BOTTLENECK MANAGEMENT WITH THROUGHPUT CURVES: A SIMULATION IN PRACTICE

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Abstract:
The performance in many manufacturing companies is limited through bottlenecks in both production and assembly divisions. For this reason, bottlenecks are often the starting point of improvement initiatives. While there has been much work done on bottlenecks that appear in production systems in theory, practical evidence is still rare. In this work the accuracy and the applicability of the throughput by Kreutzfeldt (1995) is analyzed and the optimization algorithm implemented are reviewed. The presented work is completed as part of the research project "DePlaVis", located at the University of Applied Sciences in Hamburg. The starting point of its development is the throughput curve, which identifies and evaluates bottlenecks in the manufacturing environment. In order to verify the findings, an event-discrete simulation was programmed and analyzed. The simulation that is conducted partially supported the developed model. It produces similar results for the throughput and thus for the performance. The possible applications of the throughput curve lies principally in the planning and control of orders for manufacturing processes. Furthermore, it is also possible to derive information from the curve that can be used to improve performance and efficiency.

Keywords: bottleneck management, throughput curve, event discrete simulation model, case study

Introduction

A good and quick manufacturing of products and processes is important for companies, who work in a make to order (MTO) environment. The competitive advantage of these companies is based on the fulfillment of individual customer requirements (Westkämper, 2006), which can be satisfied by designing and manufacturing the product according to the customer’s preference. The approach demands a high
flexibility and capability in manufacturing and engineering processes and the success factor is the capability to deliver the specific order in time (Handfield, 1994). In many production environments, the system performance is constrained or reduced by bottlenecks (Gutenberg, 1976). The greatest bottleneck in the system has an impact on every logistical target parameter. Bottlenecks cause queues in front of work stations. Furthermore queues are the reason for extended and distributed lead times, which can result in delivery date problems. Another effect is a reduction in the supply of orders to succeeding work stations and the appearance of idle times. Bottlenecks are often the starting point for improvement initiatives (Goldratt, 1990). However, which bottleneck must be addressed first, in order to achieve a quick and accurate optimization of the whole production system? If the production system contains more than one bottleneck, the question arises as to which bottleneck offers the greatest potential for optimization. For this reason, not only is the identification of bottlenecks is important, but also the evaluation of them in terms of their optimization potential. Throughput curves are an accepted and useful approach to identify, assess and select bottlenecks for improvement (Kreutzfeldt 1995; Schultheiss and Kreutzfeld, 2009).

Often, bottleneck approaches stemming from Operations Management are viewed in practice as being too complicated and difficult to communicate. Improvement measures have to be undertaken and understood by shop floor workers. For the implementation of these measures, the shop floor workers have to be convinced and inspired. Visual approaches have a good acceptance in practice (Eppler and Mengis, 2009) and a graphical solution for linking capacity and work load to the overall performance of the production system and planning quality information is preferred.

Hence, the implementation of bottleneck management, especially supported by modern information technology, in practice still remains poor. A software demonstrator was developed during the research project DePlaVis for a more convenient implementation of throughput curves. The research project DePlaVis was introduced to develop a visual bottleneck management solution for production systems. The project is founded by the German Federal Ministry of Education and Research and the project consortium consists of three mechanical engineering companies, two software houses and two Universities. The bottleneck management approach of DePlaVis is based upon the theory of logistic operation curves (Nyhuis and Wiendahl, 2003). In contrast to the original approach, the research team uses the throughput curve, which is able to visualize and assess bottlenecks in the production system (Schultheiss and Kreutzfeldt, 2009). This solution draws the causal relation of particular bottlenecks and the overall system performance. With the developed software demonstrator on hand, the throughput curve can be computed and directly communicated on the shop floor to discuss countermeasure or improvement initiatives.

However, a verification of throughput curves in practice is currently only available for series production (Hinckeldeyn et al., 2010). Objective of this research project is to investigate the applicability of the throughput curves and its optimization mechanisms in small series and single part manufacturing systems. The remainder of this work is organized as follows. The next section will cover the basics on bottleneck management. In section 3 the methodology used is described and section 4 will present the. Finally, section 5 discusses and the last section concludes and presents directions for future research.

### Bottleneck Management with Throughput Curves

The first approach to describe logistical systems also graphically was the funnel model, (Bechte, 1984; Wiendahl, 1992). This analogy describes a work system, like a work station or even a whole factory. The fill level of the funnel depicts the work load of the system. The width of the funnel opening, through which the production orders flow, presents the capacity. The relationship between these parameters can be found of the throughput diagram, the first visual impression of the logistical parameters of a work system, which depicts input and output over time. Based on this analogy, the Theory of Logistic Operating Curves was developed (Nyhuis, 1991, 2006, 2007) (Wiendahl and Nyhuis, 2003). In a deductive-empirical approach, the performance and the throughput time of a work system are considered as
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dependent variables, which are related to the order backlog as independent variable. A C-Norm function provides the mathematical basis for the computation of the logistical curves. As this approach is working with average values, the curve is only suitable for static analysis of logistical system. The application of logistic operation lies therefore more in the strategic positioning of logistical systems and not in the operative control. Wiendahl and Hegenscheidt (2002) use an operating curve to describe the utilization of assembly lines as a function of the operational availability; therewith determining the buffer sizes between the individual workstations. However the curve for assembly processes operates also with average values and its application lies more in the strategic area for decisions in assembly lines, especially in the dimensioning of buffer sizes between assembly stations. An operative bottleneck management is not considered within this approach.

The throughput curve as a bottleneck management instrument is developed by Kreutzfeldt (1995). It enables a bottleneck management with a visual approach linked to an approximation algorithm. To represent the relationship between the input variables (e.g. load, work plans and capacity) and output variables (e.g. performance, utilization and inventory) of work systems, the throughput curve was selected as the basis for the identification and evaluation of bottlenecks. To apply it, three assumptions in an analogy to electrical systems are made (Kreutzfeldt, 2007):

1. A bottleneck restricts the flow of production orders in a similar manner that a resistor limits the flow of electrical current in an electrical network. This similarity can be assumed, if discrete order flows are considered as continuous flows. The probability that an order is processed depends on the ratio of the workload to the capacity at the work station with the greatest workload. This work station is termed the throughput limiter. The throughput limiter is defined as the work station with the greatest ratio of work load to capacity.
2. Thus, a parallel can be drawn between the continuous flow of orders through a production system and an electrical current as it flows through an electrical network. All orders that move through the same limiter become a continuous flow of orders. This flow contains the workload of all orders on all work stations in a period.
3. In this way, just as an electrical network can be described by electric currents and resistors, a production network can be modeled based on bottlenecks and flows of production orders.

A detailed overview with examples of the calculation of the approximation algorithm can be found in Schultheiss and Kreutzfeldt (2009). The approach presented by Kreutzfeldt (1995) provides an easy to understand and communicate solution for bottleneck problems in the manufacturing environment. Even thought there is an extensive body on literature dealing with the benefits of bottleneck synchronized operations management (i.e. Pegels and Watrous 2005; Taj and Berro 2006; Kühnle et al. 2009), a verification of the approach by Kreutzfeldt (1995) in practice cannot be found. The scope of this paper is to verify the approach by using discrete event simulation.

A bottleneck management software for engineering companies

The software demonstrator developed in the research project DePlaVis is used to calculate, visualize and communicate the throughput curve. The demonstrator frontend is programmed in Microsoft ® Visual Basic .net Framework and the backend is based upon a Microsoft SQL Server ® 2008. The frontend allows showing the user to calculate and display the throughput curve either for the entire production system or a single bottleneck. Figure 1 depicts the graphical user interface of the DePlaVis Demonstrator for shop floor workers and production scheduling and controlling staff members. It is divided in three sections. Section (1) charts the throughput curve for the selected workstation and section (2) shows the most relevant data such as workload, direct and indirect throughput as well as calculated processing factor. Section (3) classifies the orders according to their part family for each workstation and shows the cumulated proportion of the part family to the relative workload. The relative workload is calculated by dividing the processing time by the capacity. The classification of production order according to their

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part family allows the production scheduling and controlling staff to outsource manufacturing orders to level the workload of bottleneck workstations stations.

Methodology

The throughput curve and its optimization mechanisms are verified with a discrete event simulation model. The use of discrete event simulation in the context of operations management is appropriate since the discrete flow of materials and orders of production can be modeled (Law 2007). One of the main advantages of simulation is ability to execute scenarios that would take weeks in reality, in a short matter and changes in the input data do not affect the performance of the company under analysis. Yet, one has to mention, that the quality of the simulation is highly dependent on the quality of the input data and the simulation model is only a reproduction of the real production system. Therefore, the interpretation of the results must be reconciled with the expected values.

For the verification of the approach by Kreutzfeldt (1995) two averments are enunciated: First the accuracy of throughput curves depend upon the average job workload in relation to the overall capacity of the bottleneck. In order to verify this averment three datasets over four, eight and twelve weeks are analyzed and reviewed according to their usability for the simulation of throughput curve. The most usable dataset is then used for a comparison of the simulated and calculated throughput curve in order to determine its accuracy. Second, the in the DePlaVis Demonstrator implemented optimization algorithm is tested upon its applicability and accuracy. Since production systems are mostly characterized by shifting bottlenecks, the predicted optimization of the DePlaVis Demonstrator might not be realistic.

The production system is modeled in the simulation tool Plant Simulation from Tecnomatix. The model consists of around 400 work- and queuing stations, which can process production orders. In order to work with confined capacities, the cumulated capacity of the used observation period is uniformly distributed over its total duration in weeks with 5 working days per week. Due to the fact that more than one machine is controlled by one worker; the capacity of a single workstation is only consumed, when
the workstation is loaded by a production order. Further assumptions in the simulation model are: (1) neglecting the transportation between workstations and (2) 100% of the capacity can be used for manufacturing. Workstation stoppages and maintenance time are not directly considered, since the capacity extract from the ERP system is reduced by planned maintenance and empirical based downtime.

Findings

The input data of the simulation model are provided from an ERP system of a mechanical engineering company for high performance gears, which can be classified as a MTO. The mechanical engineering company is the world market leader in turbo gear units and designs and produces integral and planetary gear units as well as parallel shaft gear units. With approximately 360 employees and a turnover of 85 million Euro the company is still classified as mid-tier business. The productions orders are scheduled in periods of one week. Since the average manufacturing throughput time of the turbo gear units is about 12 weeks and in order not to have a strong fragmentation in production orders, an analysis of the production orders are done. In order to generate an appropriate set of input data, three observation periods P 1 - 4, P 1 - 8 and P 1 - 12 are formed by combining the individual production orders per week. The observation period P 1 - 4 is 4 weeks long, P 1 - 8 has got duration of 8 weeks and P 1 - 12 one of 12 weeks. As shown in Table 1, there is only a slight difference in the three observation periods. But since the algorithm uses the ratio of workload to capacity, the free capacity in the observation period P 1 - 12 would lead to false simulation results and a wrong interpretation. On the other hand, the manufacturing orders have an average cumulated processing time of about 6 to 8 weeks. Since a fragmentation of the manufacturing orders can be found in the period P 1 - 4, it seems more adequate to use the observation period P 1 - 8. Therefore, for all further simulation scenarios in this paper the observation period P 1 - 8 is used. In order to revise the outcomes of the simulated and computed throughput curve, the results are further verified by problem-centered interviews in practice (Mayring, 2008).

Table 1: Comparison of the production orders observation periods P 1 - 4, P 1 - 8 and P 1 - 12

<table>
<thead>
<tr>
<th>Parameter</th>
<th>P 1-4</th>
<th>P 1 - 8</th>
<th>P 1 - 12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of production orders</td>
<td>550</td>
<td>606</td>
<td>659</td>
</tr>
<tr>
<td>Number of suborders</td>
<td>2073</td>
<td>2413</td>
<td>2633</td>
</tr>
<tr>
<td>Workload [min]</td>
<td>1.081.136</td>
<td>1.595.199</td>
<td>1.795.752</td>
</tr>
<tr>
<td>Cumulated capacity [min]</td>
<td>12.504.788</td>
<td>24.271.813</td>
<td>35.704.355</td>
</tr>
<tr>
<td>Number of workstations</td>
<td>218</td>
<td>218</td>
<td>218</td>
</tr>
</tbody>
</table>

For the analysis of the applicability of the throughput curves and its optimization mechanisms in small series and single part manufacturing systems, two simulation scenarios were defined. The first scenario represents the throughput curve once calculated by the DePlaVis approach (SR 1) and by event discrete simulation. In order to realize a simulations series for the projection of the throughput curve to different methods were selected. The first method (SR 2) resizes the workload for each workstation by a factor between 0 and 1, whereas the second methods (SR 3) uses a self programmed random generator to create fictive manufacturing orders, which represent typical production orders of the engineering company. In order to determine the number of simulation point per series, the calculated throughput curve is approximated by a polynomial of degree 10. Simulations were performed where the first derivative of the polynomial showed the most significant accession.

Figure 2 depicts the three different simulation series. Up to nearly 70.000min of workload all three series show similar results. In the area of 70.000 to 130.000 min of workload the factorized simulated throughput curve corresponds to the calculated one. With a workload of 120.000 min or higher both simulations series deviate from the calculated throughput curve and especially the factorized simulation series shows a mercurial behavior. Even though the factorized simulation series with a workload of 120.000 min or higher has been performed several times, the mercurial behavior is still present. An ex-
planation for this behavior might be a set of extra large manufacturing orders, which are de-allocated and are resulting in disproportionate throughput.

Figure 2: Comparison of calculated and simulated throughput curves.

For the prediction of dynamic behavior due to a capacity increase, a solution is needed that can calculate the point at which the bottleneck changes its location. This point is important for the implementation of improvement measures. Through an enlargement of capacity at the bottleneck, further effects can be measured on subsequent work stations as load increases. Wiendahl and Hegenscheidt (2002) show that at the major bottleneck in a linear process, only enough capacity should be added up to the maximum capacity of the next highest bottleneck. Any further increases will only create new idle capacity and therewith inefficiencies. Hence, the point of shifting of the bottleneck is important to address targeted improvement measures. This statement may also be applied further to production networks on the whole because any adjustments of the capacity at the bottleneck resource will also affect the flow of orders that do not directly pass through the bottleneck itself. This appears, due to reduced order supply of work stations behind the bottleneck. Due to an increase in throughput at the bottleneck, additional capacity at upstream and downstream work stations is also needed. This in turn can lead to erratic bottleneck behavior.

In complex situations beyond linear processes, such as job shop productions, an implementation method without extensive computing time is necessary. One basis for the application are the known Branch and Bound algorithms (Dakin 1964), through which it is possible to model the whole production network. They reduce the computing time by cutting unnecessary parts of the system from the operation. Starting from the bottleneck station, the relations between the material flows of the upstream and downstream work stations can be modeled using a tree model (Altfeld, 2008). A detailed explanation of DePlaVis Branch and Bound algorithm can be found in Altfeld (2008) and Schultheiss and Kreutzfeldt (2009) and in summary the DePlaVis Branch and Bound algorithm is used to calculate the maximum capacity increase of a workstation in consideration of the maximum increase of throughput. Due to the long processing times, the time step for the calculation of the capacity increase is set to 15min. This allows for a moderate fast calculation by still providing a good accuracy.

To validate the DePlaVis Branch and Bound algorithm three workstations were selected based on the ratio of throughput potential. The ratio of the throughput potential is calculated by dividing the indirect by direct throughput. The higher this ratio is the higher are the effects on the overall performance of the production system. The workstations (WS) under analysis are two multi process centers (WS 3307 and
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WS 3308) and one testing bay (WS 4095501). All the workstations are bottlenecks and confine the performance of the production system to a great extent.

Table 2: Overview of suggested increase of capacity and the predicted increase in throughput for the three workstations under analysis.

<table>
<thead>
<tr>
<th>Workstation</th>
<th>Suggested increase of capacity [min]</th>
<th>Capacity increase per period [min]</th>
<th>Predicted increase in throughput [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>WS 3307</td>
<td>9.645</td>
<td>1.206</td>
<td>45.233</td>
</tr>
<tr>
<td>WS 3308</td>
<td>2.073</td>
<td>204</td>
<td>6.799</td>
</tr>
<tr>
<td>WS 4095501</td>
<td>30</td>
<td>4</td>
<td>3.493</td>
</tr>
</tbody>
</table>

Table 2 shows the calculated and predicted results provided by the DePlaVis-Demonstrator. Since the simulation model uses a observation period with the length of 8 weeks, the suggested increase in capacity is portioned uniformly and rounded up to the whole minute. The simulated results are in all three cases lower than the predicted and calculated ones, see Figure 3. The biggest difference can be found at the workstation WS 3308, where only 27% of the predicted increase of throughput was attained. Yet, one has to mention, that despite the fact of the not reached increase of throughput all three workstations show still a positive effect on the overall performance of the production system.

Figure 3: Comparison of the simulated results with the predicted and calculated ones.

Discussion

The findings indicate a limited applicability of throughput curve over small periods in small series and single part manufacturing systems. In particular the relation of workload and capacity of the bottleneck plays an important role. As the relation decreases and fragmentation of the manufacturing orders increases, the accuracy of the overall throughput decreases also. This can be traced back to the fact that throughput curves are based upon stochastic assumptions, e.g. equal distributed probability of order processing and continuous order flows. Thus the throughput curve seems only applicable for long term and strategic bottleneck management.

The shown optimization potential of the Branch and Bound algorithm in the DePlaVis Demonstrator cannot be confirmed. Even though in all cases an increase in throughput could be analyzed, the simulated results are lower than the calculated ones. One explanation of this result is based upon the fact that
the capacity increase on the bottleneck resulted to an overextended workstation within the material flow, which then restrain the overall performance of the production system. Furthermore, the long processing times of 2500 min or more on one single workstation result to another started, but not finished manufacturing order, which balks the throughput of the system. This finding was also confirmed during interviews and practical tests in the company. However, the interviewees apply now throughput curves in daily business, especially for strategic and tactical bottleneck management problems, e.g. outsourcing or subcontracting decisions.

**Conclusion**

The bottleneck management method presented here is a further development the theory of logistic operation curves (Wiendahl and Hegenscheidt, 2002). Focusing on the specific influence of workload and capacity relation the simulation made clear that throughput curves are more applicable for long term bottleneck management. Reason for this is the decreasing accuracy of the throughput curve with the decreasing relation of workload and capacity.

Moreover, targeted optimization methods at the bottleneck workstation are only useful with sufficient idle capacity on non-bottleneck workstations. The higher the global workload throughout the whole production system, the lower is the effect of single improvement attempts. The practical findings indicate a good implementation in the field of strategic bottleneck management. During investigation in practice interviewees mentioned an application in the field of outsourcing of a component group. However, throughput curves take currently only single components and orders into account. Therefore the bottleneck management approach should be extended to a more aggregated visualization of component groups.

In spite of the shown applicability of the DePlaVis approach for small and medium sized MTO companies, it is questionable of the approach could also be confirmed in an engineer to order (ETO) or mass manufacturing environment. Especially ETO companies have limited master data for their production planning and scheduling systems, since components are individually designed and engineered for one customer. Future research should therefore concentrate on the synchronization of engineering and manufacturing to expand the concept of bottleneck management and throughput curves on engineering departments as well as ensure the availability of engineering master data for the production planning and scheduling system.

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