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DETECTING SHIFTING BOTTLENECKS

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ABSTRACT

This paper provides a novel method for detecting production bottlenecks and the shifting of the production bottlenecks. All production systems are constrained by one or more bottlenecks. Improving the bottleneck will improve the whole production system. Yet, finding the bottleneck is no trivial task. Furthermore, the system may change over time or due to random events, and subsequently the bottleneck may shift from one machine to another machine. The presented active duration method determines the bottleneck based on the duration a machine is active without interruption. The method is very robust, easy to apply and able to detect the primary and secondary bottlenecks in a wide range of production systems. The method is demonstrated using different examples. The measurement of the likelihood of a machine being the bottleneck aids in the decision-making regarding the allocation of the available resources.

INTRODUCTION

This paper describes a method to detect and monitor the bottleneck in steady state and non-steady-state production system subject to random variation, both for flow shop and job shop systems. Within this paper, a bottleneck is seen as a stage in a production system that has the largest effect on slowing down or stopping the entire system, either for an instant in time or averaged over a longer time period. Therefore, it is of interest to determine the bottleneck in order to improve the throughput of the production system by improving the throughput of the bottleneck, also known as the theory of constraints (Blackstone 2001; Goldratt 1992). The paper further distinguishes between a momentary bottleneck, describing the bottleneck at any given point in time, and an average bottleneck, describing the bottleneck behavior over a selected period of time. Yet, finding the bottleneck is no trivial task, and (Cox 1997) for example simply recommends that ‘… the best approach is often to go to the production floor and ask knowledgeable employees …’.

Furthermore, in all but the simplest applications the bottleneck is not static. Instead, the bottleneck shifts between different machines, depending on the preceding random events. A non-bottleneck machine may become a bottleneck, for example due to a machine failure, and similarly a bottleneck machine may become a non-bottleneck machine. Over longer periods of time, a system therefore may not only have one primary bottleneck, but also secondary and tertiary bottlenecks, i.e. machines which are also occasional bottlenecks, yet to a lesser extent than the primary bottleneck. The method presented in this paper considers the shifting of both momentary and average bottlenecks.

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Currently there are a number of methods in use to find the bottleneck for production systems. One approach measures the utilization of the different machines of the production system (Law 2000). The machine with the highest utilization is considered to be the bottleneck. (Adams 1988) uses disjunctive graphs to detect the bottleneck in order to optimize the scheduling in a shifting bottleneck procedure. (Uzsoy 2000) compared the shifting bottleneck procedure to the theory of constraints. Another frequently used method analyses the queue lengths of the machines in the production systems. In this method, either the queue length or the waiting time is determined, and the entity with the longest queue length or waiting time is considered to be the bottleneck. The disadvantages of these methods will be described in more detail below. (Chiang 2002; Kuo 1996) uses the sensitivity of the machine performance to the overall throughput as a theoretical bottleneck measure.

BOTTLENECK DETECTION METHOD

The presented method will be able to detect and monitor the shifting momentary bottleneck of a production system, and also determine the average bottleneck over a selected period of time. This method is a continued development and improvement based on the method of the average active duration (Roser 2001).

The active duration

The presented method is based on the duration a processing machine is active without interruption. As a first step, it is necessary to group all possible machine states into two groups, being either active states or inactive states. A state is active whenever the machine may cause other machines to wait. For example working on one part may cause a subsequent idle machine to wait for the completion of the part, or a machine under repair may block previous machines. A state is inactive if the associated machine is not active but instead waiting for the completion of another task, for example the arrival of a part or service, or for the removal of a part. Table 1 shows a possible grouping of selected states for different entities of a production system into active and inactive.

TABLE 1: ACTIVE – INACTIVE EXAMPLES

Machine	Active	Inactive
Processing Machine	Working, in repair, changing tools, serviced	Starving, blocked
Automated Guided Vehicles (AGV)	Moving to a pickup location, moving to a drop off location, recharging, being repaired	Waiting
Factory Worker	Working, on scheduled break	Waiting

The momentary bottleneck

The underlying idea is that the longer a machine is working without interruption, the more likely it is that this machine constrains the performance of other machines. Therefore, at any given time the machine with the longest uninterrupted active period is the momentary bottleneck at this time. The overlap of the active period of a bottleneck with the previous or subsequent bottleneck represents the shifting of the bottleneck from one machine to another machine. The following method describes how to determine which machine of a production system is the sole bottleneck or part of a shifting bottlenecks at any time t.

If at time t no machines are active, then there is no bottleneck. If one or more machines are active at the time t, the machine with the longest active period at the time t is the momentary bottleneck machine, and the active period of this machine is the current bottleneck period.

The shifting of the bottleneck from the previous bottleneck machine to the current bottleneck machine happens during the overlap of the previous and the current bottleneck periods. Similarly, the shifting of the bottleneck from the current bottleneck machine to the subsequent bottleneck machine happens during the overlap of the current and the subsequent bottleneck periods. During the overlaps between the bottleneck periods no machine is the sole bottleneck, instead the bottleneck shifts between the two machines. If a bottleneck machine is not shifting, then this machine is the sole and only bottleneck at this time. Using this method, it can be determined at any given time if a machine is a non-bottleneck, a shifting bottleneck, or a sole bottleneck, and the shifting of the bottleneck can be monitored over time.

Figure 1 visualizes the method using a simple example consisting of only two machines. The figure shows the active periods of the machines over a short period of time. At the selected time *t*, both machines M1 and M2 are active. Yet, as M1 has the longer active period, M1 is the bottleneck machine for the time *t*. At the end of the current bottleneck period, M2 is active and has the longest active period. Therefore the subsequent bottleneck machine is M2. During the overlap between the current bottleneck period and the subsequent bottleneck period the bottleneck shifts from M1 to M2. Similarly, at the end of the bottleneck period of M2, the bottleneck shifts back to M1.

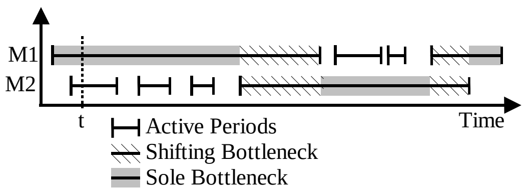

Figure 1: SHIFTING BOTTLENECKS

The average bottleneck

The above method detects and monitors the momentary bottleneck at any instant of time. However, in many cases it may be of interest not to investigate an instant of time but rather a period of time. To determine the bottleneck during a period of time the available data is analyzed and the momentary bottlenecks are determined over the selected period of time. Next, the percentage of time a machine is the sole bottleneck machine and the percentage of the time a machine is part of a shifting bottleneck is measured for the selected period of time.

Figure 2 visualizes this method using the example with two machines as shown in Figure 1. The percentages of the machines being the sole bottleneck or the shifting bottleneck have been measured over the period of time shown in Figure 1. M1 is more likely to be the bottleneck than M2, and therefore is the main bottleneck. Yet, M2 is also sometimes the bottleneck, although less likely than M1, and therefore is a secondary bottleneck. Overall, an improvement of the performance of M1 would yield a larger overall improvement of the system than an improvement of M2.

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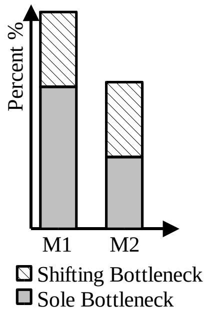

Figure 2: Average bottleneck over period of time

COMPUTATIONAL EXAMPLES

This section will describe two computational examples. The first example is a flow shop with four stations each, taken with small modifications from (Lawrence 1994). The second example is a complex branched system with seven machines and two different part types.

(Lawrence 1994) also devised a bottleneck shiftiness measure β as shown in equation (1), where c_v is the coefficient of variation of the bottleneck probability of the different machines and n is the number of machines in the system. The bottleneck shiftiness measure β ranges from zero for a system with a unique bottleneck to one for a system were all machines are equally likely to be the bottleneck. The bottleneck shiftiness measure can also be applied to the active duration method and will be utilized in the examples below.

$$\beta = 1 - \frac{c_v}{\sqrt{n}} \quad (1)$$

The method was implemented as software tool GAROPS Analyzer to analyze the simulation data from the GAROPS simulation software as shown in (Kubota 1999) and (Nakano 1994). The software tool analyses the machine status information over time and creates an excel file containing a statistical description of the simulation including the change of the sole and shifting momentary bottlenecks over time and also the sole and shifting average bottlenecks of the complete simulation.

Flow shop

The flow shop example has an exponential inter arrival rate with a mean inter arrival time of 1.25s. The processing times of the four machines has an exponential distribution with a mean service rate μ_i of 1s for machines M1, M2, and M4, and 1.1s for machine M3. All parts are processed by all machines in sequence. The utilization p_i is 80% for machines M1, M2, and M4, and 88% for machine M3. Figure 3 shows the layout of the flow shop system.

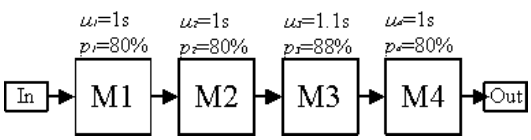

FIGURE 3: FLOW SHOP LAYOUT

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The simulation was run for 120 000s, of which a warming up period of 20 000s was removed. The results of the analysis using the GAROPS Analyzer are shown in Table 2. The last row shows the bottleneck shiftiness measure β for the different bottleneck measurements according to equation (1). The results of Table 2 are also visualized in Figure 4.

TABLE 2: FLOW SHOP SIMULATION RESULTS

Machine	Utilization	Bottleneck	Shifting	Sum
M1	80.1%	12.7%	20.4%	33.1%
M2	80.2%	6.7%	15.9%	22.7%
M3	88.0%	32.5%	29.3%	61.8%
M4	80.0%	7.3%	15.2%	22.5%
Shiftiness Measure β		0.59	0.84	0.74

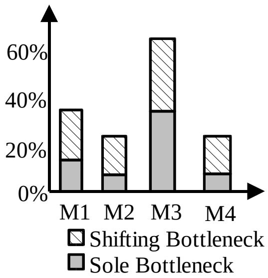

Figure 4: FLOW SHOP BOTTLENECKS

Machine M3 is clearly the bottleneck, as all measures in Table 2 indicate M3 as the main bottleneck. Machine M3 is the sole bottleneck for about 1/3rd of the time, and a shifting bottleneck for another 1/3rd of the time. This makes M3 a sole or shifting bottleneck for about 2/3rd of the time. However, due to random variations, machines M1, M2 and M4 are also occasional bottlenecks, although to a lesser extent than machine M3. Therefore, an improvement of the machines M1, M2 and M4 will also improve the overall system performance, although to a lesser extent than M3. The shifting bottleneck detection method was also applied to a job shop example with similar results.

Complex example

The complex example consists of a branched system with seven machines and two different part types as shown in Figure 5, including different buffers. The simulation was run for 200 000s, of which the warming up period was removed.

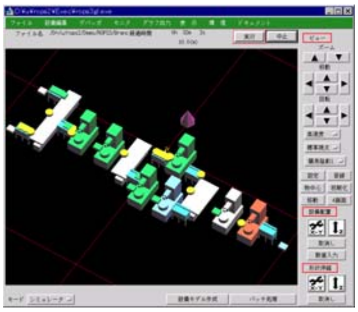

Figure 5: GAROPS SCREENSHOT

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Figure 6 shows the utilization of the seven machines, including the ranges of the 95% confidence intervals. The potential primary bottlenecks are shaded. Based on this simulation, it cannot be said for sure which machine is the primary bottleneck. Statistically it is not known if M3 or M5 has the larger utilization, and the primary bottleneck cannot be determined. Due to the small differences in utilization it is difficult to detect the primary bottleneck by measuring the utilization, let alone secondary and tertiary bottlenecks.

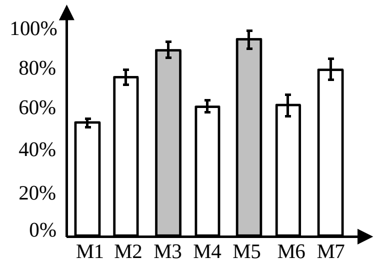

Figure 6: UTILIZATION OF COMPLEX EXAMPLE

Figure 7 and Table 3 show the result of the bottleneck detection using the active period. Here the results are very clear, showing that M5 is indeed the main bottleneck, being a sole bottleneck for 45% of the time and a shifting bottleneck for 37% of the time, i.e. M5 is part of a bottleneck for 82% of the time. Calculating the 95% confidence intervals reveals that the results are statistically significant and M5 is indeed the bottleneck. This example also indicates that M3 is a potential secondary bottleneck and M7 is a potential tertiary bottleneck.

TABLE 3: COMPLEX EXAMPLE SIMULATION RESULTS

Machine	Utilization	Bottleneck	Shifting	Sum
M1	54%	0.0%	0.1%	0.1%
M2	76%	2.2%	3.3%	5.6%
M3	89%	1.2%	29.3%	30.5%
M4	62%	0.1%	0.0%	0.1%
M5	94%	45.1%	37.3%	82.4%
M6	63%	1.5%	3.6%	5.1%
M7	80%	7.0%	12.5%	19.5%
Shiftiness Measure β		0.24	0.54	0.46

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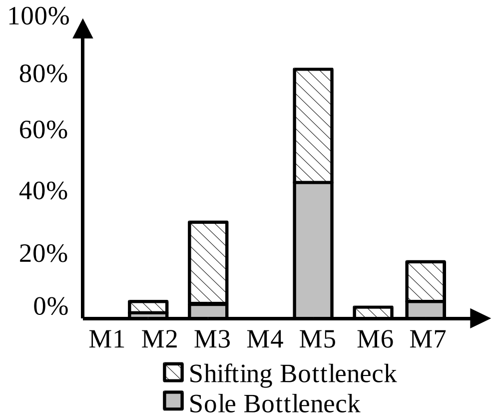

Figure 7: COMPLEX EXAMPLE BOTTLENECKS

In summary, an improvement of the performance M5 would improve the overall system performance. Machines M3, M7 and M2 may also be considered for improvements depending on the trade off between the cost of the improvement and the benefit of the improved system performance. Furthermore, the bottleneck analysis determines that an improvement of M1, M4 and M6 is unlikely to increase the system performance, and no resources should be invested into an improvement of M1, M4 and M6 at this time.

SUMMARY

The active period method has many advantages over other methods for bottleneck detection. For example, the measurement of the queue length or waiting time in order to detect the bottleneck cannot be used if the queue lengths are limited. In addition, the queue length may fluctuate frequently, complicating a reallocation of the resources in a "chase the bottleneck" approach. Using the utilization as a bottleneck detection method may give inaccurate results for the detection of the primary bottleneck, and it is usually impossible to detect secondary and tertiary bottlenecks.

The active period method as presented in this paper, however, is a very flexible tool and can be used for a wide range of job shop and flow shop systems as for example production systems, computer networks or traffic systems. The method is easy to apply, and the required data is usually readily available. As the active period is measured directly at the machine, there are no errors due to outside limitations as for example in the indirect measurement of the machine activity using the queue length. Both, short term and long term average bottlenecks can be detected. For non steady state systems there is no long-term average bottleneck. However, the likelihood of a machine being a bottleneck during the analyzed period of the non steady state system can be determined.

Knowing the likelihood of each machine to be the bottleneck aids the manager in making a trade off between the effort of adding capacity to the machines and the benefits of improved throughput.

Research is in progress to adapt the active period method for the optimization of the production systems.

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