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Dynamic Bottleneck Starvation Control

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Abstract. Choosing the most fitting manufacturing principle largely depends on the technical divisibility of jobs and the quantity to be produced. In most cases, a high quantity causes a higher degree of automation. What to do, however, if the production programme is evolving into various product modifications in the long run, thus developing from monolithic flow lines to a quasi-continuous batch production by means of bottleneck machines?

Classic push-controlled routines are failing here, since the batchwise manufacturing in combination with performance-reducing parameters within production systems will cause discontinuous outputs that are difficult to control and, moreover, feature an increased creation of work in process (WIP).

This problem is intensified by a combined influence of necessary setup activities, which often lead to sporadic machine failures. As a matter of fact, this invariably causes a dramatic delay in delivery times, not least because of the extension of the throughput times.

In this paper, we will introduce a manufacturing control that is based on dynamic WIP-oriented bottleneck planning, which will allow to maintain the automatically regulated output optimum by means of a self-controlling system.

Keywords: production system control, bottleneck, solution approach, practical application, industrial case.

1 Introduction

When customers' call-offs are highly volatile, suppliers are forced to provide flexible manufacturing processes and/or secure supply chains in order to safeguard the readiness for delivery. This is especially difficult to configure and control for complex products. The key to success in this respect is a combination of the lowest possible WIP orientation and the highest possible response capacity, so as to ensure an economical and logistical efficiency combined with high functionality of the supplier systems [1, 2].

As for the operational implementation, it is often organisational, usually WIP-limiting regulations that prove to be essential, which serve as operational routines individually adjusted to the respective production system [3]. Coupled with existing, case-specific boundary conditions, this will invariably lead to individualised manufacturing controls adjusted to the respective capacity of the production system, which depends on both the technological features and the specific customer-supplier-relations [4].

The development of such an individually adjusted manufacturing control will be illustrated in the present paper. Our fundamental approach may also provide similar production fields with the means to meet this issue in a systematic and methodically profound way. While the individual solutions arising from that are only transferable in a limited way in their respective versions, the approach for determining the basic functionality usually results in optimised manufacturing control [5, 6, 7].

2 Basic principles

To start with, controlling a system requires the analysis and understanding of its behaviour. One essential model for the systemic description of production processes is the control loop model [cf. 8].

A closed-loop control works in the following way: the control unit transfers information (the control variable) to the system to be controlled (production process), while the result of the manipulation (the process value) is transmitted to the control unit. Since the control process is arbitrarily selectable, control loops are very much suited for describing production systems, especially against the background of utilising runtime-dependent control variables.

Besides displaying the typical time response (sequencing rules), another advantage is constituted in the fact that system-inherent parameters are imaged in the control process. Provided that clear customers' call-offs exist, this results in an organisationally worthwhile WIP, for which a changing – but still defined within limits – throughput time can be used as an output basis. This leads to a “sound, super-efficient” WIP which, in most cases, is not an operating point but, as a consequence of interacting parameters, rather a field of operation (setting range) for the optimal correlation of the system's WIP and output [9].

Referring back to Little's Law (or, in modified version, to the Funnel Model), this field of operation can be defined accordingly, with the throughput time of the jobs arising from the relative evaluation of WIP against output. Taking into account the combined interactions of the parameters, this will result in a quasi-stable system behaviour. By definition, this will, in turn, provide a high level of predictability regarding the completion times and, accordingly, on-time delivery, with the production system getting closer to an optimum system behaviour [3, 10, 11].

The complexity of the control unit (here: the manufacturing control method) depends on the type and constitution of the controlled process (here: the production system). Simple and sturdy production systems featuring a high degree of determination or high degree of organisation respectively (i.e. strictly connected flow lines) induce defined, stable performance characteristics which ought to be aspired when faced with the increased complexity of other systems.

According to [3], the following can be stated: Job-shop structures manufacturing a high diversity of products with very different operational sequences mostly require complex scheduling and release methods as well. The fewer variants a production system has to produce, featuring almost identical operational sequences, the simpler it is to design the required scheduling and release method.

Thus, scheduling and release methods should be as simple as possible.

In the present case, three product versions are manufactured in one production system, with the respective operational sequences being identical. Each operation requires the utilisation of several machines of the same type which, every so often, results in time-consuming re-settings due to the product variants. In general, this production system is regarded as a flow shop system with multiple machines, where different lots are produced on individual or shared resources [12].

A rather simple method for job control in such systems is called ConWiP [13]. Here, the material flow is directed in a way that the WIP will be limited during the manufacturing. Similar to a car park, the job release will only be given (“drive in”) once the completion of a certain job amount has been signalled (“free space available”), in other words the maximum number of WIP has not been reached. The feedback of the release information is designed here as a global pull, while the jobs are moved from machine to machine in form of a local push [13].

Should there be a bottleneck in the controlled system, this very bottleneck might also work as a signal, i.e. the release will be conducted according to the signalled WIP behind the bottleneck. The benefit is that an automatic bottleneck control is carried out, so that the limiting factor of the production system can be utilised in the best possible way. Analysing the behaviour of the evaluated system will now show that the control process is shortened, making the system more manageable as a whole. Hence, [3] refer to this ConWiP version as “pull-from-the-bottleneck”.

All in all, the success of such a scheduling and release method largely depends on the correct determination of the maximum permissible WIP or the limits of variation respectively. The above-described correlation to the performance provides a setting range whose upper and lower thresholds can be determined by using aggregated evaluation methods according to the principles of Little's Law (or the Funnel Model respectively). If the setting range and the parameters are known for their position, they can be used as variable for the controlling of the production system. Acting inside the determined setting range allows for a maximum exploitation of the WIP, thus securing the optimal utilisation of product resources [10, 11].

3 Research Approach and Control Methodology

The control method presented below combines the fundamental bottleneck and WiP-Control mechanisms to form a dynamic bottleneck starvation control method, designed for flow shop systems with multiple machines, where different lots are produced on individual or shared resources (cf. **Fig. 1**).

As a matter of fact, dynamic schedule rates can be determined for such production systems, with each released WIP showing the systemic availability of the respective bottleneck situation. A defined WIP in front of the bottleneck simplifies the control process, thus increasing the basic output with regard to both quantity and time.

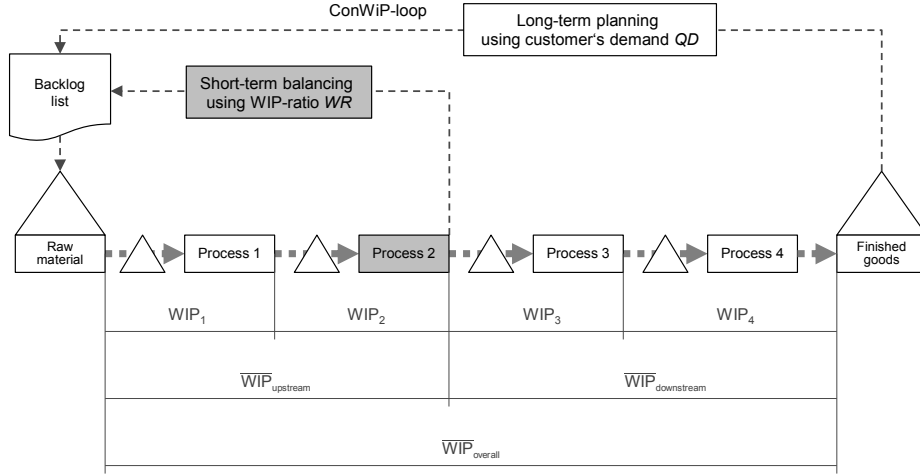


Fig. 1. The basic concept of the dynamic bottleneck starvation control.

Here, the bottleneck process determines the maximum throughput rate THR required to meet the customer's demand QD for the given time t . In other words, for a steady-state system, the throughput rate is equal for each process step i and corresponds to the throughput rate of the bottleneck process:

$$QD(t) = THR \cdot \sum_i WC_i \quad (1)$$

This model-based evaluation makes it easier to determine and monitor the necessary WIP levels within the value stream in front of and directly at the bottleneck by means of averaged figures. There are two crucial values in this respect:

- WIP-ratio at the bottleneck (WR_{BN})

$$WR_{BN} = \frac{WIP_{BN}}{WIP_{overall}} \quad (2)$$

This value is taken for a continuous evaluation of the WIP in order to avoid bottleneck starvation. Additionally, the customers' call-off behaviour will be somewhat shifted via the bottleneck towards the production system, which reduces the response time to fluctuations in the quantity of the individual product variants.

- WIP-ratio upstream the bottleneck (WR_{up})

$$WR_{up} = \frac{WIP_{upstream}}{WIP_{downstream}} \quad (3)$$

This value is used for a demand-driven quantity and capacity balancing in order to control the value stream in front of the bottleneck (upstream).

Both values act as an equalization valve in the classical ConWIP control loop. With the help of defined thresholds, a WIP shortage will cause a short-term quantity and capacity balancing of the jobs to be integrated, securing a sufficient WIP in front of the

bottleneck. In practice, the determination of these thresholds took place in correlation with

- the present batch size and demand fluctuations,
- the OEM specifications of the delivery service level as well as
- the equipment's failure behavior.

4 Use case scenario

In this paper, relevant data and control algorithm were obtained and verified from a real case study of a company manufacturing system, which is a one of the largest manufacturers of steering system parts. This manufacturing system consists of 6 basic manufacturing technologies and can be characterised as a disconnected flow line with partially shared resources. Three product variants are produced with the same operating sequence in one directed material flow. There were moderate variant shifts in form of quantity fluctuations for the period of evaluation.

The practical planning and control take place according to a weekly production plan based on a monthly master production schedule (MPS). On the one hand, one regularly has to cope with modifications in type or quantity of the manufacturing batch sizes due to a short-term change in customers' call-offs. On the other hand, there is a significant fluctuation of the operational output (expressed via process reliability and machine availability).

In order to ensure the highest possible system utilisation, the bottleneck is scheduled according to the principle "buffer stock before is always full" (identified beforehand as manufacturing technology 3). The installed control loop works entirely independent and is defined as a push system with a limiting WIP.

Downstream the bottleneck, products are undergoing another three processes whose WIP can be regarded as latently available stock because of the high availability of the manufacturing technologies applied there. So, it is used as cumulative control variable.

The available stock was adjusted by means of a specific controlling instrument (cf. **Fig. 3**), while the fluctuation range between minimum and maximum was determined as a planning parameter for the resource management (see setting range: minimum WIP 72,000 pieces, maximum WIP 88,000 pieces). The entire system behaviour is illustrated by **Fig. 2** (given as point cloud).

The illustrated operating points were measured specifically for the case scenario and adjusted as setting range for an intervention logic in order to adjust the production resources in a flexible manner.

- Upper limit:
 - a favourable constellation of the weekly customers' call-offs without any significant machine breakdowns (high OEE-level); When the upper limit was about to get reached, which became apparent by the successive run-up of the WIP downstream the bottleneck, capacity adjustments were initiated with a planning horizon of about 10 working days (change of working shift).
- Lower limit:

- modifications in products' type and quantity on account of changed weekly customers' call-offs as well as significant machine breakdowns (low OEE-level); When the lower limit was about to get reached, which became apparent by the successive run-out of the WIP upstream the bottleneck, additional production resources were used to (i.e. extra shifts).

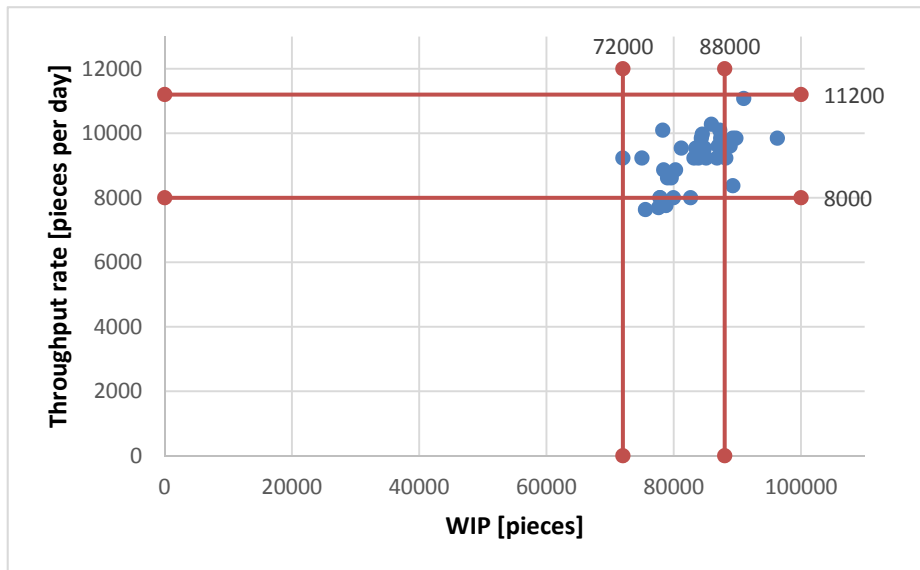


Fig. 2. The setting range.

The planning horizon had to correspond to the reactivity of the production system. This, according to the respective capacity need, allowed for the fact that shifts could be over- or under-staffed in a selective manner, so as to compensate early for possible machine breakdowns, for example.

The following overview of the WIP evaluation introduces a snapshot for the daily check-up of available stock upstream and downstream the bottleneck (cf. **Fig. 3**).

In it, the WIP-ratio upstream and downstream the bottleneck will be determined as the moving average of the total WIP for each product group in terms of occupied technology, so that changes in product ranges can be made visible in the WIP. Depending on a high and timely booking precision the presented approach is of crucial importance for the control of the entire production system.

As a result of the WIP-oriented control of the system, on-time delivery was kept at any time during the period of evaluation, while the output was raised by about 15% with more or less fixed personnel expenses

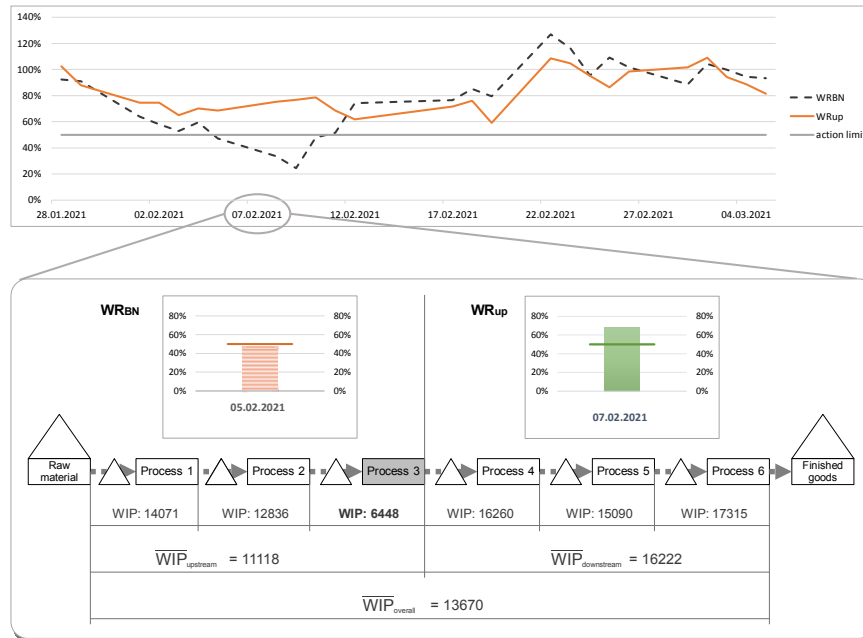


Fig. 3. The developed controlling instrument.

5 Conclusions and Outlook

The application of the introduced control method ensures a quasi-continuous production by means of fixed intervention thresholds. Based on the idea of flow shop systems, it offers the chance for a fast and flexible resource planning and control depending on the customers' call-offs. A quasi-continuous capacity adjustment will be rendered possible, which by recourse to operational regulations and routines will significantly improve the economical situation.

Moreover, with increasing degree of utilisation, the fluctuations of disruptive events could be reduced in the system. As a result, predictive maintenance could be performed (instead of ad-hoc repair with sporadic machine breakdowns) or idle times avoided by automatic releases of subsequent jobs.

Thus, it can be stated that an increased WIP transparency of the entire system combined with clear scheduling and release routines represents a significant step towards operational optimisation.

Further implementations of the introduced control method in more complex systems by the authors illustrate the prerequisites for using.

- a serial manufacturing structure with a directional as well as branched material flow (multistage production process)
- a stable production program over a long period of time (e.g. financial year)

- a manageable amount of product variants (similar product families)

Not suitable are manufacturing structures as a customer-ordered individual production of a high number of very different variants (single part production) with a bidirectional and partly returning material flow.

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