

# Capacity Flexibility within Production

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**Abstract**—Due to high dynamics in current markets the expectations regarding logistics increase steadily. However, the complexity and variety of products and production make it difficult to understand the interdependencies between logistical objectives and their determining factors. Therefore specific models are needed to meet this challenge. The Logistic Operating Curves Theory is such a model. With its aid the basic correlations between the logistic objectives can be described. Within this model the capacity flexibility represents an important parameter. However, a proper mathematical description for this parameter is still missing. Within this paper such a description will be developed in order to make the Logistic Operating Curves Theory more accurate.

**Keywords**—Capacity flexibility, Production controlling, Production logistics, Production management.

## I. INTRODUCTION

PRODUCTION companies currently find themselves in a competition marked by increased variant diversity and shortening product lifecycles as well as economic uncertainty and subsequently fluctuating orders. As a result dynamic can be observed which leads to steadily increasing expectations regarding logistics. In order to remain successful in the market companies have to meet these expectations. At the same time, the complexity and variety of processes make it more difficult to recognize the interdependencies between the logistic objectives as well as the possibilities for influencing them. In order to make these connections describable specific models are needed. In the area of production management, the Logistic Operating Curves Theory, developed by Nyhuis is such a model [6]. With its aid the basic correlations between the logistic objectives can be described. Furthermore, it provides a foundation for designing and controlling the production focused on specific targets. Within this model the capacity flexibility plays a major role. However, its influence can only be empirically considered based on experimental research. Up until now, an appropriate mathematical description of capacity flexibility which can be used within the model does not exist.

This paper pursues the objective of developing such a description. It presents the results of a research project entitled “Mathematically Describing and Evaluating the Influence of

the Capacity Flexibility and Load Variation on the Behavior of Logistic Systems”. This project was financed by the German Research Foundation (DFG) and conducted at the Institute of Production Systems and Logistics at Leibniz University Hannover. The aim of this project is to increase the reliability of information gained from the Logistic Operating Curve Theory. Moreover, the basis for a logistic and monetary evaluation will be created which in turn can be used as a support in deciding which measures for controlling capacities (e.g., over-time, additional shifts etc.) or smoothing the demand should be selected.

## II. STATE OF THE ART

Capacity flexibility is a term commonly used in the field of production management and within production respectively. It describes the ability of manufacturing to vary its capacity fast, cost-efficiently and, if necessary, in a high extent [1]. In that context capacity stands for both working systems and personnel. The current literature provides several approaches that pursue the goal to describe capacity flexibility. The capacity graph, the capacity envelope and a suggestion to calculate capacity flexibility are presented in the following.

### A. Capacity Graph

The capacity graph contrasts capacity load with available capacity. An example can be seen in Fig. 1. It is typically used for capacity planning which is part of the production planning and control process.

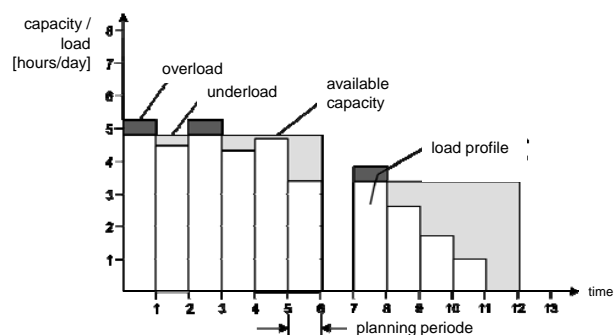


Fig. 1 Capacity graph

The capacity graph visualizes clearly capacity overload and capacity underload. In periods with light grey areas there is enough capacity to meet the load requirements, utilization losses can occur here. In contrast, in periods with dark grey areas the capacity load exceeds the available capacity. Without load or capacity adjustments scheduled orders cannot be manufactured in time. Depending on how urgent the

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adjustment has to be implemented different adjustment measures can be found within the current literature. They vary from measure with short reaction times such as overtime to measures with long reaction times such as the purchase of new manufacturing resources [2].

The capacity graph can be used to identify periods where capacity flexibility will be needed. It clearly shows where capacity adjustment is necessary. However, it does not describe to what extent the capacity of a production has to be flexible. It does not provide a key figure to measure capacity flexibility.

### B. Capacity Envelope

The capacity envelope represents an approach that is able to describe the ability of working systems to build up and reduce capacity respectively. It includes reaction as well as minimum installation times. The reaction time describes the time which passes by until a capacity adjustment makes an impact. In contrast, the minimum installation time describes how long the additionally installed or uninstalled capacity at least has to be kept up [3]. A capacity envelope is shown in Fig 2.

In Fig. 2 (a) positive and negative capacity adjustments are plotted over reaction time. For instance, an additional capacity of four hours per day can be installed within five days. In Fig. 2 (b) the corresponding minimum installation time is pictured. It can be seen that the additional capacity of four hours per day has to be kept installed for at least five days. Usually the minimum installation time increases with the amount of additional capacity. The product of additional capacity and minimum installation time represents the minimum total capacity. It can be used to decide if capacity adjustment measures make sense or not [3].

The capacity envelope represents a model that is able to describe the ability of working systems to build up and reduce capacity respectively. Therefore it takes reaction times and minimum installation times of capacity adjustment measures into account. However, it does not provide the possibility to measure capacity flexibility by key figures.

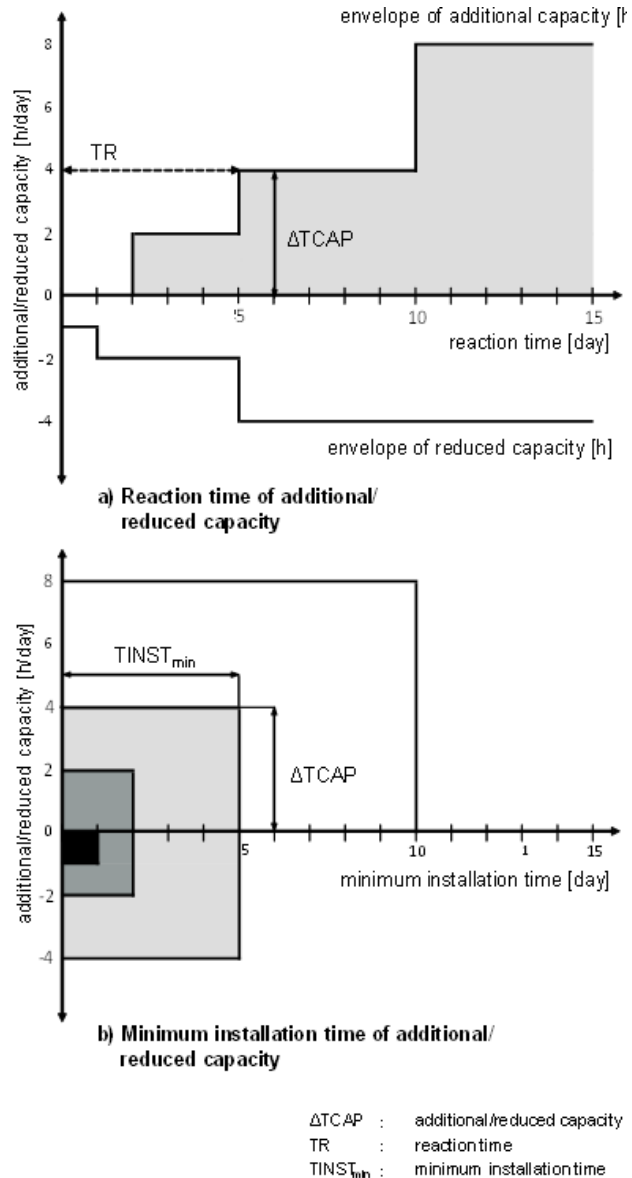


Fig. 2 Capacity envelope

### C. Capacity Flexibility Calculation

The current literature only provides few papers that pick the actual calculation of capacity flexibility as their central theme. Exemplarily the approach developed by Petersson will be presented here [4]. It claims that the developed key figure is able to describe both effects of capacity increase and effects of capacity reduction [4]. In order to depict the approach Fig. 3 will be used.

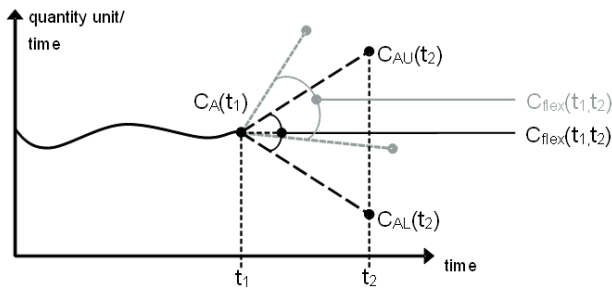


Fig. 3 Capacity development

In Fig. 3 continuous capacity development can be observed. At the time  $t_1$  the actual capacity level is certain and can be named with  $C_A(t_1)$ . The extent of capacity flexibility within the time span  $t_1$  until  $t_2$  depends on both the capacity level at the time  $t_1$  and the minimal and maximal possible capacity at the time  $t_2$ . In Fig. 3  $C_{AU}(t_2)$  represents the upper capacity restriction,  $C_{AL}(t_2)$  in contrast represents the lower capacity restriction at the time  $t_2$ . The resulting angle between both capacity restrictions can be interpreted as key figure  $C_{flex}(t_1, t_2)$  which describes capacity flexibility [4]. This angle can be calculated as follows:

$$C_{flex}(t_1, t_2) = \frac{C_{AU}(t_2) - C_{AL}(t_2)}{t_2 - t_1} \quad (1)$$

The major disadvantage of the derived key figure can be explained with the grey angle which is also displayed in Fig. 3. This angle shows a scenario which can be characterized by both a very high upper capacity restriction and also a high lower capacity restriction at the time  $t_2$ . In the aforementioned scenario the upper capacity restriction was high and the lower capacity restriction was low. Nevertheless, both resulting angles, and hence, the capacity flexibilities in both scenarios are equal. This means that capacity increase and capacity reduction are able to compensate each other within this model. Moreover, a statement regarding the magnitude of the ability to vary capacity cannot be made with this key figure [4].

### III. BASIS FOR THE MODELING

In order to develop a common understanding, at first some relevant fundamentals of production logistics will be presented and explained. In particular the Funnel Model as well as the Throughput Diagram will be discussed. Within production logistics both models are commonly used to describe correlations. In this paper they represent the basis for the derivation of a key figure that is able to describe capacity flexibility properly.

The Funnel Model represents the foundation for lots of logistical models. It can be seen in Fig. 4.

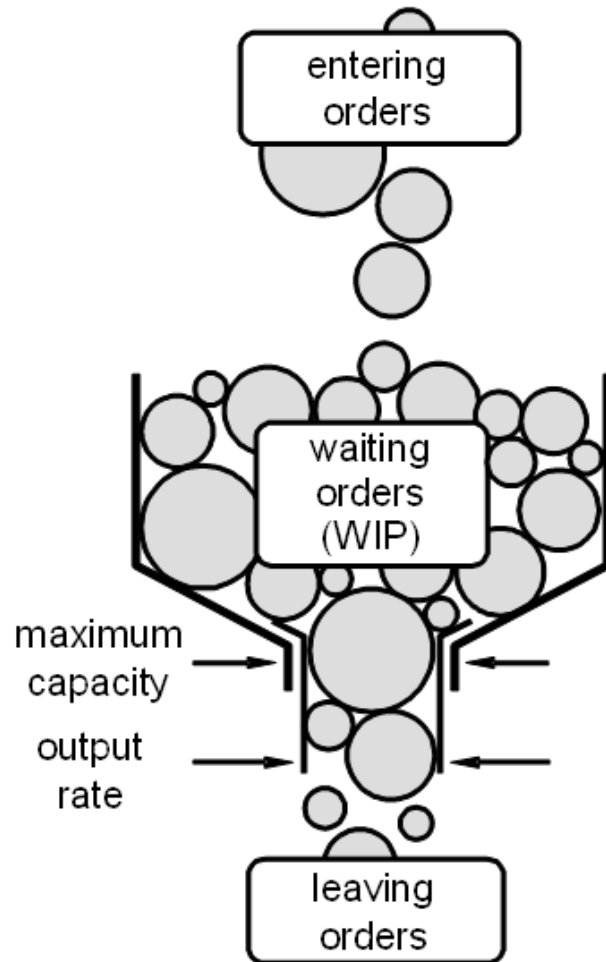


Fig. 4 Funnel Model

Similar to the flow systems found in process engineering, the Funnel Model describes the throughput behavior of a capacity unit through the input, work-in-process (WIP) and output. In doing so, the capacity unit can be embodied by the funnel itself. The contents within the funnel represent production orders. In this model three different types of production orders can be distinguished. There are orders entering and leaving production as well as those already in production. All together they represent the WIP. Within the model the current output rate of a working system can be visualized by the opening of the funnel. Hence, the maximum opening symbolizes the maximum capacity of the regarded working system [5].

Generally, the Funnel Model can be applied on lots of different units of capacity. It does not matter if the regarded capacity unit is a single working system or a whole production.

In this paper, the focus lies on individual workstations.

All of the events in the funnel can be transferred to the Throughput Diagram. An example can be seen in Fig. 5.

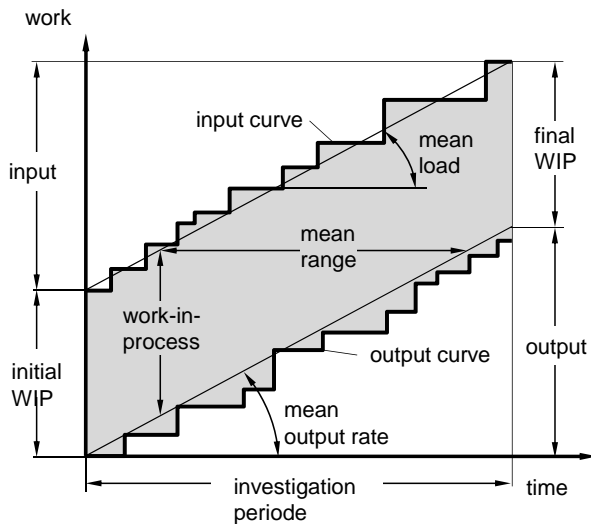


Fig. 5 Throughput Diagram

The two main components of the Throughput Diagram are the input and output curve. Orders entering production are chronologically plotted cumulatively according to their work content and form the input curve. The same applies to the completed orders. Orders leaving production are also chronologically plotted cumulatively according to their work content and form the output curve. In this model the output and input date on a workstation correspond. In fact the output date on a workstation represents the input date on the subsequent workstation. The initial WIP of the capacity unit during the investigation period can be read easily off the Throughput Diagram. The starting point of the input curve simply embodies it. Also the WIP within the investigation period can be determined with the aid of the model. At every time the difference between input and output curve represents the current WIP. The Throughput Diagram provides the opportunity to read off two more important key figures, namely the mean load and the mean output rate. The mean slope of the input curve equals with the mean load. In contrast, the mean slope of the output curve embodies the mean output rate [5].

The Throughput Diagram can be used to depict relevant logistical key facts of a workstation. The dynamic behavior of a system can be described qualitatively and down to the minute. In doing so, the Throughput Diagram can be used by companies to pursue the primary production logistic objectives (utilization, WIP, throughput time and schedule adherence) [6].

#### IV. EVALUATING THE CAPACITY FLEXIBILITY

Capacity flexibility describes the ability of manufacturing to vary its capacity fast, cost-efficiently and in a high extent [1]. Based on this definition, a key figure that is able to describe capacity flexibility properly has to consider the effects of reaction and minimum installation times of capacity adjustment measures as well as the actual amount of the

capacity adjustment. In this chapter such a key figure will be developed. In the future it should help to quantitatively evaluation capacity flexibility which is necessary to improve the Logistic Operating Curves Theory.

The previously described Throughput Diagram provides the foundation for the key figure. As explained in chapter III the difference between input and output curve represents the current WIP at every time. Based on this knowledge a WIP curve can be created and be integrated into the Throughput Diagram. This can be seen in Fig. 6.

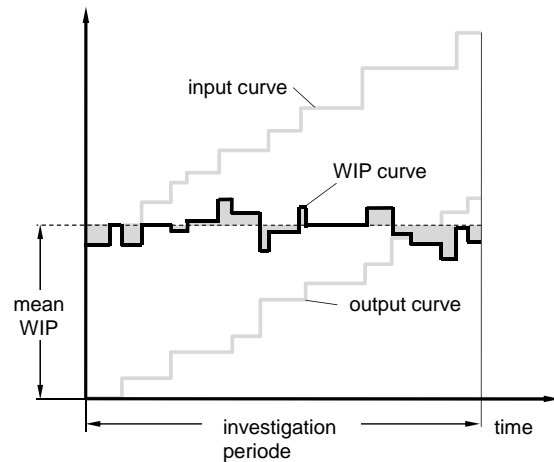


Fig. 6 Throughput Diagram including WIP curve

The WIP curve can be averaged. The resulting mean WIP  $WIP_m$  can also be calculated as

$$WIP_m = \frac{\sum_{T=T_0}^{T_1} WIP(T)}{z} \quad (2)$$

whereas  $WIP(T)$  represents the WIP in time segment  $T$  and  $z$  the number of time segments within the investigation period [6]. As measure for the capacity flexibility the area  $A$  between the actual WIP and the mean WIP will be used. In Fig. 6 this area is highlighted grey. If a working system is able to respond fast and in the right amount to load variation its WIP will be constant. Hence, the mentioned area  $A$  will be small; the system's capacity flexibility will be high. If, in contrast, the working system responds slowly and in the wrong amount to load variation the variation of the WIP will be high. Consequently the area  $A$  between the actual WIP and the mean WIP will be large; the system's capacity flexibility will be rather low. In order to create a usable key figure out of the area  $A$  three steps have to be carried out. Firstly the key figure has to be made independent from the length of the investigation period. Therefore the area  $A$  has to be related to the existing investigation period  $UT$ . Secondly the key figure has to be made independent from the existent load variation. Consequently it has to be related to the relative load variation  $LV_{rel}$  [7]. Thirdly the key figure has to be made independent

from the underlying work content spectrum. For that reason it has to be related to the ideal WIP  $WIP_{min}$ . Considering these three steps the key figure for capacity flexibility  $CF_{rel}$  can be calculated as follows:

$$CF_{rel} = \frac{A}{WIP_{min} \cdot UT \cdot LV_{rel}} \quad (3)$$

By using the area between actual WIP and mean WIP and the WIP variation respectively the developed key figure takes all effects that have an influence on capacity flexibility into account. However, the key figure can only be applied on working systems with permanent WIP. For working systems with only partial WIP (often no waiting orders in front of the working system) another key figure has to be found.

#### V.CONCLUSION

This paper pursued the target to develop a key figure that is able to describe capacity flexibility quantitatively. The key figure is needed to improve the Logistic Operating Curves Theory. Based on the Throughput Diagram such a key figure could be developed. As a measure for capacity flexibility the area between actual and mean WIP within the Throughput Diagram was used.

Future research has to clarify how this new key figure can be integrated into the Logistic Operating Curves Theory and if another key figure for working systems with only partial WIP is necessary. It has to be analyzed how capacity flexibility influences the logistic system performance and how the new key figure can be used to describe the behavior of these systems mathematically.

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