation in WITNESS. In: *Proceedings of 7th Conference WITNESS,* Kozov, Czech Republic, June 3-4, 2004, pp. 78-84 (in Slovak)

KUO C.-T., LIM J.-T. AND MEERKOV S.M. (1996): Bottlenecks in serial production lines: A system-theoretic approach, *Mathematical Problems in Engineering* **2** (1996), pp. 233–276

MARKT, P.L., MAYER, M.H. (1997), WITNESS simulation software: a flexible suite of simulation tools, *Proceedings of the 1997 Winter Simulation Conference,* pp.711-17.

LAWRENCE, S. R., BUSS, A. H. (1995): Economic analysis of production bottlenecks. *Mathematical Problems in Engineering*, Volume 1 (1995), Issue 4, pp. 341-363

LI, L., CHANG, Q., XIAO, G., BILLER, S. (2007): Bottleneck Detection of Manufacturing Systems Using Data Driven Method. In: *Proceedings of the 2007 IEEE Int. Symposium on Assembly and Manufacturing*, Ann Arbor, Michigan, USA, July 22-25, 2007, pp. 76-81

ROBINSON, S. (1996): *Successful Simulation. A Practical Approach to Simulation Projects.* McGraw Hill Book Co Ltd , 1996, ISBN 9780077076221

ROSER, CH., NAKANO, M., TANAKA, M. (2001): A practical bottleneck detection method. In: *Proceedings of the 2001 Winter Simulation Conference, WSC 2001,* Arlington, VA, USA. ACM, December 9-12, 2001, pp. 949-953

ŠVANČARA, J., KRÁLOVÁ, Z. (2009): Simulation Based Performance Analysis of the Multi-product Manufacturing System. In: *Proceedings of the 17th International Conference on Process Control '09,* Štrbské Pleso, Slovakia, June 9 - 12, 2009, pp. 249–253