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Adaptive Job-Shop Control using Resource Accounts

Niehues, M.[a], Sellmaier, P.[a], Steinhaeusser, T.[a,*], Reinhart, G.[a]

[a]Institute for Machine Tools and Industrial Management (iwb), Technical University of Munich (TUM), Boltzmannstr. 15, 85748 Garching, Germany

* Corresponding author. Tel.: +049-89-289-15454; fax: +049-89-289-15555. *E-mail address:* tobias.steinhaeusser@iwb.tum.de

Abstract

The control of todays production systems has become more complex due to an increasing number of products, product variants, randomly incoming orders and non-standardized production processes. Specifically job-shop production is indispensable for single- and small-series-productions with low repetition rates. However, their productivity yields disadvantages compared with flow production. Self-regulating methods of production control like the Decentralized WIP-oriented manufacturing control (DEWIP) by Loedding [2] offer potential for compensating this disadvantages. Though, with an increasing variety in order sequence, it is getting increasingly difficult to estimate the effects of control activities on other orders in the following production flow. Thus, job-shop production with widely ramified material flows is usually organized manually. Decisions to overcome disturbances and deviations from the production plan are made locally by foremen or workers. Those decisions base on their experience and know-how, however with the same deficit regarding the estimation of the subsequent production process concerning disruptions. This paper presents a work in process (WIP) regulating method of production control which has been designed specifically for the requirements of typical job-shop productions. It combines the advantages of load balancing over the complete production, as proposed by Bechtes Load-Oriented Order Release [3] with the adaptivity of decentralized production control, like in DEWIP. By balancing current and prospective utilization via so-called resource accounts, bottlenecks are identified before they appear on the shop floor. Thus, alternative material flows bypassing the bottleneck processes can be activated adaptively as well as measures to extend the capacity can be undertaken. This paper presents the concept and its elaboration to a practical method for job-shop control. In addition, it was implemented in a simulation model in order to demonstrate the suitability and the effectiveness for production control in manual job-shop production systems.

1. Introduction

In today's market situation manufacturing organizations are confronted with two trends: the variety of products is increasing while production volumes and product life-cycles are decreasing [4]. This leads to shorter payback periods for products-specific investments. Hence, highly flexible production systems organized as job-shops remain an efficient production setup, especially in the engineer-to-order industry [5,6]. However, job-shop production systems are well-known for their drawbacks concerning customer requirements like short delivery times and high delivery reliability [5,6], resulting from typical characteristics of job-shop production. Due to the high variety of products, the material flow is usually undirected and the processing time differs between the products [7]. The resulting complexity of Production Planning and Control (PPC) is typically simplified by backlogging orders to dampen existing imbalances [8,9]. This entails a high Work In Process (WIP) together with rush orders and an elevated uncertainty regarding the delivery date. Since the production process in single and small-series production is not as predictable in matters of time and stability as they are in mass production, job-shop production systems are confronted more often with deviations from the planned schedule caused by longer processing times or rework [7]. Therefore, a high production performance has to be reached by an adaptive reaction on deviations instead of highly stable processes [10]. Since the product variety of job-shop production hinders reaching stable processes, PPC systems for job-shop and small series production usually aim at a high adaptability to new situations. The next section contains a survey of different trends in production control for job-shop production. Subsequent to the deficits of existing systems, this paper presents an approach for an adaptive production control based on accounts to control the WIP level.

2. Survey of trends in job-shop production control

The coordination of job-shops is an important field of research in production management. Many studies focus on the job-shop scheduling problem which derives from the task to schedule a given number of jobs using available machine inventory in such a way that total production time is minimized [11]. Therefore, solving algorithms have been developed focusing on a high solution quality and average computation times. An overview of these studies is given in [12,13]. This development culminates in Advanced Planning and Scheduling systems (APS), which have been established in the industry for creating exact and optimal production schedules [14]. However, due to the occurence of unpredictable disturbing events, the exact schedule is usually not realizable at the shop-floor [6]. Thus, an efficient management of measures addressing such events is necessary. Based on the scheduled production plan, several researches focused on approaches originating from control theory [15–17] by recording process data and adapting the input parameters of the shop floor control accordingly. These central approaches can be divided into two groups: While approaches of artificial intelligence apply case-based rules on the production plan [18–20], the control procedure of rescheduling approaches recalculate the production plan considering the new situation [17,21]. Since every control measure is executed in consideratoin of the impact on the whole production system, both groups of centralized scheduling are promising approaches to realize an efficient job-shop production control. However, an adaptive centralized control system requires a permanent availability of real-time data. Various factors listed in [9] confirm that the real-time acquisition of shop floor data is still a challenge in manual job-shop production systems.

Due to the lack of real time data as well as the complexity of centralized production control, several researchers focus on controlling the WIP level to achieve short throughput times and a high delivery reliability [22–24]. Whereas early studies concentrate on a centralized control of order release to keep the WIP on a steady level [3,25], later approaches cover the decentralized control of the WIP level between the workstations [2,26–28]. A commonly used centralized approach is the Load-Oriented Order Release (LOOR) from Bechte [3]. The LOOR concept enables a good levelling of the WIP load to avoid bottlenecks. However, it does not offer any control option to avoid a temporary overload at single resources. The Decentralized WIP-oriented Manufacturing Control (DEWIP) of Loedding [2] focusses on a decentralized production control to overcome this drawback that is inherent in all concepts of centralized control. However, decentral approaches only determine the local order sequence at single machines, leaving out the global situation on the shop-floor, which creates new disturbances in the subsequent job-shops. Although some studies have advanced the DEWIP concept [29,30], the combination of a decentralized control and a global balancing of WIP load has not yet been addressed in the literature.

A third trend in production control are so-called Multi-Agent Systems (MAS), which act autonomously by decentralized decision making in heterarchical structures. They use agents as software representatives of e. g. orders, products and resources [31,32]. MAS also lack in central coordination. Due to their high complexity and low transparency, their field of applica-
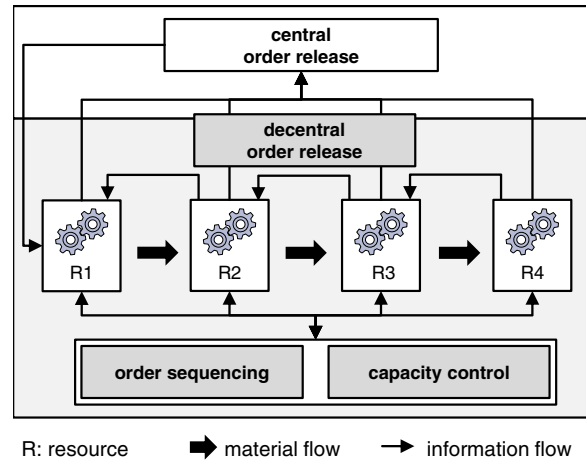

R: resource → material flow → information flow

Fig. 1. Elements of the resource account method

tion are automatized Flexible Manufacturing Systems (FMS). Therefore, an application in a manual job-shop is not reasonable, even more so because they also require real time data for their decision-making processes.

3. The concept of resource accounts

3.1. WIP-based production control

The approach of job-shop control by using resource agents is a hybrid principle for production control based on WIP and due date, which are easy to measure and insensitive to short delays in data acquisition. The combination of elements of the central LOOR approach and the decentral DEWIP approach tend to reduce the drawbacks of existing concepts, especially concerning the distribution of WIP load between resources (cf. fig. 1). The core idea is the use of so called resource accounts, in which the load of all orders being processed are booked. This enables a load balancing between the processes, similar to the DEWIP concept.

3.2. Structure of resource accounts

Resource accounts form the basis for central and decentral order release decisions. Each resource in form of a work station has its own account with two views, a central and a decentral one. Both of them are necessary for order release. The central perspective enables the release of new orders for production start and contains the WIP load of all orders being released for production and of those which will pass the considered production system on their way through it.

The complete load level of the WIP consists of the WIP of the orders physically waiting to be processed (physical) and the WIP of all orders being processed in the previous operation (indirect WIP). Both kinds of WIP are used for the central and decentral order release. In addition, the perspective for central order release contains the WIP of orders which have been released for production and will pass the considered resource during their production process, but which has not arrived at the antecedent resource. Similar to the LOOR concept, this WIP
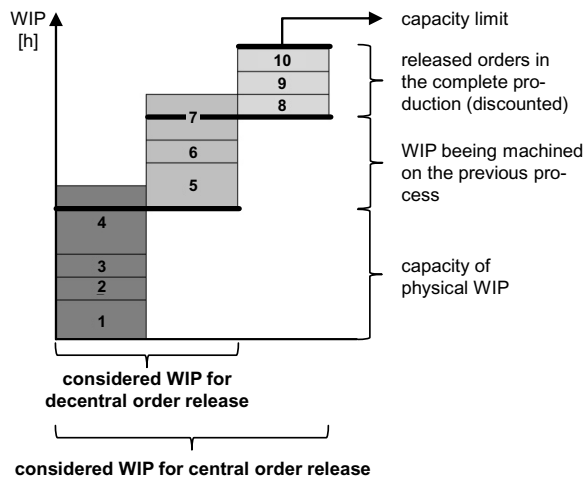
Fig. 2. Resource accounts for central and decentral order release

load has been discounted to reduce their impact compared to the other stages of WIP on control decisions (discounted WIP). The structure of resource accounts is pictured in fig. 2.

The limit for the physical WIP equates the average WIP level based on the model of logistic operation curves of Nyhuis [35]. The C_{Norm} function of [35] is used to calculate the average WIP level as a function of the output rate. Thus, the resource account concept additionally enables the logistical positioning of the production. The limit for the indirect WIP is similar to those of DEWIP, thus the formula describing the indirect WIP limit is equal to the one used by [2]. The limit for the discounted WIP can be calculated in the same way as the indirect WIP, with the exception that the operation time must be discounted. The discounting factor depends on the remaining time until the order arrives at the corresponding production system. It decreases linearly from 100 % to a predefined minimum factor. This factor is reached at exactly half of the lead time. The minimum discounting factor depends on the probability of a resource being a bottleneck resource. It is calculated by dividing the sum of times in the bottleneck mode by the correlating period of time.

For the identification of bottlenecks, each resource is equipped with queue account in addition to the normal account. The queue account contains all orders which cannot be processed due to fully loaded resource accounts of the subsequent production system. The queue account is an essential element for deriving control measures. The third resource account contains order backlog. If the level of backlog orders exceeds a predefined limit, decentral measures for capacity expansion, such as overtime, are undertaken to return to a status of steady capacity utilization.

3.3. Data and information flow

The implementation of the resource account approach requires the availability of data concerning estimated process times as well as the respective due dates. Since both dates belong to typical orders master data, their availability can be assumed. Hence, this approach do not presuppose real time data acquisition technologies and is thus suitable for classical man-

ual job-shop production systems.

Each resource account enables to obtain information about the resource's load of current and foreseeable WIP at any time. Therefore, it has to be updated permanently by three types of events (see fig. 3).

- Arrival of orders at a resource
- Completion of processing the order
- Leaving order at a resource

The creation of the events can either be executed manually by using classical Production Data Acquisition (PDA) terminals or, if available, automatically via Machine Data Acquisition (MDA) systems in combination with Radio Frequency Identification (RFID)-based surveillance of incoming and leaving orders at each resource.

3.4. Assumptions

It is necessary that the following assumptions hold for the use case in order to assure the functionality of the resource account method:

- The operators of all resources being controlled by the resource account method have access to a PDA terminal to create status events.
- Order release occurs only based on WIP load, all tools, mediums and devices to execute the related operations are available.
- The WIP load of orders differ only marginally. If the WIP load of an order is higher than a predefined limit, the order has to be subdivided into several smaller orders. This is necessary because large orders will block the account of a production system. In this case, further orders cannot be released and a bottleneck arises.

3.5. Central order release

The central order release is similar to the LOOR concept. If an order is ready for production, the accounts of all resources required for the respective order processing are checked with regard to whether the additional load exceeds the maximum WIP level. If not, the order is released for production. Otherwise, the order is restrained and the procedure starts over with the next order. One existing deficit of the LOOR concept is concerning orders consisting of many operations. The more production systems need to be checked concerning their respective WIP levels, the lower the likelihood that all of them have spare capacity. So an extreme scenario is that orders with many operations will never be released for production. Therefore, a date limit depending on the planned start date has to be defined to enable a prioritization of orders. If an order exceeds this limit, following orders scheduled on the same production system as the prioritized one will not be released. After all backwarded orders had been released for production, the central order release will switch to normal mode.

3.6. Decentral order release

The material and information flow of released orders is controlled decentrally between resources to keep the production
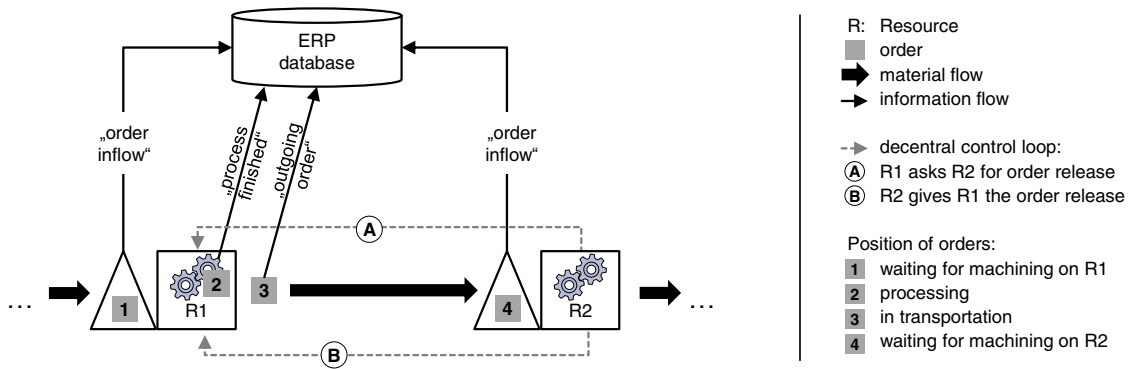
Fig. 3. Required information flow to administer the resource accounts

running. Hence, orders are only released for a considered resource if the subsequent resource has the capacity to continue production. Orders passing a current bottleneck resource are restrained in favor of orders whose subsequent process is free of congestions. This procedure is similar to the order release process of DEWIP, but the initial central order release process reduces global bottlenecks. Thus, local bottlenecks can only evolve if a certain amount of orders request processing in such a way that the resource is not able to manage it.

Nomenclature

L   value of an action limit
n_{W_p} number of orders in the physical WIP
$\bar{P}$ average performance of a production system
P_m maximum performance of a production system
p_s probability of not necessary set-ups
$\bar{t}_s$ average duration of set-up of an order
t_t transition time
z z-score of standard normal distribution

3.7. Priority rules and capacity control

Another important control element of the resource account method is the order sequencing. It is realized by a combination of priority rules which allocate a priority number to each order of a physical WIP. Orders are then released according to their priorization.

The application of priority rules takes into account the respective WIP load with the aim of keeping the capacity utilization on a steady level to avoid congestion.

If the production is in a normal mode in a sense that a steady WIP level is present and no order is at risk to exceed a delivery date, the order sequencing procedure based on the *Extended Work in Next Queue* (XWINQ) priority rule [33,34] in combination with the Least Slack per Remaining Operation (LSK/RO) priority rule [34]. XWINQ gives the highest priority to the order whose WIP level (sum of physical and indirect WIP) on the subsequent production system is lowest. Thus, it avoids bottlenecks as well as breaks in the material flow. LSK/RO assures that an order that is at risk to exceed the planned end date will receive the highest priority. An order is considered as delayed,

if the timespan between the respective point in time and the planned end time is smaller than the sum of the planned process times and the minimum transition times. Thus, the action limit for changing from XWINQ to LSK/RO priority rule depends on the minimum buffer time, which absorbs differences between planned and real times for processing and transition. Since the planned process usually times correlate with the real ones, the differences are more likely at the transition times. Thus, the action limit is defined as:

$$L_{LSK/RO} \quad = \quad z \cdot \sigma_{t_t} + \bar{t}_t \tag{1}$$

All orders that cannot be released due to overload are registered in the queue account of the subsequent resource. If the load level of waiting orders in the queue account exceed a defined action limit, the priority rule changes to bottleneck status. Now the order with the shortest set-up time is prioritized in order to increase the throughput of the considered production system. The corresponding priority rule is named Least Set-Up Time (LSUT) [34]. It enables a fast reduction of the WIP in the queue account. If an order's delivery time is at risk to be exceeded, the order's status in the queue account changes to backlog. This means that the order is classified as rush order and is thus prioritized first at each production system. The action limit of LSUT depends on the duration of set-up activities needed for processing the orders of the physical WIP. The higher it is, the more time can be gained on the bottleneck mode. In addition, a low probability p_s that there are orders in the physical WIP which do not require any set-up activities, reduces the action limit:

$$L_{bottleneck} \quad = \quad \bar{t}_s \cdot n_{W_p} \cdot p_s \tag{2}$$

If an order is classified as backlog which means that the planned end date and probably the delivery time will be exceeded, the LSUT priority rule is modified, so that only orders which do not require any set-up activities are prioritized before a backlog order. This avoids a reduction of capacity in case of prioritizing backlog orders most highly. In addition, measures for capacity extensions are undertaken. Thus, the third action limit for the backlog account depends on the ability of the considered production system to enlarge its capacity. Since the usual measure is overtime, the limit equals the difference

between normal performance (hours per day) and maximum performance

$$L_{backlog} \quad = \quad P_m - \bar{P} \tag{3}$$

4. Simulation

The resource account method for production control has been implemented in a simulation model to demonstrate the suitability and effectiveness for production control in manual job-shop production systems. A component manufacturer in the automotive industry is the use case for this simulation. The component manufacturer's production process consists of different machining, surface finishing and heat treating processes. Although a basic process exists, each customer order requires some modifications causing different material flows for different products. All assumptions for the resource account method (cf. sec. 3.4) apply in this use case. The simulation model was implemented in Technomatix Plant Simulation 10.1. It models 50 job-shops, each of them contain one to five machines. Each job-shop has an own resource account. The input data comprises the orders of about four months which come up to 3059 production orders and 28,000 single operations. The simulation model has been validated by comparing its results to those of a decision-based manual production control. In addition to that, the simulation results were compared to actual completion confirmation data. As the difference between simulation results and actual completion data is below than one percent, the model can be considered as valid. The validation of the implemented resource account method was carried out by reducing the data of production systems and the order's operations. Based on this reduced model, each control decision can be tested if the model reacts like it is defined in the method. Thus, the method was validated step by step.

The resource account method has been modelled in three scenarios:

- RA 0: Resource account method without WIP limits (only order sequencing, necessary to calculate the WIP limits for the following scenarios).
- RA 1: Resource account method without modifications.
- RA 2: Resource account method with additional consideration of set-up activities in the normal mode (no bottlenecks, no delays). If no resource account of the subsequent production systems is at risk of running idle and no order is urgent, orders are prioritized if no set-up is necessary (instead of XWINQ/LSK-RO).

The basic scenario is the manual production control based on experience and intuition. This scenario was not simulated instead real production data was used for comparison.

5. Experimental results

The results of the simulation experiments are listed in table 1. In addition, the development of the WIP level is displayed in fig. 4. Orders finished within 3 days after the planned start time can be delivered on time, because the delivery date is later than the planned start time.

Table 1. Experimental results of the simulation

Szenario	Basis	RA 0	RA 1	RA 2
max delay 3 days	48.3%	85.3%	63.2%	69.0%
10 days delay or more	34.2%	7.7%	27.5%	24.5%
lead time under 10 days	51.8%	39.4%	56.8%	47.5%
lead time more than 60 days	5.3%	2.3%	0.3%	2.2%
utilization of bottleneck machines	95%	99%	93%	93%

As can be seen from delivery reliability and lead time, scenario RA 0 without WIP limits outperforms all other scenarios. The high WIP level results of releasing all production orders of the simulation period at the starting point. It guarantees the utilization of all production systems, but a practical implementation of RA 0 would fail in case of limitations in space to store all physical orders temporarily. Also scenario RA 0 shows the efficiency of combining priority rules. It ensures short throughput times and high delivery reliability. In both scenarios RA 1 and RA 2 the WIP stabilizes at a lower level compared to the real production scenario. In addition, both scenarios enhance delivery reliability and reduce lead times. The utilization of the bottleneck machines is lower than actual production data as well as in scenario RA 0. This effect results from the missing capabilities of capacity extension, as the bottleneck machines were already working in 24/7. Thus, situations where machines run idle in case of bottlenecks occur. However, the resulting lower utilization is only marginally under those of the basic scenario. Scenario RA 2 with additional consideration of set-up times in the normal mode outperforms scenario RA 1 in respect of delivery reliability. However, it results in higher lead times. This is due to the fact that an unlikely set-up constellation is an additional reason for retaining orders.

6. Conclusion

This paper presents a WIP regulating method for production control which has been designed specifically for the requirements of typical job-shop productions in order to reduce the impacts of control activities on other orders by combining central and local elements of production control. The use of so called resource accounts enables to balance current and future workload in such a way, that bottlenecks can be identified before they arise on the shop floor. Additional measures for order sequencing and capacity extensions enable an adaptive activation of alternative material flows to bypass the bottleneck processes. The simulation of the resource account method based on a real use case demonstrates, that the resource account method outperforms the manual production control process based on worker experience and intuition. Our results led us to the conclusion that the developed method provides a high potential to improve the PPC of job shop production systems. Compared to control systems acting on the basis of a complete schedule, the resource account method can also handle with short delays of data acquisition. As our method is sensitive to highly diverse material flows, its application achieves best results if differences of material flows remain moderate. Since WIP-based methods cannot perform load balancing across a large number of production systems, such cases require a central production
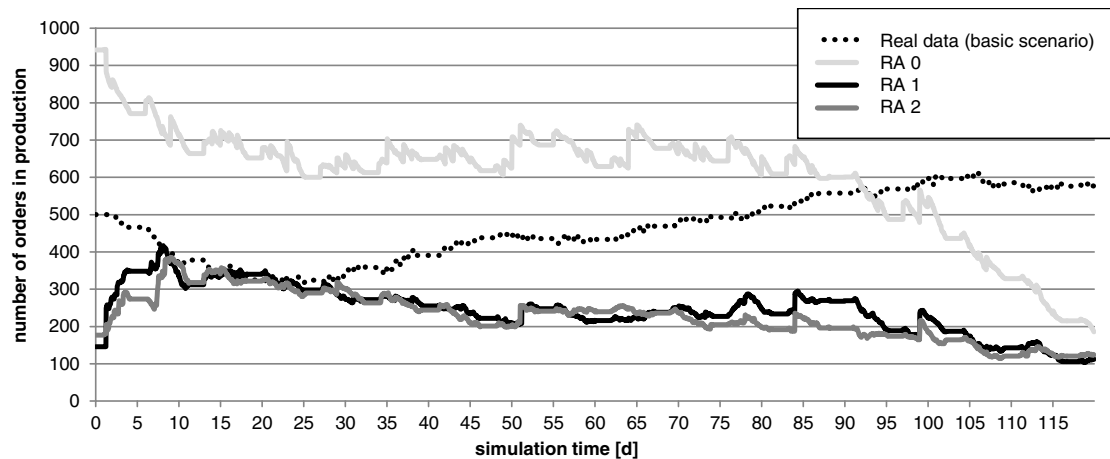
Fig. 4. Development of the WIP level during the simulation experiments

control system based on the production schedule.

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