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Coping with the uncertainties of make-to-order production: a new approach for determining reliable delivery times with the throughput diagram

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ABSTRACT

Make-to-order companies have to deal with particular uncertainties in their offer processing. At the early stage of planning offers, it is particularly uncertain 1) which open offers will be accepted by customers and 2) what capacity these will require. Therefore, it is particularly challenging for make-to-order companies to determine and keep to binding delivery times, so that many companies have problems achieving a high delivery reliability. In this paper, we show a simple model-based procedure to determine delivery times using the throughput diagram with early available information such as the offer requests in the planning process. Simulation studies show that the procedure, especially in combination with a CONWIP order release and an EODD sequencing rule, achieves a high delivery reliability without sacrificing other logistic objectives such as utilisation. Furthermore, the procedure proves to be very robust against random deviations of the planning parameters.

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Order acceptance and planning; production planning; modelling

1. Introduction

Delivery time and delivery reliability are key evaluation criteria for customers of make-to-order companies. Consequently, from an internal perspective, schedule reliability is regarded as the top logistical goal, according to surveys among German manufacturing firms (Nyhuis 2016; Schilp 2021). However, many make-to-order companies have problems determining reliable delivery times (Schilp 2021). As a consequence, a poor on-time delivery performance occurs (Schuh 2006).

Companies have the task to determine realistic delivery dates that correspond as closely as possible to the customer's wishes when the customer requests an offer. It thus has a particularly direct influence on schedule reliability. In companies, order planning forms the link between sales and production. It also has a significant influence on other logistic objectives, such as the utilisation of production.

The challenge is to confirm a binding delivery time to the customer at a very early stage in the order process. At this stage, there are several uncertainties which complicate planning: For one thing, the future load is uncertain, because it is unclear how many and which offers will be successful. For another, work plans with detailed standard times are usually not yet available.

Inappropriate load forecasts cause serious problems. If the forecasts underestimate the load, an overload of production, the build-up of backlogs and thus delayed deliveries will be the consequence. Conversely, if forecasts overestimate the load, there is a risk of capacity utilisation losses. Improved forecasts can therefore help protect production from overload by helping to shift the load in planning or rejecting orders if necessary. In addition, the forecast can be used early in capacity planning to keep sufficient capacity available.

Measured by the importance of the task, the implementation of order acceptance and planning is inadequate in many companies: it is common for companies to work with standard delivery times (Schilp 2021) or to systematically accept more orders than production can handle when the economy is strong.

According to a survey, the majority of companies are not able to communicate reliable delivery times when offers are accepted by the customers (Schilp 2021). In addition, companies usually do not take open offers sufficiently into account when determining due dates for orders. Moreover, different delivery time requirements of customers complicate production planning (Schilp 2021). It is therefore hardly surprising that customers of make-to-order companies complain about low delivery reliability (Schuh 2006).

This paper presents a simple procedure for determining delivery times with the help of throughput diagrams, the so-called Planned Output Control (POC). In this case, the term planned output control refers to the procedure of determining the individual delivery dates for each order in such a way, that an overload of the production is avoided. The aim of the procedure is to determine reliable delivery dates based on information that is available at an early stage. Section 2 therefor clarifies the basics of delivery time determination and the deficits of existing approaches. Section 3 presents a modelling of the acceptance rate of offers for

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orders. It makes it possible to predict the future load of open offers. Section 4 presents the procedural rules of the Planned Output Control. Section 5 explains the evaluation concept and presents the evaluation results. Section 6 presents a summary and outlook.

2. Fundamentals of delivery time determination for make-to-order companies

The following section describes the basics of determining delivery times for make-to-order companies. Section 2.1 starts with presenting and explaining relationships in production logistics, such as the order throughput of make-to-order companies and the production logistics parameters. Section 2.2 then clarifies the state of research on planning of offers and emphasises the deficits of existing approaches.

2.1. Basics of production logistics

The following section firstly presents the order throughput of make-to-order companies, which is an important basis for the development of the delivery time determination procedure. Subsequently, basic parameters and correlations from production logistics, which are important for the understanding of this article, are presented and explained.

2.1.1. Order throughput from make-to-order companies

The order throughput of make-to-order companies starts with an offer request from the customer and includes all necessary process steps from offer processing to delivery (cf. Figure 1). The process begins as soon as a customer submits a request for an offer to a company. The order acceptance and planning then prepares an offer for the customer in which the price, the quality and also the delivery time are already promised. After the offer has been prepared, it is sent to the customer. The customer response often takes a few days, weeks or months (Schilp 2021). Following the customer response time, the offer is either rejected or accepted. Accepted offers become customer orders for which the company internal process begins. Customer orders usually first pass through the design department in order to prepare them technically if necessary. Also, the work plan is created in the work preparation department and planning and control tasks are performed by the PPC department. This step results in production orders that are waiting to be released for production. Following this order release, the orders are processed in production. Between the completion of the order and the delivery to the customer a delivery time buffer compensates for uncertainties in the process (cf. Park et al. 1999; Schuh 2006).

The order throughput is subject to some uncertainties, which are shown in Table 1 for each process step. At the early stage of the request in the order throughput, there is a very high level of uncertainty about the placing of an order (order risk) and the possible load on the production (order throughput, work content). The order risk is reduced after the offer has been prepared, as the basic technical and economic feasibility has been assessed at this point. However, at this early stage, the load on production can often only be estimated by comparing the order with previous ones. The offer should only be valid for a limited period of time (offer validity). Within this period the customer can accept it at the offered conditions. Otherwise, a late order intake can exceed the capacity and thus jeopardise order planning (Kingsman 2000). During offer processing, there are usually no precise routings or work contents available to calculate the delivery time. Moreover, it is unclear whether the customer will accept the offer or not (cf. Schuh 2006).

Confirmed customer orders then go through design and work preparation, so that a production order can be generated. In this process step, work plans with routings and work contents are created, bringing transparency about the future production load. These production orders can then be

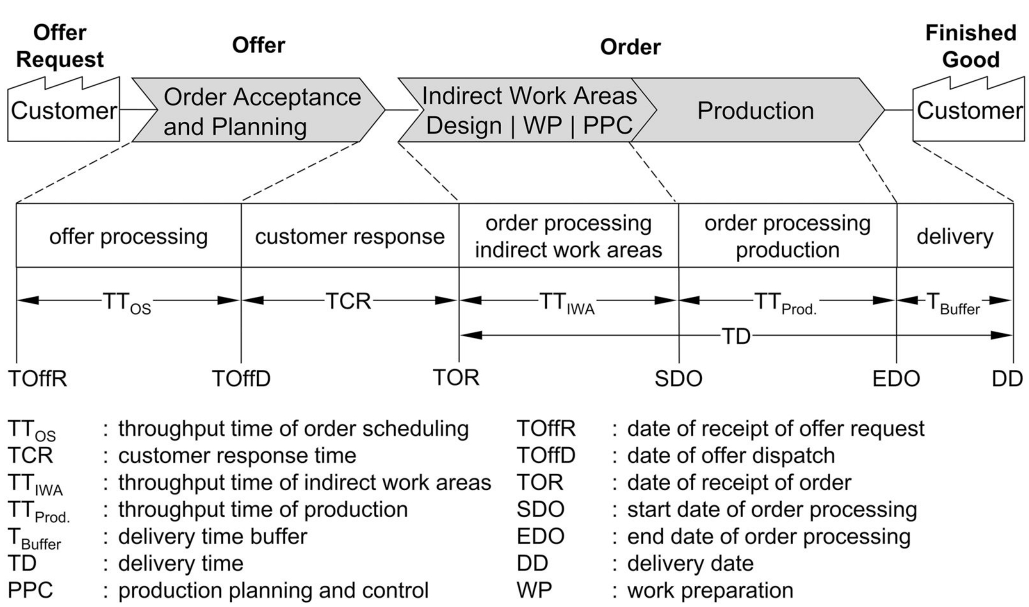

Figure 1. Order process for make-to-order companies (own illustration cf. Park et al. 1999).

Table 1. Process steps from the offer request to the completion of an order.

Order status	Responsibility	Inventory type	Order risk	Transparency about work load	
Offer Request	Customer	Open Offer Requests	Very High	Very Low	Processing Direction ↓
Offer	Sales	Open Offers	High	Estimate	
Customer Order	Customer	Confirmed Customer Orders	Low	Estimate	
Production Order	Engineering	Order Inventory	Low	Planned Values	
Planned/Released Production Order	Production Planning and Control	WIP	Low	Planned Values/Actual Values	
Completed Order	Manufacturing	Finished Goods Inventory	Low	Actual Values	

released to production. After completion, they are delivered to the customer (cf. Schuh 2006).

The uncertainty of the production load decreases during the order throughput of MTO companies. The determination of delivery times therefore faces the challenge of high uncertainty, especially in regard to requests and offers.

2.1.2. Parameters in production logistics

The following paragraphs describe relevant parameters for the planning of make-to-order companies. The majority of the definitions are based on the funnel model and the Hanoverian model of the PPC (cf. Bechte 1984; Nyhuis and Wiendahl 2009).

The ***acceptance rate*** describes the ratio of accepted to submitted offers (1). It is a decisive factor in order to be able to take the future load on production into account at an early stage in planning. The determination of the acceptance rate from historical data has already been examined in detail in the literature (cf. Brankamp 1967; Kingsman, Tatsiopoulos, and Hendry 1989; Wiedemann 2016). This is sometimes done separately for individual customers or product groups. The acceptance rate is used to correct the load of offers in planning, according to the expected order intake.

$$AR_m = \frac{O_{acc.}}{O_{sub.}} \tag{1}$$

where AR_m, mean acceptance rate; $O_{acc.}$, number of accepted offers; $O_{sub.}$, number of submitted offers

The ***customer response time*** describes the time span between the submission of an offer and its acceptance or rejection by the customer. Park et al already described this time span within the order process in 1999, but they conclude that the customer response time is negligible small (Park et al. 1999). According to a survey of German companies, however, this time span can often take days, weeks or even months (Schilp 2021) and therefore can have a significant influence on the planning procedures

The sales department can determine the average customer response time from historical data of previous offers. It may be useful to consider the average response time separately for different products or customers in order to be able to take a more accurate customer response time into account in the planning system. The average customer response time is calculated as the sum of the response times of all offers divided by the number of all offers that have been submitted (2).

$$TCR_m = \frac{\sum(DOrR - DOfP)}{O_{sub.}} \tag{2}$$

where TCR_m, mean customer response time; DOrR, date of order reception; DOfP, date of offer preparation; $O_{sub.}$, number of submitted offers.

The calculated average response time may be distorted by non-responses. One way to avoid such outliers is to set an offer validity as mentioned above.

The ***delivery time*** (3) refers to the entire time from the receipt of an order to the delivery of the product (Schönsleben 2023). It is often measured in shop calendar days, meaning working days (Lödding 2013).

$$TD = DD - DOR \tag{3}$$

where TD, delivery time; DD, delivery date; DOR, date of order receipt.

The delivery time is made up of various time components that define the passage of an order through indirect work areas such as design, production planning and control, work preparation, procurement, a throughput time of unreleased orders and the throughput times of direct working areas of production. The delivery time can also contain a load shift, to postpone orders into the future, due to a lack of capacity. Additionally, the delivery time often contains a delivery time buffer to protect the order from being delayed due to production uncertainties such as machine breakdowns (Lödding 2013).

The ***throughput diagram*** (see Figure 2a) is derived from the funnel model (Bechte 1984) which models the workstations of a production as funnels. The throughput diagram represents the cumulative input and output of either a workstation or the entire production over time (Bechte 1984; Nyhuis and Wiendahl 2009; Lödding 2013). It can also represent the cumulative planned and actual outputs (see Figure 2b) (Wiendahl 1997). The input and the output are measured in number of orders or planned hours.

If there are already orders in the WIP at the beginning of the investigation period, the input curve starts vertically offset by the work content of the so-called initial WIP (cf. Figure 2a). This means that the vertical distance between the actual input and the actual output always corresponds to the current WIP at the workstation or in the production.

The slope of the output curve corresponds to the output rate of a workstation or of the production. This parameter indicates the amount of work that has been performed per time unit. It is measured in number of orders per shop calendar day or planned hours per shop calendar day (Nyhuis and Wiendahl 2009; Lödding 2013).

The horizontal difference between input and output describes the range of a workstation or the entire

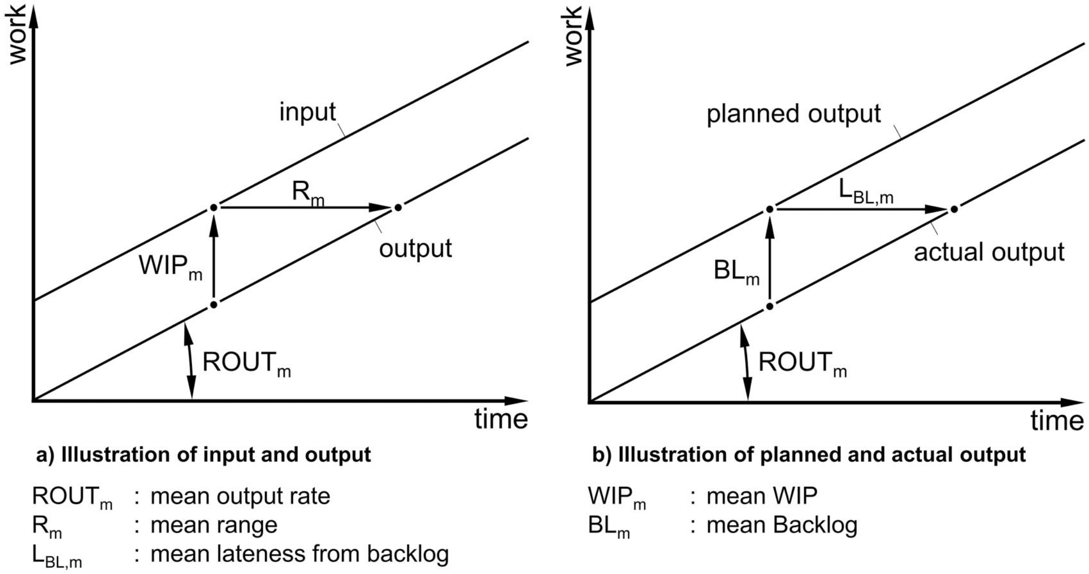

Figure 2. Throughput diagram (a) cf. Nyhuis and Wiendahl 2009; (b) cf. Lödding et al. 2014.

production. The term 'range' is not a statistical parameter in this context, but indicates how long the WIP is sufficient to supply the work station with work and is thus closely linked to the throughput time.

The ***backlog*** (6) of a workstation or of the production (see Figure 2b) is the difference between the actual output and the planned output. It is measured in number of orders or working hours (Schmitz 1961).

$$BL\ (t) = \sum OUT_{plan}(t) - \sum OUT_{act}(t) \quad (4)$$

where BL, backlog; OUT_{plan}, planned output; OUT_{act}, actual output; t, time.

A positive backlog means, that the workstation or production is behind schedule with the completion of orders. A negative backlog means, that the workstation or the production has completed orders early (Lödding 2013).

The ***lateness*** describes the difference between the actual and the planned dates in the order throughput. In particular, the output lateness (see Figure 2b) is a relevant parameter for make-to-order companies and is calculated (5) as the difference between the actual and the planned completion date of an order (Nyhuis and Wiendahl 2009; Lödding 2013).

$$L_{Out,i} = EDO_{act,i} - EDO_{plan,i} \quad (5)$$

where $L_{Out,i}$, output lateness of order i; $EDO_{act,i}$, actual end of order processing of order i; $EDO_{plan,i}$, planned end of order processing of order i.

The aim is to achieve a mean output lateness of zero and a low variation of the output lateness, so that orders are not delivered too early or too late. In addition, the maximum output lateness should not exceed the delivery time buffer, otherwise the customer will be directly affected by a late delivery. The main factors affecting the lateness are the order sequence deviations and the backlog (Nyhuis and Wiendahl 2009; Lödding 2013).

For the customers, the ***delivery compliance*** is an important objective, along with the delivery time. The delivery compliance is the percentage of orders that have been delivered on time. For many companies, delivery reliability is an important logistic objective, as delivery lateness can lead to high costs and a loss of customer confidence (Lödding 2013).

2.2. State of research on delivery time determination for offers

As a link between a company and its customers, the determination of delivery times plays an important role in the design of PPC systems. In research, various approaches exist to determine planned end dates.

One way to design planning is to develop procedures based on engineering modelling of the relationships in production, such as the funnel model (Bechte 1984; Nyhuis and Wiendahl 2009). These methods have in common that they try to carry out planning using general cause-effect relationships and easily determinable process parameters. The aim is to be able to carry out planning and to give a realistic delivery date, even in an early offer phase in which often no precise order information, such as work plans, is available. For this purpose, Brankamp already suggested in the 1960s, that offers should also be taken into account in capacity planning at an early stage of the order throughput. To consider the possible rejection of orders, he multiplies the unplanned capacities with a factor that is higher, the lower the probability is, that customers accept an offer and place an order. The resulting capacity requirements should be sufficient to meet the promised delivery date (Brankamp 1967). Various authors show further ways to determine the acceptance probability of offers (cf. Brankamp 1967; Wiedemann 2016).

The application of the throughput diagram used in this work in the context of production planning is also already established. In their Statistical Throughput Control (STC), Hopp and Spearman use a throughput diagram to monitor production throughput. For this purpose, they compare the planned, the actual and the probable future production output with each other. Differences between these values are then used to derive control decisions (Hopp and Spearman 2008). In a similar way Bakke and Nyhuis are using throughput diagrams in their operation-oriented controlling system. They notice that not only the view into the past data, but also controlling the future development is relevant. For this reason, they expand the throughput diagram by a future prognosis of the capacity and the planned output (Bakke and Nyhuis 1992), but without considering offers.

Kingsman, Tatsiopoulos and Hendry have pioneered the planning of offers (Kingsman, Tatsiopoulos, and Hendry 1989; Hendry and Kingsman 1993; Kingsman 2000). They use the acceptance probability to consider offers in their workload control. They realised early, that order acceptance is the key lever to protect the production from overload.

Kingsman, Tatsiopolous and Hendry have created an effective model-based order acceptance and planning procedure that focuses on the work in process and the projected throughput time. Moreover, they use an order release logic and specify capacity control, thus taking an important production control task into account. Their logic of order acceptance and planning is based on viewing the order throughput as a hierarchical chain of WIPs (cf. Figure 3). In addition to the orders in production, the total WIP also includes orders waiting for release and the WIP of open offers. These WIPs are linked to each other by input and output relationships (Kingsman, Tatsiopoulos, and Hendry 1989).

Based on the WIP and the planned output rate of production, the authors calculate different WIP ranges. They take offers into account with their probability of acceptance. The aim is to keep the WIP ranges and thus also implicitly the throughput times within predefined limits. For this purpose, delivery dates are postponed, capacities are adjusted and orders are rejected (Kingsman, Tatsiopoulos, and Hendry 1989; Hendry and Kingsman 1989, 1991, 1993; Kingsman 2000).

The procedure of Kingsman, Tatsiopoulos and Hendry represents one of the most comprehensive works for the fundamentals of engineering-based order acceptance and planning.

Nevertheless, the procedure is not easy to implement in practice, because 1) it requires a comparatively high amount of data, 2) it requires complex decisions or actions from the companies and 3) it does not easily allow the assessment of schedule reliability as the most important logistic objective.

Firstly, planning takes place at the level of the workstations. However, the necessary routings and standard hours of the operations are not always available at the early stage of order acceptance, as Hendry et al. themselves point out (Hendry et al. 2008). This complicates the implementation of the procedure and reduces the intended accuracy if only estimated values are used for planning.

Secondly, complex rules and decision problems complicate the implementation of the method. This begins with the parameterisation, which requires simulations (Kingsman and Hendry 2002) and is therefore relatively complex. Furthermore, as Kingsman himself states (Kingsman 2000), input control by rejecting orders is in practice a complex decision-making problem, as various other business objectives can have an impact as well. Rejecting orders is therefore not always feasible. If, at the same time, capacities cannot be increased, production overload is inevitable. Output control via capacity adjustments cannot be implemented automatically either, since employees often have a right of involvement and different departments also need to be included. It is also questionable whether a capacity adjustment is always necessary if, for example, the resulting lateness is particularly small and lies within the planned delivery time buffer. Together with other management decisions (cf. Kingsman 2000), such as the prioritisation of individual orders, a multitude of possible solutions arises, which have to be weighed against each other. On the one hand, this complexity opens up a large margin of flexibility, but on the other hand it makes clear application more difficult.

Thirdly, the procedure does not allow a simple assessment of the achievement of the logistic objectives. In particular, the procedure does not consider the logistical laws on schedule reliability that have since been developed. Therefore, even by using the WIP ranges as a process parameter, a user cannot draw a simple conclusion about the schedule reliability in practice. Finally, it can also be stated that the procedure has not been able to establish itself in business practice.

With Cobacabana, Land takes the basic logic of workload control and simplifies it in a card-based system for the PPC (Land 2009). This method was later improved and extended (Thürer, Land, and Stevenson 2014; Thürer et al. 2016).

In the procedure, cards are assigned to the orders that correspond to the capacity requirements of the order at the

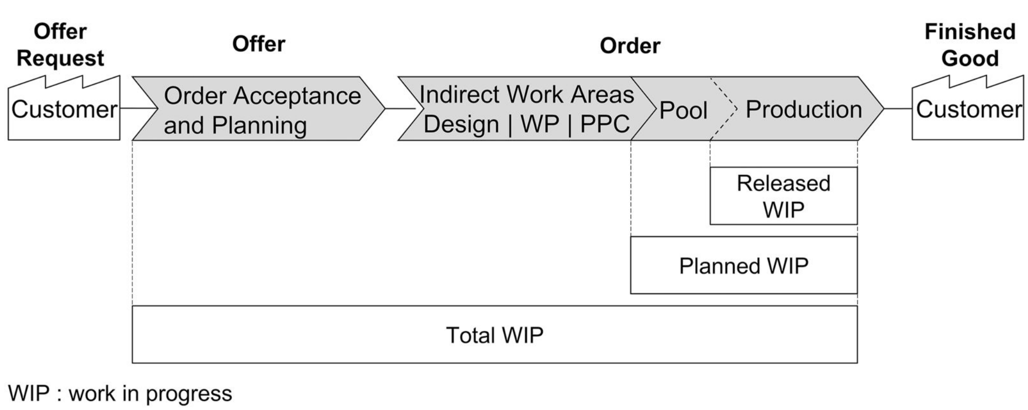

Figure 3. Hierarchy of WIPs in the procedure of Kingsman, Tatsiopoulos, and Hendry (1989).

individual workstations. The procedure is composed of two card loops for order release and order acceptance.

The card loop in the production regulates the release of orders. The release of a new order requires a sufficient number of cards of the respective workstations.

The separate card loop for order acceptance regulates the inflow to the order pool and is particularly necessary to plan the orders.

The Cobacabana has comparatively simple rules. It Similar to the method of Kingsman et al, the planning of the Cobacabana method takes place at the workstation level, which makes it difficult to use. In addition, Cobacabana does not comprise the process of order acceptance.

In addition to planning procedures on the basis of engineering-based modelling of cause-effect relationships, many authors conduct research in order acceptance and planning on the basis of mathematical optimisations and simulations.

The mathematical optimisation of make-to-order production is part of the revenue management. The aim is to minimise the utilisation losses of the used capacities and to maximise the contribution margins of the accepted orders with the help of profit-maximising optimisation (Klein 2001). Some authors take other decision criteria into account in order to make an acceptance decision, such as different customer values in the monetisation of orders (Mohaupt and Hilbert 2013, Mohaupt and Hilbert 2014, Lohnert and Fischer 2019).

These models often neglect or greatly simplify the order throughput. Therefore, these methods are particularly unable to assess the influences of more complex production systems. In addition, securing schedule reliability is not taken into account, as the methods takes it for granted, that the logistic objectives of the production are being achieved.

Designing a simulative determination of delivery dates is an approach that has emerged, as the simulation capabilities have grown. For example, Taal and Wortmann determine delivery dates using an iterative forward simulation that is integrated into an MRP logic. They simulate delivery times for new orders based on an initial estimate. Taal and Wortmann vary the routeing and the lot size, whereas the delivery dates of existing orders are fixed (Taal and Wortmann 1997). Another approach simulates the future capacity requirements in order to derive the delivery date on this basis (Wiedemann 2016). Methods related to machine learning are also finding their way into order acceptance and planning. One approach to determine delivery times via a similarity analysis with orders that have already been completed (Mourtzis et al. 2014). Another approach does not only take past data into account, but also the current situation in production in order to determine delivery times (Alenezi, Moses, and Trafalis 2008).

The planning approaches based on mathematical optimisations and simulations rely on accurate input data of the orders that shall be planned. However, at the early point in the order throughput, when a company has to give its customers delivery dates, in many cases neither routings nor precise capacity requirements are available. In make-to-order productions, due to the large number of variants, it is often not worth the effort to determine capacity requirements very precisely, even in the later stages of the order throughput. Further, the implementation of simulation-based methods requires advanced knowledge and skills in IT, which makes an independent introduction and a simple application difficult.

Overall, despite a large number of approaches for order planning by make-to-order companies, poor implementation can be observed in practice. This may also be due to the fact that many of the existing procedures have a high data requirement for early planning and have comparatively complex rules. For the user, it is often difficult to understand the decisions made by the planning procedures due to either a missing or an incomprehensive visualisation. In particular, the effects of a conscious or unconscious overregulation of the methods are not considered in the literature. As a result, the user cannot assess the consequences for the achievement of the logistic objectives.

3. Acceptance rate of open offers

The acceptance rate is a crucial parameter in order to be able to consider the future load on production at an early stage in planning. As already explained in Section 2, the determination of the long-term acceptance rate for offers measured from feedback data has already been examined in detail in the literature (cf. Brankamp 1967; Kingsman, Tatsiopoulos, and Hendry 1989; Wiedemann 2016).

The acceptance rate of offers in WIP can greatly and systematically deviate from the long-term acceptance rate measured from feedback data, if the customer response times differ. For example, if the response time for rejected offers is higher than for accepted offers, the offers to be rejected remain longer in the WIP and therefore have a larger WIP share. If the response time for rejected offers is shorter than for accepted offers, their inventory share is correspondingly smaller. Equations (6) and (7) show the work in process for accepted and rejected offers.

$$WIP_{offer,acc.} = AR_m \cdot R_{offer} \cdot TCR_{acc,m} \quad (6)$$

$$WIP_{offer,rej.} = (1 - AR_m) \cdot R_{offer} \cdot TCR_{rej,m} \quad (7)$$

where $WIP_{offer,acc.}$, mean WIP of offers to be accepted; $WIP_{offer,rej.}$, mean WIP of offers to be rejected; AR_m, mean long-term acceptance rate; R_{offer}, offer rate; $TCR_{acc.,m}$, mean customer acceptance time; $TCR_{rej.,m}$, mean customer rejection time.

The following numerical example, with a rate of requested offers of two requests per day and an acceptance rate of 50%, illustrates the effect. An average acceptance time of one day and an average rejection time of four days are assumed. In this case, there are on average four times as many orders to be rejected (4 orders) in the WIP as there are orders to be accepted (1 order). The acceptance rate of the WIP of open offers is therefore only 20%.

If the rejection of offers by customers systematically takes longer than the acceptance, there are more offers to be rejected by customers in the WIP of open offers than the long-term acceptance rate suggests. In this case, planning with the mean long-term acceptance rate from feedback data would reserve more capacities for offers than needed. If, on the other hand, customers systematically take longer to accept offers than to reject them, there are on average more offers to be accepted in the future. The result would be an underestimation of future capacity needs, which would lead to backlogs and lateness.

To the best of our knowledge, this effect has not been considered in the literature so far. This effect can be taken into account by an acceptance rate of open offers, which relates the long-term acceptance rate to the average acceptance and rejection time and thereby compensates for this effect (8).

$$AR_{OO,m} = \frac{TCR_{acc,m} \cdot AR_m}{TCR_{acc,m} \cdot AR_m + TCR_{rej,m} \cdot (1 - AR_m)} \quad (8)$$

where $AR_{OO,m}$, mean acceptance rate from open offers; AR_m, mean long-term acceptance rate; $TCR_{acc.,m}$, mean customer acceptance time; $TCR_{rej.,m}$, mean customer rejection time.

The differences between the long-term acceptance rate and the acceptance rate of the open offers are mainly dependent on the response time ratio of the mean acceptance time to the mean rejection time. Figure 4 shows the model of the mean acceptance rate of the open offers, as a function of the acceptance rate for different ratios of the two variables.

The acceptance rate of the open offers is equal to the acceptance rate from feedback data, if the mean acceptance time is equal to the mean rejection time. If customers need more time on average to accept offers than to reject them, the acceptance rate of the open offers is greater than the mean long-term acceptance rate from feedback data. Customers therefore systematically accept more planned offers than the acceptance rate from feedback data suggests. The opposite is true, if customers take longer on average to reject orders. In this case, fewer offers are converted into orders than the acceptance rate from feedback data would suggest.

The presented modelling of the acceptance rate was evaluated with the help of Monte Carlo simulations. All in all, the respective acceptance rates of the open offers were determined in various test series for different acceptance or rejection times and different mean acceptance rates. The evaluation of the modelling can be found in Figure A1 in Appendix A.

The acceptance rate of the open offers modelled in this way is used by the Planned Output Control presented below to predict the load resulting from open offers.

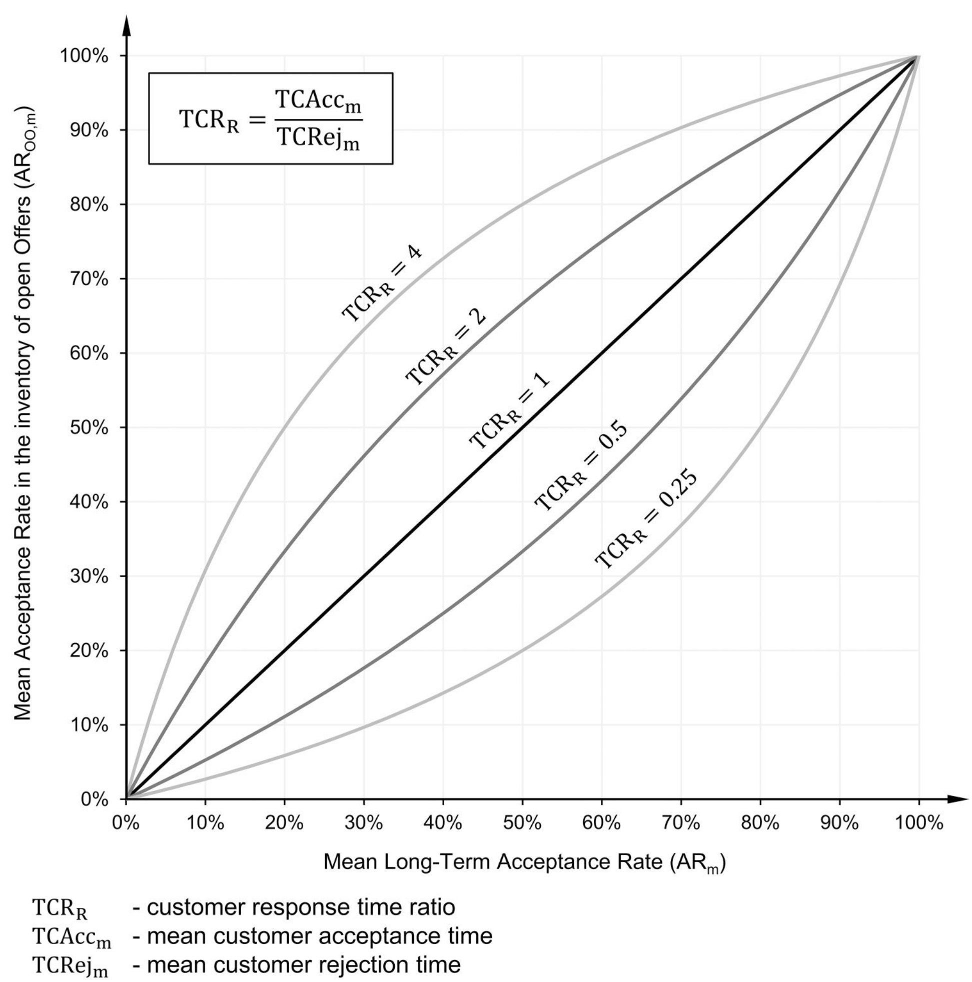

Figure 4. Dependency of the mean acceptance rate of the open offers on the mean acceptance rate from feedback data for different response time ratios.

4. Planned Output Control (POC)

The following section describes the objectives and procedural rules of the Planned Output Control. An early version of this method has already been published in a conference paper (Mundt and Lödding 2020). This publication represents the final and comprehensive status of the procedure.

Section 4.1 first formulates and explains four main goals of the method, which were decisive in the development of the method and against which the method will be measured in the evaluation. The method is based on the representation of the planned outputs in a throughput diagram. Section 4.2 explains the construction of such a throughput diagram. A procedure description (4.3) explains the various stages of planning from the preparation of the offer to the due date determination of the offer to the receipt of the order.

4.1. Objectives

The proposed method focuses on the needs of MTO companies. Make-to-order production is characterised by high uncertainties in order throughput, as incoming orders and the work content of orders may fluctuate very strongly. This particularly complicates order acceptance and planning, which must provide customers with reliable delivery dates at an early stage. Companies need robust procedures to protect production from overload in this challenging environment and to be able to keep their promises towards the customers. Many companies still use standard delivery times, even though a variety of procedures are available in research. One reason for the lack of application of methods could be the lack of clarity of the often complex methods. The presented method has to meet these constraints and intends to promote the practical use. To achieve this, it pursues four main goals: reliability, robustness, simplicity and clarity.

- *Reliability:* The procedure should reliably support the achievement of the logistic objectives. By determining the planned output, it must be able to be evaluated in particular by the assurance of the delivery compliance and the utilisation.
- *Robustness:* The robustness of the method indicates how stable the procedure reacts to uncertainties. The procedure should correct the consequences of the introduced uncertainties.
- *Simplicity:* The simpler a method is, the easier it is for companies to implement it. Therefore, the data requirements of the procedure should be as low as possible. Furthermore, the application of the method should be easy to understand, as the procedure logic makes simple and comprehensible decisions.
- *Clarity*: A descriptive method enables the user to understand decisions. In order to achieve this, the method should contain a clear representation of all relevant procedural variables, to enable a quick and simple assessment of the situation.

4.2. Planned outputs in the throughput diagram

The Planned Output Control, developed with these fundamental requirements, is based on the comparison of the planned output with the capacity in a throughput diagram. The object of consideration is the entire production as well as the complete offer and order throughput

The parts of the offer and order throughput are included in the procedure as overall systems and are not further subdivided. For production, this means, for example, that work contents are not considered at the workstation level, but for the entire production orders. This also makes it possible to include offers or orders at an early point in the order throughput in planning where no work plans are yet available. Work contents and planned outputs are either measured in planned hours (total work content) or in the unit number of orders. A detailed view on units follows at the end of this section. Figure 5 shows the throughput diagram used for planning. The throughput diagram contains three

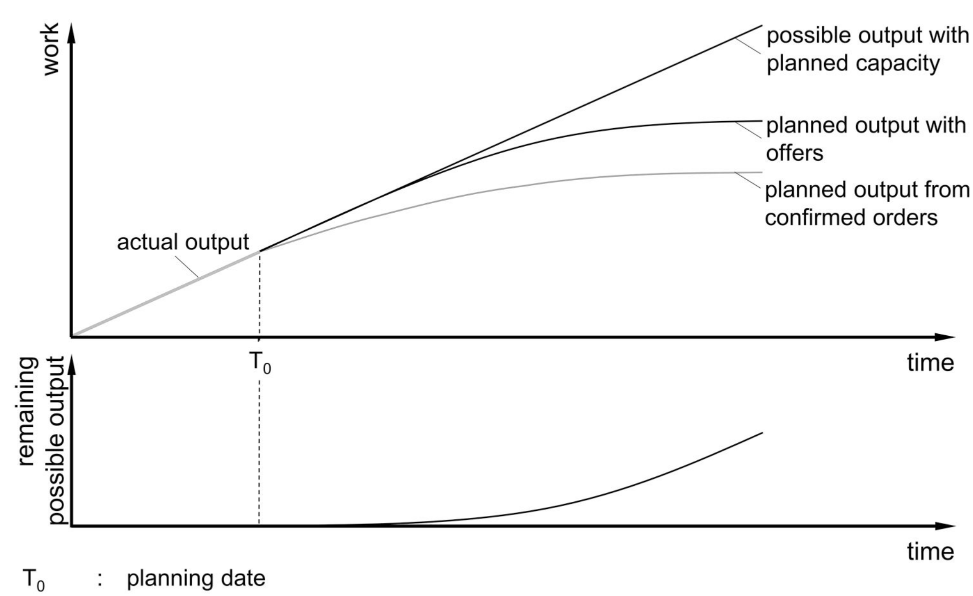

Figure 5. Representation of planned outputs in the throughput diagram (cf. Mundt and Lödding 2020).

curves illustrating 1) the possible output with planned capacity, 2) the planned output from confirmed orders and 3) the planned output including open offers.

The possible output with planned capacity is used to align capacities and the planned output. It is calculated from the planned productivity and the provided capacity according to the following Equation (9).

$$OUT_{poss}(t) = \int_{0}^{t} CAP_{plan}(t) \cdot PRO_{plan}(t)dt \quad (9)$$

where OUT_{pos}, possible output with planned capacity; CAP_{plan}, planned capacity; PRO_{plan}, planned productivity; t, time.

The second curve describes the planned output from confirmed orders. This planned output thus contains 1) the released orders in production, 2) orders that have not yet been released and are waiting to be released and 3) orders that have not yet been released in design, work preparation or PPC. It is calculated in number of orders or in planned hours by cumulating the work contents at their planned end dates over time (10).

$$OUT_{plan,or}(t) = \sum_{i=1}^{NO} WC_{order,i} \ \forall \ i \text{ with } EDO_{plan,or.} \leq t \quad (10)$$

where $OUT_{plan,or}$, planned output from confirmed orders; $WC_{order.i}$, total work content of order i; NO, number of orders; $EDO_{plan,or.}$, planned end date of orders; t, time.

The third curve shows the total planned output and contains, in addition to the planned output from orders, also the expected planned output from open offers. Offers are discounted with the acceptance rate from open offers to account for the uncertainty caused by the acceptance decision. The procedure for applying the acceptance rate is explained in Section 4.3. It is calculated according to the following Equation (11).

$$OUT_{plan,tot.}(t) = \sum_{i=1}^{NO} WC_{order,i} + \sum_{j=1}^{NOf} WC_{offer,j} \cdot AR_{OO,m} \ \forall \ i, \ j \text{ with } EDO_{plan,tot.} \leq t \quad (11)$$

where $OUT_{plan.tot.}$, total planned output including offers and orders; $WC_{order.i}$, total work content of order i; $WC_{offer.j}$, total work content of offer j; NO, number of orders; NOf, number of offers; $AR_{OO,m}$, mean acceptance rate of open offers; $EDO_{plan,tot.}$, planned end date of orders and offers; t, time.

The method plans all offers and orders in the throughput diagram on a fixed or provisional planned end date. For this purpose, provisional planned throughput times and work contents must be estimated for the offers and for some of the orders. They will later be replaced with fixed planned values by the work preparation or PPC. The resulting planned output makes it possible to estimate the capacity requirements. This in itself is a considerable gain for business practice, since the more accurate prediction of capacity requirements increases the lead time for capacity planning and its accuracy.

The lower part of Figure 5 shows the remaining (cumulative) possible output. This is the difference between the possible output with planned capacity and the planned output including open offers (12).

$$OUT_{Rem.}(t) = OUT_{poss}(t) - OUT_{plan,tot.}(t) \quad (12)$$

where $OUT_{Rem.}$, remaining possible output; OUT_{poss}, possible output with planned capacity; $OUT_{plan,tot.}$, total planned output including offers and orders; t, time.

This describes the remaining capacity at any time and is a measure for the possible acceptance and planning of further orders.

The Planned Output Control considers the output as a planning parameter. It distinguishes the future load in terms of time and thus allows the planning to be differentiated over time. If customers request an order far in advance, for example because they already know their future demand, the Planned Output Control can plan this order without delaying delivery times of following offer requests. Methods, such as Cobacabana, have a problem with such early orders, as they increase the orders on hand and thus directly affect the delivery time of orders with an earlier delivery date.

Despite our focus on planning due dates, we also consider capacity planning and control to be indispensable in a comprehensive planning system, as also proclaimed by Kingsman (cf. Kingsman 2000). Though the adjustment of capacities is sometimes complex to implement, as it has to be coordinated with the social partners, it is particularly necessary if the planned capacity deviates greatly from the load. Conversely, adjusting the load by setting due dates is very easy to implement. While it is often sufficient for smaller deviations of the load and the capacity it is clearly not sufficient for bigger deviations. It is important to note that the illustration of the planned output including open offers in the throughput diagram also supports capacity planning and control, as it shows the capacity requirements at an early stage.

4.2.1. Unit for the planned output

A company should choose the unit of the output in a way that it reflects the capacity requirements of the orders as closely as possible. Planned hours can often reflect the capacity requirements of an order well. However, it usually takes some effort to estimate the work content at the time of offer preparation. If accurate work contents are available directly or after work preparation has been completed, the total work content of an order is calculated as follows (13).

$$WC_{order,i} = \sum_{k=1}^{NOP} WC_k \quad (13)$$

where $WC_{order,i}$, remaining possible output; WC_k, work content at operation k; NOP, number of operations.

If a company produces a lot of orders, large and small work contents balance each other out. In this case, it is often sufficient to measure the output in number of orders. This simplifies the calculation of the planned output, especially for open offers, if a company cannot yet estimate the work content in planned hours. Alternatively, mean work contents can be used. After work preparation, orders can then be incorporated into planning with their calculated work content.

In the following, we will present the planned output in planned hours and will use the mean work content for open offers.

4.3. Planning procedure

In the following, the logic for determining delivery times is described in detail (cf. Mundt and Lödding 2020). In three steps, the order acceptance and planning procedure first determines the possible delivery time for the offer (step 1), then plans the offer with a preliminary planned end date in the throughput diagram (step 2) and finally determines the final delivery date or planned end date of the order after the customer response (step 3).

1) Determination of the possible Delivery Time

In the first step, the procedure determines a possible delivery time for the customer offer. This delivery time is bindingly promised to the customer and thus forms the basis for the subsequent logistic objective achievement.

The procedure determines the possible delivery time of an offer as the sum of the possible throughput time and a delivery time buffer. The latter serves as a reserve against disruptions or other uncertainties in production (cf. Section 2). Figure 6 shows, how the procedure determines the delivery time based on three conditions in the throughput diagram.

Condition 1: Every production requires a throughput time set by the company to complete orders, regardless of the delivery date. This throughput time results from a logistical positioning and reflects the conflict of objectives between the goal of high utilisation and the goals of low throughput times or low WIP levels. The following therefore applies to the possible throughput time of an offer (14).

$$TT_{1,j} \geq TT_{m,plan} \tag{14}$$

where $TT_{1,j}$, throughput time of offer j under condition 1; $TT_{m,plan}$, mean planned throughput time.

Condition 2: In order to avoid increased finished goods inventories, companies should not plan offers earlier than necessary to meet the delivery time requested by the customer. The delivery time buffer is deducted from the requested delivery time of the customer to secure the internal planned end date ($T_{2,j}$) against uncertainties in production (cf. Figure 6). The following therefore also applies to the possible throughput time of the offer (15).

$$TT_{2,j} = TD_{req.} - T_{Buffer} \tag{15}$$

where $TT_{2,j}$, throughput time of offer j under condition 2; $TD_{req.}$, requested delivery time; T_{Buffer}, delivery time buffer.

Condition 3: The procedure checks at which point in time ($T_{3,j}$) there is enough spare capacity in production for the offer. At this point in time, the remaining possible output with planned capacity should at least correspond to the expected work content of the offer (cf. Figure 6).

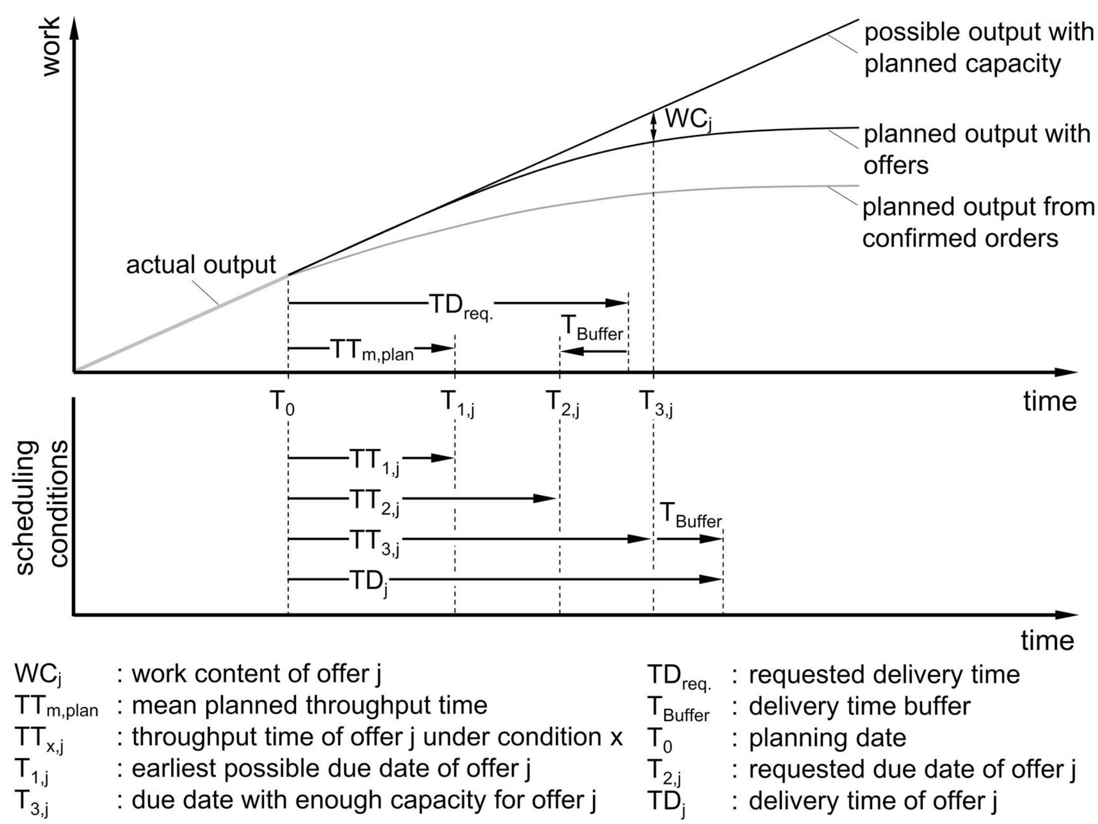

Figure 6. Delivery time determination with the throughput diagram.

The following equation shows the order throughput time from a capacity point of view (16).

$$OUT_{Rem.}(T_0 + TT_{3,j}) \geq WC_j \quad (16)$$

where $OUT_{Rem.}$, remaining possible output; T_0, planning date; $TT_{3,j}$, throughput time of offer j under condition 3; WC_j, work content of offer j.

The user should not plan the offer on an earlier date, as otherwise there would not be sufficient capacity for processing. This would result in backlogs or lateness.

The time for the offer quoted delivery is determined as the maximum of these three throughput times and a delivery time buffer (17).

$$TD_j = \max\{TT_{1,j}; TT_{2,j}; TT_{3,j}\} + T_{Buffer} \quad (17)$$

where TD_j, delivery time of offer j; T_{Buffer}, delivery time buffer; $TT_{x,j}$, throughput time of offer j under condition x.

This delivery time takes both, the capacity restrictions and the realistic throughput times determined from the logistical positioning, into account. However, it may contradict the customer's wish, because it prioritises the feasibility. Kingsman explains different ways to deal with this conflict of objectives (cf. Kingsman 2000). Depending on whether a lack of capacity or insufficient standard throughput times are responsible, different options for action should be considered. If a lack of capacity is the reason for not meeting the requested delivery time, an increase in capacity is necessary. If the desired delivery time cannot be achieved due to a high standard throughput time, it is possible to consider the strategic use of rush orders. How rush orders can be implemented in the presented planning procedure is shown in a separate publication (Mundt, Beck, and Lödding 2022).

As explained earlier, the customer feedback time can have a significant impact on the acceptance rate and thus also on the planning uncertainty (cf. Section 3). In order to avoid great uncertainty due to a very late customer response, the offer should contain, in addition to the delivery time, a validity after which the promised conditions expire.

2) Planning an Offer

In the second step of the procedure, directly after the determination of the delivery time, the planning of the offer takes place. This step updates the throughput diagram. In addition to the delivery time, the planning of offers also considers 1) the response behaviour of the customers and 2) the work content of the offers adjusted by the acceptance rate.

Surveys of companies show that it can take several days, weeks or even months before the customer responds to an offer (cf. Schilp 2021). The presented procedure takes the mean customer response time for accepted orders (see Section 2) into account in order to avoid systematic planning errors.

The work content of an offer can often only be estimated e.g. by comparing it with other orders. However, the entire work content of an offer is not equivalent to its capacity requirements, as there is a probability of rejection by the customer. Planning the entire work content would therefore lead to a systematic overestimation of the future capacity requirements of offers. For this reason, the work content of offers is corrected by the acceptance rate of open offers.

The procedure for planning offers is illustrated in Figure 7. It first determines the planned end date of the offer and afterwards plans it with the adjusted work content.

The procedure determines the provisional planned end date ($T_{4,j}$) of the offer by adding the mean customer response time and delivery time minus the delivery time buffer to the planning date (18).

$$T_{4,j} = T_0 + TCR_{acc.,m} + (TD_j - T_{Buffer}) \quad (18)$$

where $T_{4,j}$, expected due date of offer j; T_0, planning date; $TCR_{acc.,m}$, mean customer acceptance time; TD_j, delivery time of offer j; T_{Buffer}, delivery time buffer.

The adjusted work content of the offer is then added to the planned output with offers.

3) Planning an Order

If the customer rejects an offer or the offer validity expires, the offer is removed from the planned output and no further action is required. If the customer accepts the

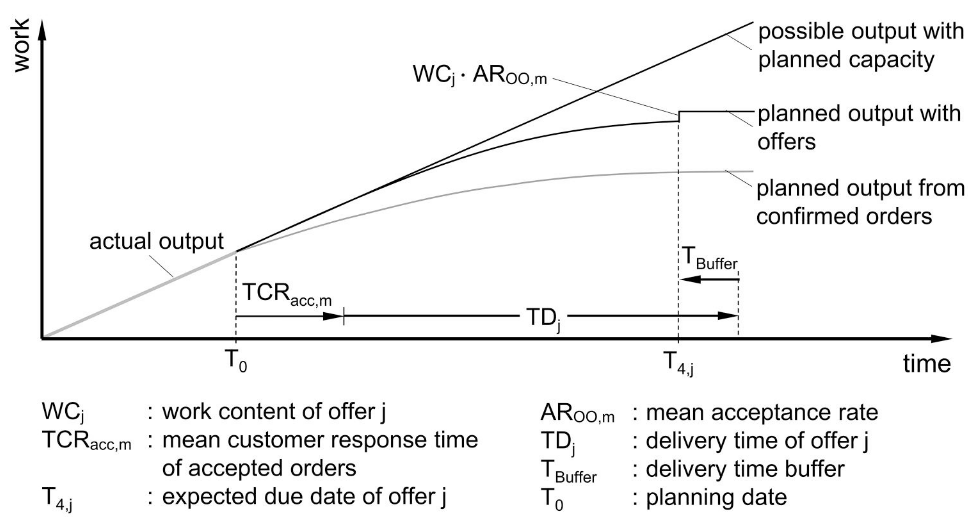

Figure 7. Planning offers with the throughput diagram.

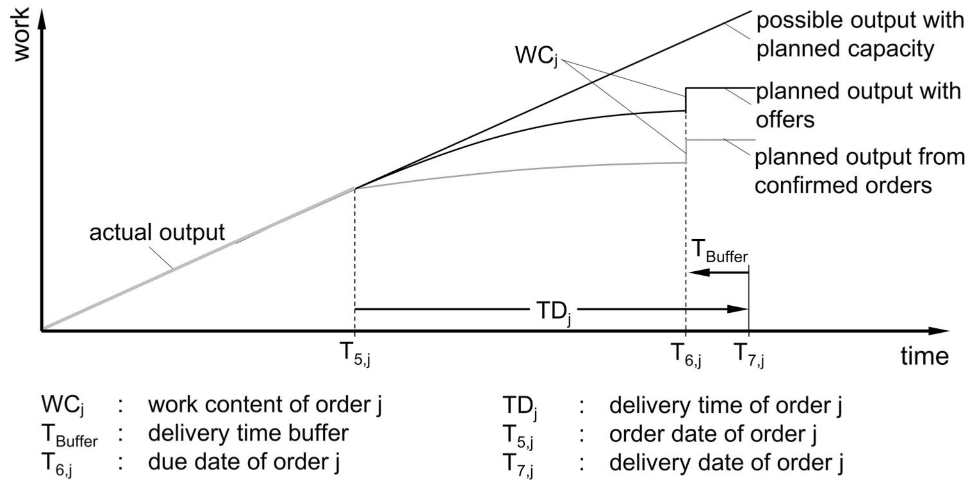

Figure 8. Planning orders in the throughput diagram.

offer, the customer order is removed from the planned output as well and then reinserted with its full work content (see Figure 8).

The previously determined delivery time is added to the actual ordering date to determine the delivery date ($T_{7,j}$) unless a different delivery date is agreed upon with the customer (19).

$$T_{7,j} = T_{5,j} + TD_j \tag{19}$$

where $T_{7,j}$, delivery date of order j; $T_{5,j}$, expected due date of offer j; TD_j, delivery time of offer j.

To determine the planned end date ($T_{6,j}$), the delivery time buffer is subtracted (20).

$$T_{6,j} = T_{5,j} + (TD_j - T_{Buffer}) \tag{20}$$

where $T_{6,j}$, due date of order j; $T_{5,j}$, actual ordering date of order j; TD_j, delivery time of offer j; T_{Buffer} delivery time buffer.

The work content is determined in the same way as for offers, since work plans are often not available at the time the order is received. As soon as the work content has been calculated, the planned output will be updated accordingly. In contrast to offers, orders count into the planned output with their entire work content, since the acceptance of the order is no longer uncertain.

5. Evaluation with simulation

The following section describes the evaluation of the previously presented Planned Output Control with the help of simulation experiments. On the one hand, we compare the planned output control with a reference that sets the delivery dates using constant planned throughput times. On the other hand, we check the robustness of the Planned Output Control by examining the behaviour of the procedure in the case of large input uncertainties. Section 5.1 gives an overview of the simulation environment and its influencing factors. Section 5.2 presents the simulation results of reference experiments in which POC is investigated and examined in an isolated manner. Section 5.3 shows the potentials of POC in combination with a configured production control. Section 5.4 illustrates the robustness of POC in the presence of large random uncertainties in the input parameters.

5.1. Simulation experiments

Evaluating the method with simulations has the advantage that it can 1) selectively vary the influencing variables, 2) define the framework conditions and 3) carry out different experiments very quickly. In addition, conducting simulation experiments allow the comparison of the Planned Output Control with a reference. Thus, simulation experiments make it possible to evaluate the Planned Output Control under defined conditions and to check the robustness of the Planned Output Control in case of large input uncertainties. This is not possible in a practical evaluation.

The simulation experiments were performed with a simulation model in the *Plant Simulation* software. In addition to the production, the simulation model includes areas upstream of production, such as the order acceptance and planning.

The simulated Production consists of seven workstations, each of which can process one job at a time. As it is typical for make-to-order companies, these workstations are arranged in a job-shop layout. Each workstation performs a different manufacturing process and has its own queue. Sequencing rules and order release methods can be varied to investigate different configurations of production control. For sequencing a First In - First Out rule (FIFO) and earliest operation due date rule (EODD) is implemented. Orders are released using constant work in process (CONWIP) or according to the planned start date. Capacities are deliberately not controlled in the experiments in order to be able to assess the unchanged effect of the acceptance and planning procedure on the lateness. Nevertheless, we consider capacity control to be indispensable in practice. Figure A2 shows the basic structure of the information and material flows in the simulation model.

The job shop produces ten different products. In the long term, the proportion of products is equally distributed, but for each new order the product is randomly selected. The mean work content across all products is seven hours.

Work contents contribute to the random uncertainties in the experiments via their variation coefficient (WC_V). The variation coefficient describes the ratio of the standard deviation and the mean value of the work contents. The products go through at least four of the ten workstations. Tables A2 and A3 in Appendix A show the routings of the products.

Set as basic conditions are the volume of simulated requests, mean acceptance rate, the mean customer response time and the production capacity. The (constant) interarrival time between two requests is calculated from the load and the acceptance rate. The random process of order acceptance ensures a highly variable order input.

10,000 offers were simulated in every experimental run. In the simulation experiments, an initial WIP was set in order to accelerate the run-in behaviour of the simulation. For this purpose, 100 requests were generated at the beginning of each simulation. The mean acceptance rate of orders by the customer is 50%. According to the binomial distribution, this is the case with the largest standard deviation in order acceptance. The mean customer response time in the simulation experiments is five days for both, confirmed and rejected offers. The capacity of production is 186 hours per shop calendar day. Different load situations can be set by varying the interarrival time, in which the customer requests an offer. The interarrival time of the requests depends on the load percentage and the time share of disturbances. Table A1 shows the general conditions and the determination of the interarrival time.

Three simulation studies were carried out to assess the Planned Output Control in a basic state (simulation study 1), to demonstrate the potential of the Planned Output Control in combination with production control methods (simulation study 2) and to test the robustness of the Planned Output Control in the presence of large external uncertainties (simulation study 3). In general, the procedure was also intended to be investigated under stress, which is why overload situations occur and there are no simulations in an explicit steady state environment. Table A1 in Appendix A shows the experimental design for the simulation studies.

Each simulation study was carried out with a determination of delivery dates based on standard delivery times as a reference.

To simulate the behaviour of the method under different load situations, simulation experiments were performed with different average loads of 95%, 100% and 105% relative to the capacity. The 95% load scenario represents approximately a balanced situation, whereas the 105% and implicitly also the 100% scenario[1] represent an overload situation. We have chosen these load situations in particular to be able to assess the behaviour of the procedure under stress. As a result, the average number of orders received per time unit in the simulation is lower, as high as or higher than the production capacity allows. The offer rate is twice as high as the ordering rate, due to the mean acceptance rate of 50%.

For the first simulation study, the production control is performed with an order release according to the planned start date and a sequencing according to FIFO in order to be able to assess the underlying behaviour of the POC with as little influence as possible from production control. In the second and third simulation study, an order release according to CONWIP and a sequencing according to EODD are used to determine the potential of the POC with the support of production control. As described, production capacities are not controlled.

The variation coefficient of the work contents is 50% for simulation studies one and two and 100% for simulation study three. Disturbances are only included in the third simulation study, with a disturbance time share of 20%.

Relevant key performance indicators (e.g. mean throughput time, mean lateness, standard deviation of lateness) were determined for each experiment. Note that especially in the simulation runs with overload, the simulations are not representing a steady state system behaviour. Rather, variables such as WIP levels and backlogs are increasing over time, when using standard delivery times. Similarly, in the overload simulation runs with POC, the promised delivery times increase over time. The growth rates of the planned and actual delivery time for each simulation experiment in Appendix A show this behaviour. This has to be taken into account, when interpreting the average values.

For each simulation experiment, ten experimental runs were carried out with different random numbers. The different random numbers cause a different behaviour of the binomial distributed order acceptance and the assignment to the variants. The results of the individual simulation runs were averaged to compensate for statistical uncertainty. The complete results of all simulation runs can be found in Appendix A (see Tables A4–A12).

5.2. Simulation study 1: Basic state

The aim of the first simulation study is to assess the influence of the Planned Output Control on the logistic objectives as independently as possible. For this reason, an order release according to the planned start date and a sequencing according to FIFO were chosen in order to minimise the influence of the production control on the logistic objectives. The order release according to the planned start date thus exactly reproduces the planning behaviour. The sequencing according to FIFO avoids order sequence deviations and therefore particularly limits this influence. A comparison with a delivery date determination using standard delivery times puts the results in perspective. Table 2 shows the results of the simulation experiments of the first simulation study with an underload of 5% (study 1.1), a balanced load (study 1.2) and an overload of 5% (study 1.3).

The presented planning procedure achieves utilisation rates between 90.9% and 91.7%. The utilisation losses result in particular from phases in which the load falls below the capacity. The mean WIP in the production is between 43.0 orders in underload and 59.4 orders in overload for the Planned Output Control and therefore comparatively constant. This corresponds to average throughput times between 1.9 to 2.6 shop calendar days. Planned Output Control causes only small negative backlogs of −23.3 to −9.5 orders, resulting in a mean negative lateness of −1.0 to −0.4

Table 2. Results of the simulation study 1 – basic conditions.

DDD	LP_m [%]	No.	U_m [%]	WIP_m [#orders]	TT [SCD] M	TT [SCD] SD	BL_m [#orders] M	L [SCD] M	L [SCD] SD	FGI [#orders]	$TD_{m,plan}$ [SCD]	DEC [%]
POC[a]	95	1.1	91.4	43.0	1.9	1.3	−23.3	−1.0	1.1	45.7	8.6	97.7
	100	1.2	90.9	55.0	2.4	1.4	−12.9	−0.6	1.3	36.4	14.6	93.8
	105	1.3	91.7	59.4	2.6	1.5	−9.5	−0.4	1.4	34.4	18.7	90.0
SDT	95	1.1	93.2	45.4	2.0	1.4	−24.2	−1.0	1.1	47.0	10.0	97.4
	100	1.2	96.0	113.2	4.8	2.8	39.9	1.7	2.4	12.3	10.0	52.6
	105	1.3	96.3	226.9	9.3	4.6	150.1	6.2	4.3	3.2	10.0	16.1

DDD: due date determination; POC: Planned Output Control; SDT: standard delivery times; LP_m: mean load percentage; No.: study number; U_m: mean utilisation; WIP_m: mean WIP; TT: throughput tim; BL_m: mean backlog; L: lateness; FGI: finished goods inventory; $TD_{m,plan}$: mean planned delivery time; DEC: delivery compliance; SCD: shop calendar day; M: mean value; SD: standard deviation.
[a]Due to the fixed capacities, the Planned Output Control causes increasing delivery times, especially in the event of an overload.

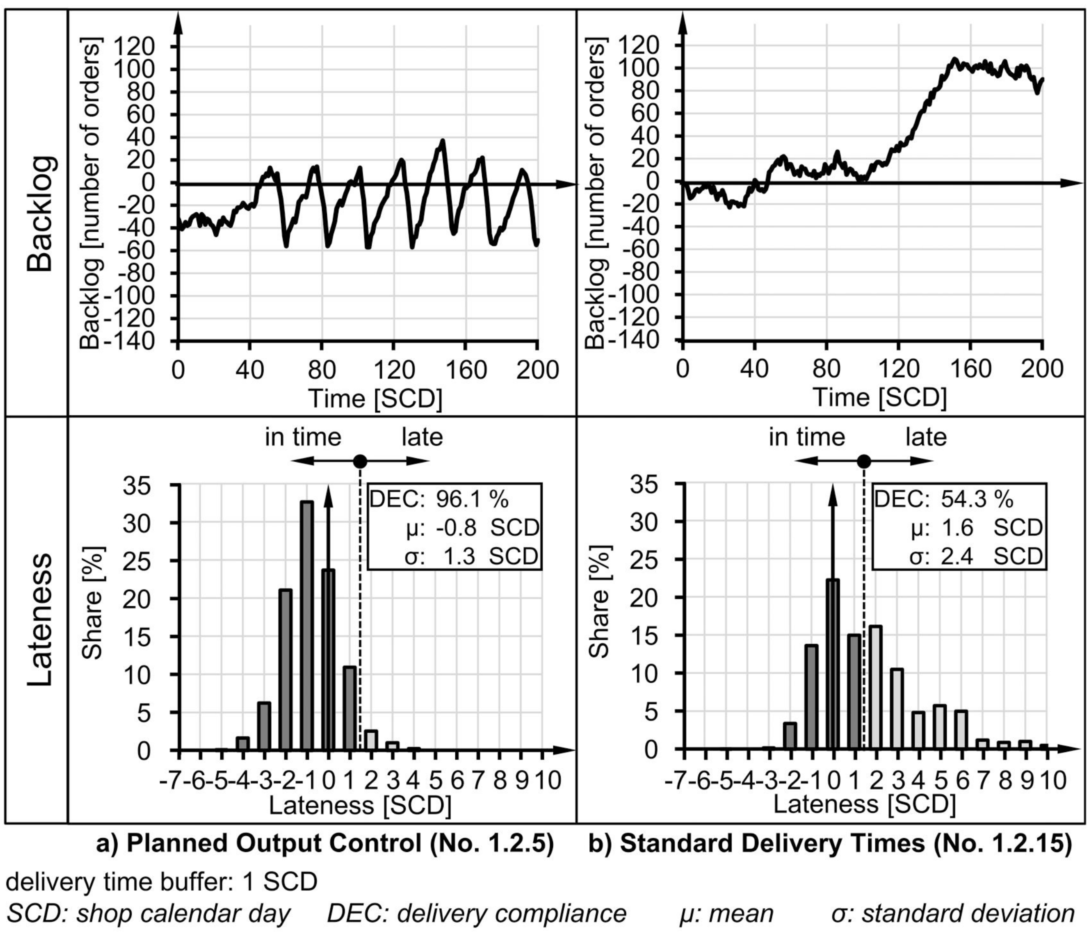

Figure 9. Exemplary backlogs and lateness distributions of the first simulation study.

shop calendar days and a delivery compliance between 97.7% and 90.0%. The standard deviation of the throughput time and the lateness are both between 1.1 and 1.5 shop calendar days. The mean stock levels for finished goods are between 45.7 and 34.4 orders. The variation of the lateness is especially resulting from the short-term load fluctuations induced by the binomially distributed acceptance decisions. Rigid capacities do not compensate for these fluctuations, resulting in lateness. At this point it is worth noting, that the delivery times were extended due to the rigid capacities (see Table A6; Appendix A). The Planned Output Control plans orders later, if there are no free capacities at an earlier point in time. During a systematic or temporary overload situation, where the load exceeds the capacity, longer delivery times are essential to avoid backlogs. On average, delivery times increase by about 0.09 days per shop calendar day in the simulation experiments with balanced load and about 0.13 days per shop calendar day in the simulation experiments with overload. For the situation with underload, however, shorter delivery could be achieved. However, in practice, the necessary capacity adjustments can avoid the extension of delivery times.

In comparison with the determination of delivery dates by standard delivery times, a few things are noticeable. This reference achieves higher utilisation rates, especially with higher loads. The utilisation reached average values of 93.2%

in an underload situation and 96.3% in an overload situation. This can be explained by the fact that this type of planning passes the load on to production unchanged and only with a time delay. This results in high WIPs between 45.4 and 226.9 orders on average, which have a positive influence on utilisation. At the same time, however, the high WIPs also cause very large and fluctuating throughput times (2.0 ± 1.3 SCD to 9.3 ± 4.6 SCD), large backlogs (−24.2 to 150.1 orders) and thus also a large lateness (−1.0 ± 1.1 SCD to 6.2 ± 4.3 SCD) that results in a low delivery reliability (97.4–16.1%). Finished goods stock levels are low due to the positive mean lateness.

When comparing the different experimental runs with each other, the great constancy of the Planned Output Control is noteworthy (cf. Appendix A). At the same time, the large differences in the mean delivery times illustrate how large the statistical uncertainties are in the various simulation runs with different random numbers. Figure 9 shows an example for the backlog curves and lateness distributions comparing the Planned Output Control and the planning with standard delivery times in the first simulation study (load = 100%; cf. Table A5; Experiment 1.2.5; Experiment 1.2.15).

Planned Output Control actively controls the backlogs and thus avoids the build-up of large positive backlogs. On average, negative backlogs result from the control behaviour of the POC. When positive backlogs are detected, Planned Output Control counteracts them quickly by planning offers later taking the backlog into account. If less offers are successful than expected, POC also reacts by offering shorter delivery times for incoming offer requests. However, as the standard algorithm does not offer shorter delivery times than customers have asked for, the process of filling the production takes more time, leading to situations with higher negative backlogs. So, the assumptions of the simulation prevent the capacities that become available later from being reallocated at short notice. Planning with standard delivery times, on the other hand, leads to large backlogs, especially in phases of overload, which are not actively reduced afterwards.

This behaviour is also reflected in the distribution of the lateness. Planned Output Control shows a comparatively low deviation of the lateness with a mean lateness of −0.8 SCD. The lateness of planning with standard delivery times, on the other hand, shows significantly greater variation. Furthermore, the mean value of the lateness deviation of 1.6 SCD is already above the delivery time buffer.

In summary, the Planned Output Control is thus able to effectively and constantly protect production from overload and to limit lateness. The disadvantage, however, is the resulting capacity utilisation losses. In Section 5.3, we examine whether and to what extend a subsequent combination of the Planned Output Control with a ConWIP order release may solve this problem.

5.3. Simulation study 2: Configuration of the production control

The aim of the second simulation study is to evaluate the Planned Output Control in combination with a coordinated production control. For this purpose, the production planning procedures were combined with an order release according to CONWIP and sequencing according to EODD.

ConWIP releases orders earlier than planned if the WIP falls below the intended WIP to process orders whose planned start date has not yet been reached. Releasing orders early is intended to avoid capacity utilisation losses and to compensate for short-term fluctuations in the load. The WIP limit of the CONWIP control amounts to 63 orders. This corresponds to a range, and therefore implicitly a projected throughput time, of about 2.6 shop calendar days.

Order sequencing according to EODD is intended to compensate for order sequence deviations that occur due to the different material flows. This has a positive influence on lateness.

For this simulation study as well, an underload of 5% (study 2.1), a balanced load (study 2.2) and an overload of 5% (study 2.3) were assumed. Again, a comparison with a delivery date determination using standard delivery times puts the results in perspective. Table 3 shows the results of the second simulation study.

The Planned Output Control still does not achieve full utilisation with a ConWIP order release. Nevertheless, the utilisation losses can be reduced to utilisation levels between 94.7% (underload) and 96% (balanced load/overload). The still occurring utilisation losses result in particular from fluctuations caused by the different variants and the complex material flow. The mean WIP for the balanced load and the overload situation reaches about 63 orders. The deviation

Table 3. Results of the simulation study 2 – potentials.

DDD	LP_m [%]	No.	U_m [%]	WIP_m [#orders]	TT [SCD] M	TT [SCD] SD	BL_m [#orders] M	L [SCD] M	L [SCD] SD	FGI [#orders]	$TD_{m,plan}$ [SCD]	DEC [%]
POC[a]	95	2.1	94.7	51.8	2.2	1.4	−45.7	−2.0	1.2	68.4	5.7	99.9
	100	2.2	96.0	62.8	2.7	1.5	−35.3	−1.5	1.5	58.6	9.8	98.9
	105	2.3	96.0	62.9	2.7	1.5	−30.4	−1.3	1.6	54.3	14.4	97.1
SDT	95	2.1	94.8	52.5	2.2	1.1	−141.8	−6.3	1.3	164.0	10.0	100
	100	2.2	96.1	62.8	2.7	1.5	−45.6	−1.8	2.8	74.1	10.0	91.0
	105	2.3	96.2	62.9	2.7	1.5	67.2	2.8	5.1	31.5	10.0	41.9

DDD: due date determination; POC: Planned Output Control; SDT: standard delivery times; LP_m: mean load percentage; No.: study number; U_m: mean utilisation; WIP_m: mean WIP; TT: throughput time; BL_m: mean backlog; L: lateness; FGI: finished goods inventory; $TD_{m,plan}$: mean planned delivery time; DEC: delivery compliance; SCD: shop calendar day; M: mean value; SD: standard deviation.
[a]Due to the fixed capacities, the Planned Output Control causes increasing delivery times, especially in the event of an overload.

from the ConWIP limit can be caused by load fluctuations. In the situation with underload, the mean work in process of about 51.8 orders is significantly below the CONWIP limit. In this case, the advance release window of the CONWIP control prevents the build-up of the intended work in process. In the situations in which the WIP limit of the CONWIP control is reached, the mean throughput time corresponds to the planned throughput time for CONWIP of about 2.7 shop calendar days. The standard deviation of the throughput time, with values between 1.4 and 1.5 shop calendar days, is comparable to the first simulation study. As a result of the CONWIP control, higher negative backlogs occur, which result in negative lateness between −2.0 and −1.3 shop calendar days for the Planned Output Control. With 1.2 to 1.6 shop calendar days, the standard deviation of the lateness is at a comparable level with the first simulation study. The delivery compliance therefore has very high values of 99.9% to 97.1%. The Planned Output Control finished goods inventories are at a comparable level of 68.4 to 54.3 orders for all workload situations. The increase in these work in process compared to the first simulation study is again due to the advance release window of the CONWIP control. Again, as a result of the regulation in the Planned Output Control, average delivery times increased by about 0.03 days per shop calendar day in the simulation experiments with balanced load and about 0.08 days per shop calendar day in the simulation experiments with overload. As stated above, capacity adjustments in practice can prevent this effect. However, when looking at the average planned delivery times, it is noticeable that the POC is responding to underutilisation and allowing customers much shorter delivery times.

The comparison with the determination of delivery dates by standard delivery times again shows some differences. This reference achieves comparable utilisation rates in combination with the CONWIP control and thus does not achieve an advantage over the Planned Output Control. The same applies to the WIPs and throughput times, which also take on comparable values through the CONWIP control. Nevertheless, planning with standard delivery times causes differing backlogs (−141.8 to 67.2 orders) which causes a different average lateness (−6.93 to 2.8 SCD). As a result, planning with standard delivery times achieves a delivery reliability of 100% in the situation with underload, but this drops to 91% with balanced load and to only 41.9% with overload. The finished goods inventories are high in relation to the delivery reliability with values between 164 orders and 31.5 orders. Especially in the case of under-utilisation, planning with standard delivery times cannot react automatically. The result in this case are much higher planned delivery times than with POC (10 SCD vs. 5.7 SCD).

Also in the second simulation study, the comparison of the different experiments shows the consistency of the results for the Planned Output Control (cf. Appendix A, Table A8). Figure 10 shows an example for the backlog curves and

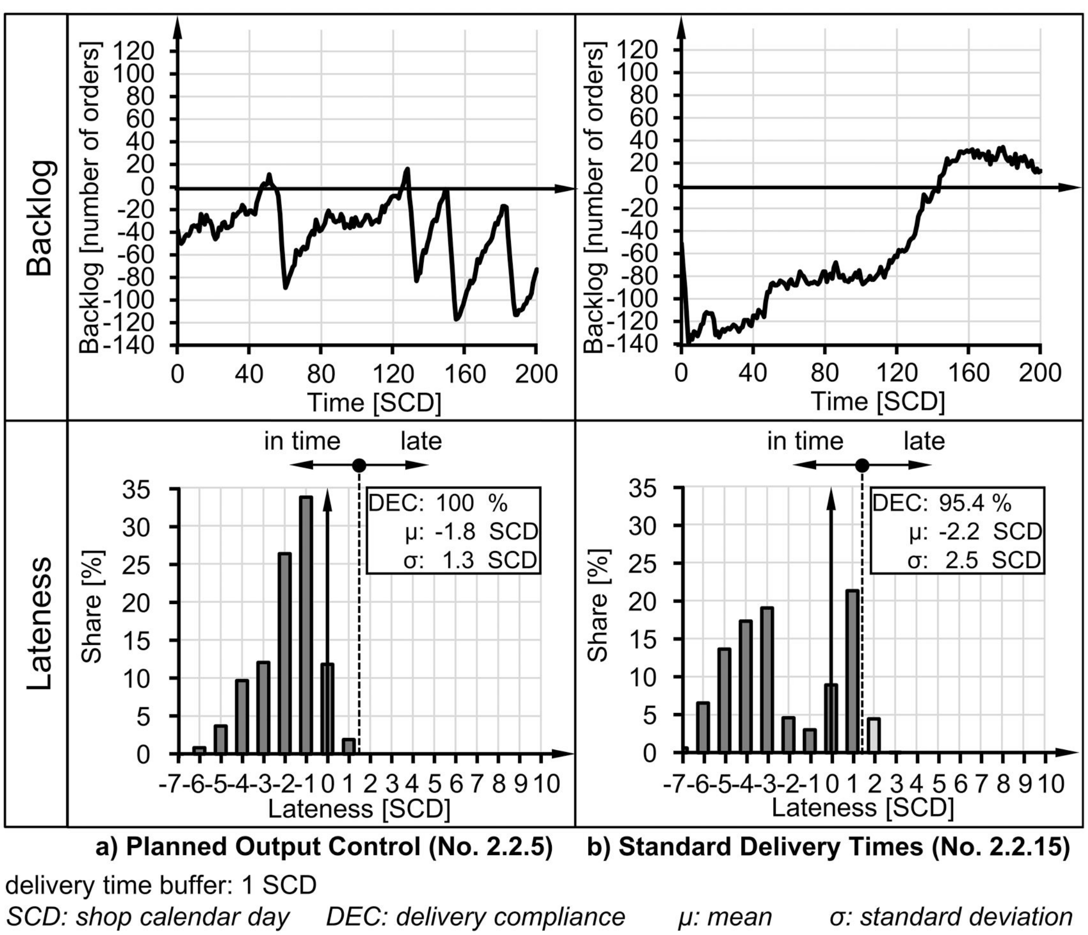

Figure 10. Exemplary backlogs and lateness distributions of the second simulation study.

lateness distributions of the second simulation study (load = 100%; cf. Table A8; Experiment 2.2.3; Experiment 2.2.13).

The backlog is significantly more negative when combining the two methods with a CONWIP control. This is due to the advance release window, which allows orders to be released earlier than planned and can therefore cause negative backlogs. Planned Output Control is again able to control the backlogs. When planning with standard delivery times, backlogs occur that are not separately controlled by the procedure.

The distribution of the lateness also shows this behaviour. Planned Output Control shows a distribution with a mean value of −1.8 SCD and a comparatively low variation. The distribution of lateness for planning with standard delivery times has a mean value of −2.2 SCD and a larger variation.

Combined with order release according to CONWIP and sequencing according to EODD, the Planned Output Control achieves high utilisation with constant WIPs and throughput times. The resulting backlogs and lateness are slightly negative. Thus, on the one hand, the presented configuration of the PPC effectively protects production from overload and from the resulting lateness. On the other hand, the process ensures high utilisation and achieves short throughput times.

5.4. Simulation study 3: Robustness against disturbances and varying work contents

The aim of the third simulation study is to assess the robustness of the Planned Output Control against large uncertainties in the input variables. For this purpose, the Planned Output Control is again combined with an order release according to CONWIP and a sequencing according to EODD. The uncertainties were significantly increased by: 1) randomly occurring disturbances with a time share per workstation of 20%[2] and 2) work contents with a variation coefficient (WC_V) of 100% relative to the mean value. These settings make it possible to assess the behaviour of the Planned Output Control in the case of high load fluctuations and rigid capacities.

For the third simulation study, a balanced load (study 3.1), an overload of 5% (study 3.2) and an overload of 10% (study 3.3) were assumed. The disturbances are considered in the calculation of the load. Accordingly, the disturbances do not increase the relative load, but they do increase the stochastic uncertainties in the process. Also in this case, a comparison with the determination of the delivery date using standard delivery times serves as a reference of the results. Table 4 shows the results of the fourth simulation study.

In this simulation study, the mean WIP is also close to the CONWIP limit due to the advance release window and is very constant across all individual simulations. The same applies to the mean throughput time. Despite the large fluctuations, the Planned Output Control achieves a constant utilisation of 93.9%. Backlogs between −23.9 and −12.0 orders across all simulations occurred. This results in a mean lateness between −1.5 and −0.7 shop calendar days. The standard deviation of the throughput time and the lateness is at a comparable level to the second simulation study. For a situation with a balanced load, the delivery compliance has a very high value of 92.3%. For the overload situations, the delivery reliability is reduced to 88.5% at a load of 105% and to 83.9% at a load of 110%. The Planned Output Control finished goods inventory is at a level of 43.7 orders for a balanced load situation and reduced to 34 orders for a situation with a load of 110%.

Utilizations, WIPs and throughput times are comparable when planning with standard delivery times. In a balanced load situation, a backlog of 22.3 orders, a mean lateness of 2.8 SCD with a standard deviation of 4.9 SCD and a delivery reliability of 43.2% could be determined. The standard deviation of the lateness is already significantly above the results of the Planned Output Control in this case, which also explains the significantly lower delivery reliability. For the situations with the overload of 105% and 110%, backlogs of about 114 and 203 orders were measured. These resulted in correspondingly high lateness of about 8.5 SCD and 13.2 SCD respectively. Also, the standard deviation of 7.8 SCD and 10.5 SCD is higher. As a result, the delivery reliability drops to values of only 22.1% and 16.8% for the situations with overload. Due to the late completion, the finished goods inventories in these situations were very low at 14.6 and 10.6 orders, respectively. Planning with standard delivery times therefore performs significantly worse than planning with Planned Output Control, especially in terms of lateness and delivery reliability.

Table 4. Results of the simulation study 3 – robustness.

DDD	LP_m [%]	No.	U_m [%]	WIP_m [#orders]	TT [SCD] M	TT [SCD] SD	BL_m [#orders] M	L [SCD] M	L [SCD] SD	FGI [#orders]	$TD_{m,plan}$ [SCD]	DEC [%]
POC[a]	100	3.1	93.9	62.8	3.4	1.6	−23.9	−1.5	2.3	43.7	14.6	92.3
	105	3.2	93.9	62.9	3.4	1.6	−17.8	−1.1	2.1	38.5	20.5	88.5
	110	3.3	93.9	62.9	3.4	1.6	−12.0	−0.7	2.2	34.0	25.6	83.9
SDT	100	3.1	93.9	62.8	3.4	1.5	22.3	2.8	4.9	26.6	10.0	43.2
	105	3.2	93.8	62.9	3.4	1.5	113.5	8.5	7.8	14.6	10.0	22.1
	110	3.3	93.9	62.9	3.4	1.6	203.2	13.2	10.5	10.6	10.0	16.8

DDD: due date determination; POC: Planned Output Control; SDT: standard delivery times; LP_m: mean load percentage; No.: study number; U_m: mean utilisation; WIP_m: mean WIP; TT: throughput time; BL_m: mean backlog; L: lateness; FGI: finished goods inventory; $TD_{m,plan}$: mean planned delivery time; DEC: delivery compliance; SCD: shop calendar day; M: mean value; SD: standard deviation.

[a]Due to the fixed capacities, the Planned Output Control causes increasing delivery times, especially in the event of an overload.

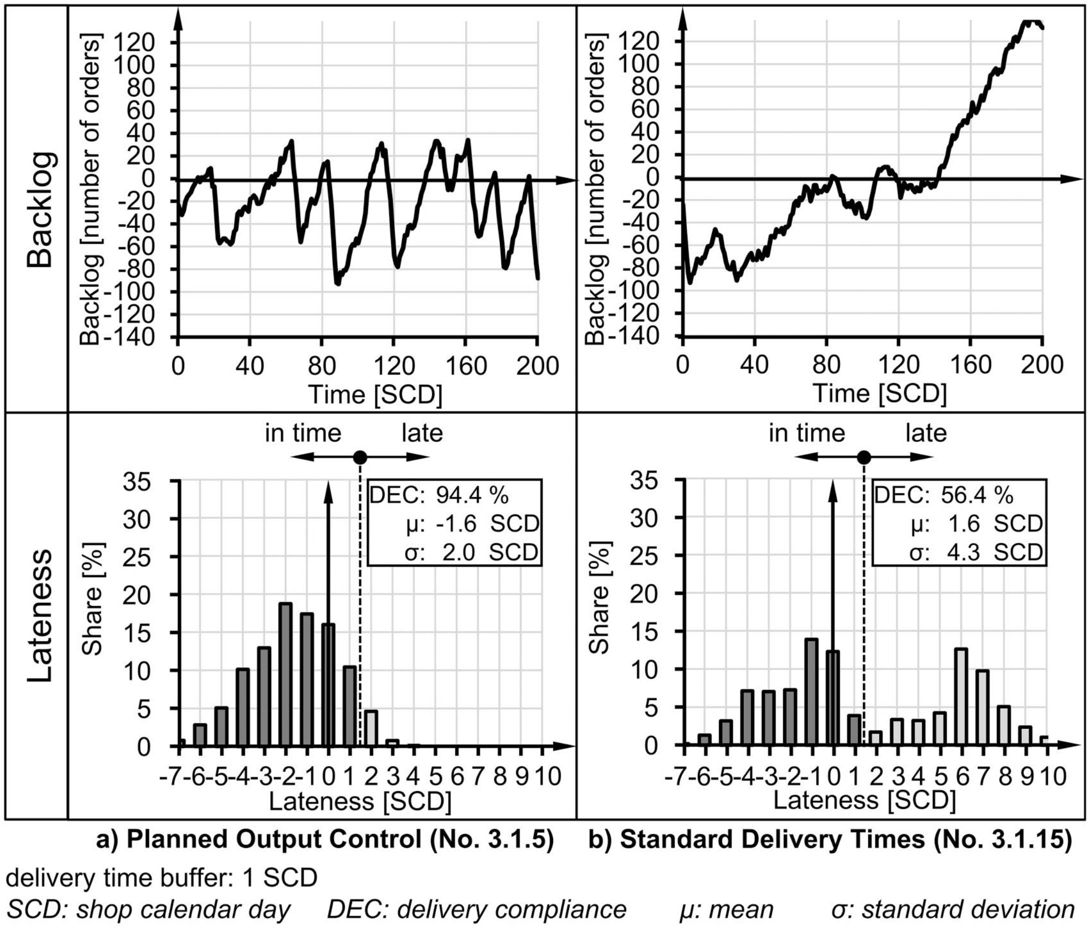

Figure 11. Exemplary backlogs and lateness distributions of the third simulation study.

The better performance of the Planned Output Control is also accompanied in this case by an increase in delivery times. The delivery times increased sharply in order to avoid backlogs during the very high overload. On average, the delivery times increase by 0.06 days per shop calendar day in the simulation experiments with a balanced load, 0.11 days per shop calendar day in the simulation experiments with an overload of 5%, and by 0.15 days per shop calendar day in the simulation experiments with 10% overload. The extension of delivery times mainly results from systematic or temporary overload and can be avoided with the help of capacity adjustments. Figure 11 shows an example of the resulting throughput diagrams of the third simulation study (load = 100%; cf. Table A10; Experiment 3.1.5; Experiment 3.1.15).

Despite the large uncertainties, the POC is able to regulate and thereby limit the backlogs. In contrast, a significant build-up of backlogs can be observed when planning with standard delivery times.

Accordingly, Planned Output Control shows a comparatively low variation of the lateness with a mean value of −1.6 SCD. The lateness of the planning with standard delivery times shows a very large variation. Even the mean lateness of 1.6 SCD is above the delivery time buffer of 1 SCD.

The increasing delivery times with POC are reflected in a rising stock of customer orders in the company. At the same time, it shows great consistency despite the very large uncertainties. In particular, the production throughput times and the lateness are very low and constant. Even with extreme input variables, the Planned Output Control can thus effectively protect the production from overload and limit the throughput time without causing large capacity utilisation losses, high WIPs or long throughput times. The method therefore reacts very robustly to a wide range of input variables.

6. Summary and outlook

This paper presents the Planned Output Control as a model-based planning method for make-to-order companies. It extends the theory of the funnel model and the workload control concept from an application viewpoint, dealing with situations that arise in practise, such as a high uncertainty of offer acceptance, delays between the submission of an offer and the confirmation or rejection of an order, the low availability of detailed data on work contents at an early stage and the high influence of production disturbances. In particular, the procedure extends theory by three aspects. First, it explicitly integrates offers into the planning procedure. Second, the procedure derives parameters such as the acceptance rate in a model-based manner. Third, it explicitly regulates the backlog and thereby the average lateness of production. Compared to many traditional planning methods, the focus lies on a high reliability in securing the logistic objectives, a simple implementation, a high robustness and a clear form of expression that makes the method comprehensible. The results of the previous sections suggest the achievement of the procedure's objectives:

- *Reliability:* The presented method protects production from overload and can thus support schedule reliability and utilisation as the main objective variables of many make-to-order companies. The method is characterised by a high degree of consistency in the results. In particular, the combination of the presented planning procedure with a WIP-regulating order control according to CONWIP and a sequencing according to EODD additionally improves and stabilises the achievement of the logistic objectives.
- *Robustness:* The presented method is suitable for a wide range of input variables due to the backlog regulating behaviour, without causing an excessive degradation of the achievement of the logistic objectives.
- *Simplicity:* Even though the practical suitability of the method has not yet been investigated in detail, the method is characterised in particular by low data requirements and comparatively simple parameterisation.
- *Clarity:* The method makes it possible to identify potential backlogs at an early stage through the depiction in the throughput diagram. As a result, it can determine possible lateness or capacity utilisation losses. Moreover, the modelling of the process parameters makes it possible to prepare for different planning scenarios. Nevertheless, the clarity for users cannot be assessed so far.

In addition to the good results of the POC as a planning procedure, the associated illustration in the throughput diagram has, in our view, another important advantage. The comparison of the outputs with the capacity in the throughput diagram is also suitable for capacity planning and control and the consideration of the open offers extends its planning horizon. This makes it possible for a company to control the entire PPC chain, as highlighted by Kingsman in his work, and thereby improve the logistical achievement of objectives. In summary, we would propose POC in combination with a CONWIP order release and an EODD sequencing as a good standard configuration for MTO production.

Our work is subject to limitations. Currently, there is no practical application experience with the methodology. The presented evaluation experiments have shown that the proposed method is suitable for order planning as a core task of PPC. However, a practical application can help to further refine the method and especially to investigate the practical implementation.

Furthermore, the method does not take into account procurement processes, which of course can have a relevant influence in practice. The method has also not been evaluated for complex, multi-stage products and for use with manufacturers that combine MTO and MTS. An investigation of these points may trigger a need to adapt the methodology.

Notes

1. Variances cause utilization losses that result in an implicit overload even in the case of a formally balanced load.
2. Mean Time To Repar (MTTR) = 30 min; Mean Time Between Failures (MTBF) = 120 min.

Disclosure statement

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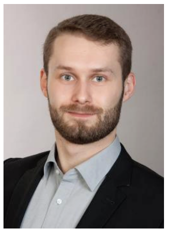
Notes on contributors



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References

Alenezi, A., S. A. Moses, and T. B. Trafalis. 2008. "Real-Time Prediction of Order Flowtimes Using Support Vector Regression." *Computers & Operations Research* 35 (11): 3489–3503. https://doi.org/10.1016/j.cor.2007.01.026.

Bakke, N. A., and F. Nyhuis. 1992. "The Use of Operations-Orientated Controlling Systems in Complex Production Environments." *Production Planning & Control* 3 (1): 99–110. https://doi.org/10.1080/09537289208919378.

Bechte, W. 1984. "Steuerung Der Durchlaufzeit Durch Belastungsorientierte Auftragsfreigabe Bei Werkstattfertigung (Control of Throughput Time through Load-Oriented Order Release in Workshop Production)." Dissertation, University Hanover.

Brankamp, K. 1967. "Ein Terminplanungssystem Für Unternehmen Der Einzel- Und Serienfertigung (A Scheduling System for Companies in Individual and Series Production)." Dissertation, RWTH Aachen University

Hendry, L. C., and B. G. Kingsman. 1989. "Production Planning Systems and Their Applicability to Make-to-Order Companies." *European Journal of Operational Research* 40 (1): 1–15. https://doi.org/10.1016/0377-2217(89)90266-X.

Hendry, L., and B. Kingsman. 1991. "A Decision Support System for Job Release in Make-to-Order Companies." *International Journal of Operations & Production Management* 11 (6): 6–16. https://doi.org/10.1108/01443579110144655.
Hendry, L. C., and B. G. Kingsman. 1993. "Customer Enquiry Management: Part of a Hierarchical System to Control Lead Times in Make-to-Order Companies." *Journal of the Operational Research Society* 44 (1): 61–70. https://doi.org/10.1057/jors.1993.7.
Hendry, L., M. Land, M. Stevenson, and G. Gaalman. 2008. "Investigating Implementation Issues for Workload Control (WLC): A Comparative Case Study Analysis." *International Journal of Production Economics* 112 (1): 452–469. https://doi.org/10.1016/j.ijpe.2007.05.012.
Hopp, W. J., and M. L. Spearman. 2008. *Factory Physics*. New York: McGraw-Hill.
Kingsman, B. G., I. P. Tatsiopoulos, and L. C. Hendry. 1989. "A Structural Methodology for Managing Manufacturing Lead Times in Make-to-Order Companies." *European Journal of Operational Research* 40 (2): 196–209. https://doi.org/10.1016/0377-2217(89)90330-5.
Kingsman, B. G. 2000. "Modelling Input–Output Workload Control for Dynamic Capacity Planning in Production Planning Systems." *International Journal of Production Economics* 68 (1): 73–93. https://doi.org/10.1016/S0925-5273(00)00037-2.
Kingsman, B., and L. Hendry. 2002. "The Relative Contributions of Input and Output Controls on the Performance of a Workload Control System in Make-To-Order Companies." *Production Planning & Control* 13 (7): 579–590. https://doi.org/10.1080/0953728021000026285.
Klein, R. 2001. "Revenue Management: Quantitative Methoden zur Erlösmaximierung in der Dienstleistungsproduktion (Revenue Management: Quantitative Methods for Revenue Maximisation in Service Production)." *Betriebswirtschaftliche Forschung Und Praxis* 53 (3): 245–259.
Land, M. J. 2009. "Cobacabana (Control of Balance by Card-Based Navigation): A Card-Based System for Job Shop Control." *International Journal of Production Economics* 117 (1): 97–103. https://doi.org/10.1016/j.ijpe.2008.08.057.
Lödding, H. 2013. *Handbook of Manufacturing Control*. Berlin, Heidelberg: Springer Berlin Heidelberg.
Lödding, H., P. Nyhuis, M. Schmidt, and A. Kuyumcu. 2014. "Modelling Lateness and Schedule Reliability: how Companies Can Produce on Time." *Production Planning & Control* 25 (1): 59–72. https://doi.org/10.1080/09537287.2012.655803.
Lohnert, N., and K. Fischer. 2019. "Booking Limit Based Revenue Management Approaches for Customer-Value Oriented Make-to-Order Production." In *Logistics Management*, edited by C. Bierwirth, T. Kirschstein, and D. Sackmann, 268–282. Cham: Springer International Publishing,
Mohaupt, M., and A. Hilbert. 2013. "Decision Support System for Customer Value-based Revenue Management in Manufacturing." PACIS 2013 Proceedings 264.
Mohaupt, M., and A. Hilbert. 2014. "Customer-Centric Revenue Management in Manufacturing-A Decision Support System." European Conference on Information Systems.
Mourtzis, D., M. Doukas, K. Fragou, K. Efthymiou, and V. Matzorou. 2014. "Knowledge-Based Estimation of Manufacturing Lead Time for Complex Engineered-to-Order Products." *Procedia CIRP* 17: 499–504. https://doi.org/10.1016/j.procir.2014.01.087.
Mundt, C., and H. Lödding. 2020. "Order Acceptance and Scheduling with a Throughput Diagram." In *Advances in Production Management Systems. The Path to Digital Transformation and Innovation of Production Management Systems 591*, edited by B. Lalic, V. Majstorovic, U. Marjanovic, and G. R. von Cieminski, 351–359. IFIP Advances in Information and Communication Technology. Cham: Springer International Publishing.
Mundt, C., E. B. Beck, and H. Lödding. 2022. "Determining Due Dates for Rush Orders." In *Advances in Production Management Systems. Smart Manufacturing and Logistics Systems: Turning Ideas into Action 663*, edited by D. Y. Kim, G. von Cieminski, and D. Romero, 293–301. IFIP Advances in Information and Communication Technology. Cham: Springer Nature Switzerland.
Nyhuis, P., editor. 2016. *Aktuellen Herausforderungen der Produktionsplanung und -steuerung mittels Industrie 4.0 begegnen: Studienergebnisse (Meeting Current Challenges in Production Planning and Control Using Industry 4.0. Study Results)*. With the Contribution of J. Mayer, J. Pielmeier, C. Berger, F. Engehausen, T. Hempel, and P. Hünnekes. Garbsen: PZH Verlag.
Nyhuis, P., and H. P. Wiendahl. 2009. *Fundamentals of Production Logistics*. Berlin, Heidelberg: Springer Berlin Heidelberg.
Park, C., S. Jungsu, K. Jae-Gyun, and K. Insoo. 1999. "Delivery Date Decision Support System for the Large Scale Make-to-Order Manufacturing Companies: A Korean Electric Motor Company Case." *Production Planning & Control* 10 (6): 585–597. https://doi.org/10.1080/095372899232885.
Schilp, J., editor. 2021. "PPS-Report 2021: Studienergebnisse (PPC Report 2021. Study Results)." With the contribution J. Maetschke, J. Fulterer, T. Janke, A. Zipfel, L. Bank, P. Theumer, C. Mundt, N. Köster, T. Kämpfer, T. Heuer, T. Hiller. Fraunhofer Publica.
Schmitz, P.-G. 1961. *Analytische Beziehungen zwischen Produktionsverlauf, Belastung und unvollendeter Produktion in Maschinenbaubetrieben (Analytical Relationships between Production Flow, Load and Unfinished Production in Machinery Manufacturing Companies)*. Berlin: VEB Verlag Technik.
Schönsleben, P. 2023. *Handbook Integral Logistics Management*. Berlin, Heidelberg: Springer Berlin Heidelberg.
Schuh, G. 2006. *Produktionsplanung und -steuerung: Grundlagen. Gestaltung und Konzepte* [Production Planning and Control. Fundamentals, Design and Concepts]. Berlin, Heidelberg: Springer Berlin Heidelberg.
Taal, M., and J. C. Wortmann. 1997. "Integrating MRP and Finite Capacity Planning." *Production Planning & Control* 8 (3): 245–254. https://doi.org/10.1080/095372897235307.
Thürer, M., M. J. Land, and M. Stevenson. 2014. "Card-Based Workload Control for Job Shops: Improving COBACABANA." *International Journal of Production Economics* 147: 180–188. https://doi.org/10.1016/j.ijpe.2013.09.015.
Thürer, M., M. J. Land, M. Stevenson, and L. D. Fredendall. 2016. "Card-Based Delivery Date Promising in High-Variety Manufacturing with Order Release Control." *International Journal of Production Economics* 172: 19–30. https://doi.org/10.1016/j.ijpe.2015.11.003.
Wiedemann, M. 2016. "Methodik Zur Auslastungsorientierten Angebotsterminierung Für Hochvariante Produkte Mit Kundenindividuellen Leistungsanteilen (Methodology for Capacity-Oriented Quotation Scheduling for Highly Variant Products with Customised Service Components)." Dissertation, Technical University of Munich.
Wiendahl, H.-P. 1997. *Fertigungsregelung: Logistische Beherrschung Von Fertigungsabläufen Auf Basis Des Trichtermodells* [Production Control. Logistical Control of Manufacturing Processes Based on the Funnel Model]. Munich: Hanser.

Appendix A

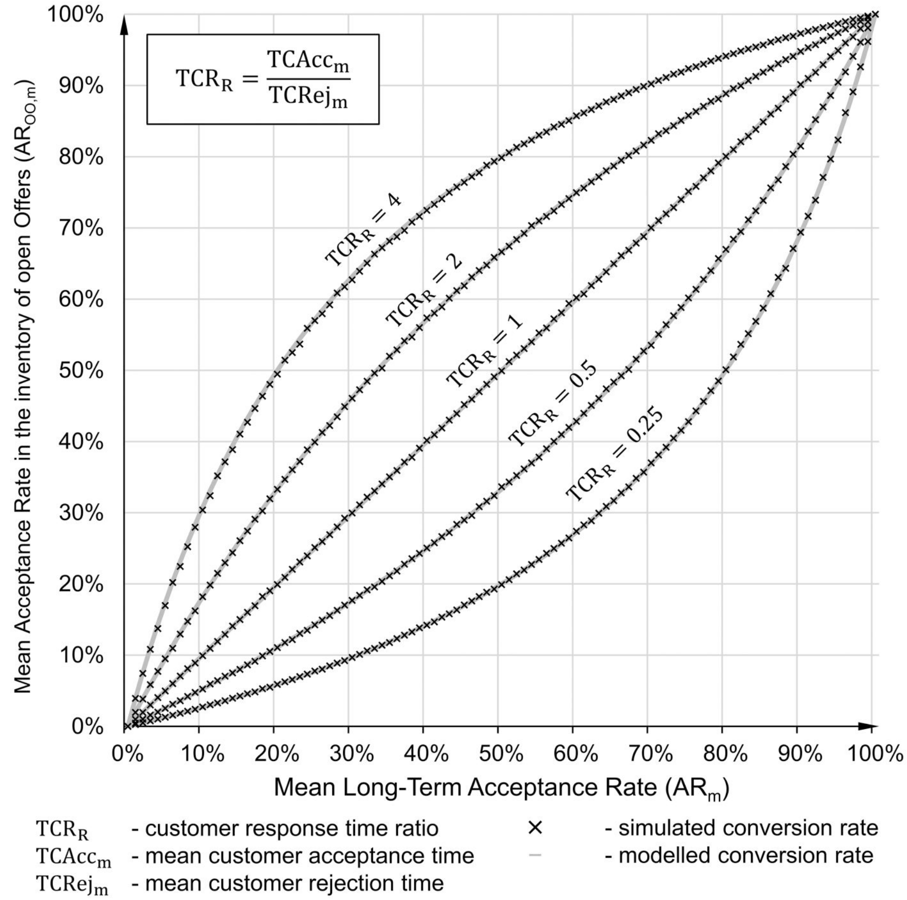

Figure A1. Evaluation results of a Monte Carlo simulation of the modelling on the acceptance rate of open offers.

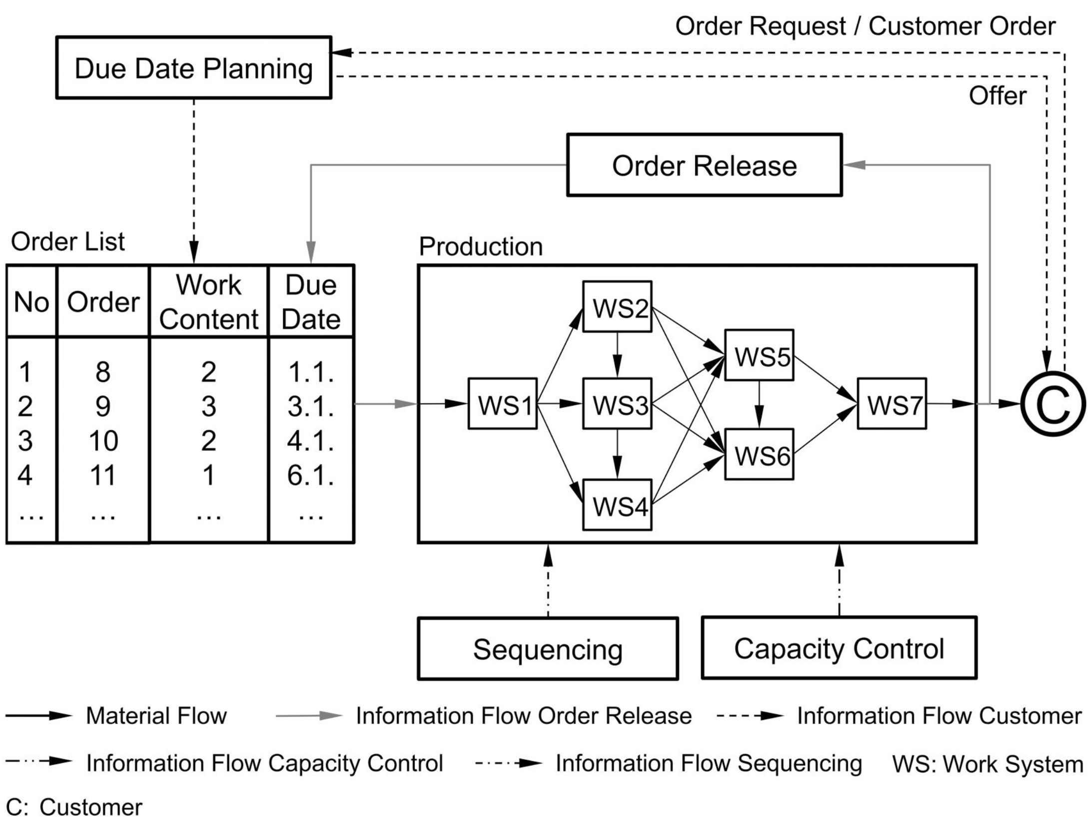

Figure A2. Design of the simulation study.

Table A1. Experimental design for the simulative evaluation.

Factor	Simulation study								
	1			2			3		
Planning method	Planned output control	Standard delivery times		Planned output control	Standard delivery times		Planned output control	Standard delivery times	
Load Percentage	95%	100%	105%	95%	100%	105%	95%	100%	105%
Production Control									
Order Release		Planned Start Date				ConWIP			
Order Sequencing		FIFO				EODD			
Capacity Control		fixed Capacities				fixed Capacities			
Variation Coefficient of Work Contents			50%					100%	
Time Share of Disturbances			0%					20%	
Basic conditions									
Simulated Volume per Simulation Run				10,000 requests					
Warm-Up Period				100 requests					
Mean Acceptance Rate				50%					
Mean Customer Response Time				5 shop calendar days					
Production Capacity				168 hours per shop calendar day					
Interarrival times of requests				$0,5\ \text{hours} \cdot \frac{1}{1-\text{Time Share of Disturbances}} \cdot \frac{1}{\text{Load Percentage}}$					

Table A2. Routings and work contents for the products in simulation study 1 and 2.

$WC_{total,m} = 7.0$ h		$WC_{totals,SD} = 3.5$ h					$WC_{total,v} = 50\%$		
Product	Probability	WS1	WS2	WS3	WS4	WS5	WS6	WS7	WC_{total}
1	10%	0.5 h	4.0 h	–	–	3.0 h	–	1.0 h	8.5 h
2	10%	1.0 h	1.5 h	–	–	–	3.0 h	1.0 h	6.5 h
3	10%	1.5 h	–	3.0 h	2.0 h	–	2.0 h	2.0 h	10.5 h
4	10%	1.5 h	–	–	1.0 h	1.5 h	–	0.5 h	4.5 h
5	10%	1.5 h	–	2.5 h	2.0 h	2.0 h	–	2.0 h	10.0 h
6	10%	0.5 h	2.5 h	–	–	–	2.5 h	0.5 h	6.0 h
7	10%	0.5 h	–	–	1.5 h	0.5 h	–	1.0 h	3.5 h
8	10%	1.0 h	2.0 h	4.5 h	2.0 h	2.0 h	1.0 h	1.0 h	13.5 h
9	10%	1.0 h	–	–	1.0 h	–	1.5 h	0.5 h	4.0 h
10	10%	1.0 h	–	–	0.5 h	1.0 h	–	0.5 h	3.0 h

WC_{SD}: standard deviation of work content; WC_m: mean work content; h: hours; WC_V: variation coefficient of work content; WS: work station.

Table A3. Routings and work contents for the products in simulation study 3.

$WC_{total,m} = 7.0$ h		$WC_{total,SD} = 7.0$ h					$WC_{total,v} = 100\%$		
Product	Probability	WS1	WS2	WS3	WS4	WS5	WS6	WS7	WC_{total}
1	10%	0.5 h	2.0 h	–	–	0.5 h	–	0.5 h	3.5 h
2	10%	0.5 h	1.0 h	–	–	–	1.0 h	0.5 h	3.0 h
3	10%	1.5 h	–	4.0 h	4.0 h	–	4.0 h	2.0 h	15.5 h
4	10%	1.5 h	–	–	0.5 h	0.5 h	–	0.5 h	3.0 h
5	10%	1.5 h	–	2.0 h	1.5 h	4.0 h	–	2.0 h	11.0 h
6	10%	0.5 h	2.0 h	–	–	–	0.5 h	0.5 h	3.5 h
7	10%	0.5 h	–	–	0.5 h	0.5 h	–	1.0 h	2.5 h
8	10%	1.5 h	5.0 h	4.0 h	2.5 h	4.0 h	3.5 h	2.0 h	22.5 h
9	10%	1.0 h	–	–	0.5 h	–	1.0 h	0.5 h	3.0 h
10	10%	1.0 h	–	–	0.5 h	0.5 h	–	0.5 h	2.5 h

WC_{SD}: standard deviation of work content; WC_m: mean work content; h: hours; WC_V: variation coefficient of work content; WS: work station.

Table A4. Results of the simulation study 1.1: basic condition (mean load = 95%).

DDD	LP_m [%]	No.	U_m [%]	WIP_m [#orders]	TT [SCD] M	TT [SCD] SD	BL_m [#orders]	L [SCD] M	L [SCD] SD	FGI [#orders]	$TD_{m,act}$ [SCD]	$TD_{\Delta,act}$ [SCD/SCD]	$TD_{m,plan}$ [SCD]	$TD_{\Delta,plan}$ [SCD/SCD]	DEC [%]
POC	95	1.1.1	93.5	38.1	1.6	1.2	−27.6	−1.2	1.0	50.4	3.1	0.00	5.1	0.00	98.6
	95	1.1.2	90.6	44.0	2.0	1.2	−22.0	−0.9	1.2	43.9	7.4	0.06	9.3	0.06	98.7
	95	1.1.3	94.4	40.7	1.8	1.2	−26.3	−1.0	1.0	49.6	3.4	0.00	5.2	0.00	97.7
	95	1.1.4	86.9	44.4	2.1	1.3	−20.7	−0.9	1.2	41.8	13.0	0.09	15.2	0.09	98.3
	95	1.1.5	90.2	34.5	1.6	1.0	−30.4	−1.3	0.9	52.2	5.8	0.05	8.1	0.06	99.4
	95	1.1.6	93.9	58.4	2.5	1.4	−11.0	−0.4	1.1	34.9	5.9	0.00	7.1	0.00	94.7
	95	1.1.7	94.8	44.3	1.8	1.2	−24.9	−1.1	1.0	47.9	4.5	0.00	6.4	0.00	98.8
	95	1.1.8	88.4	47.0	2.2	1.3	−18.5	−0.8	1.2	40.2	9.8	0.08	11.9	0.08	97.1
	95	1.1.9	87.4	41.6	2.0	1.4	−23.0	−1.0	1.3	45.0	10.9	0.10	13.0	0.09	95.6
	95	1.1.10	93.6	37.0	1.6	1.2	−28.6	−1.2	1.0	51.6	3.0	0.00	5.0	0.00	98.2
SDT	95	1.1.11	91.8	38.2	1.7	1.1	−30.2	−1.3	0.9	52.0	7.9	0.00	10.0	0.00	99.9
	95	1.1.12	93.7	47.5	2.0	1.2	−22.1	−1.0	1.1	44.6	8.2	0.00	10.0	0.00	98.6
	95	1.1.13	93.6	42.2	1.8	1.2	−27.5	−1.2	1.0	50.0	8.0	0.00	10.0	0.00	99.0
	95	1.1.14	93.6	58.4	2.6	1.9	−12.5	−0.5	1.3	37.6	8.7	0.00	10.0	0.00	89.2
	95	1.1.15	93.6	46.1	1.9	1.5	−23.6	−1.1	1.2	47.8	8.1	0.00	10.0	0.00	93.7
	95	1.1.16	93.4	39.3	1.7	1.0	−30.1	−1.3	0.9	52.3	7.9	0.00	10.0	0.00	99.9
	95	1.1.17	94.2	44.6	1.8	1.3	−24.8	−1.2	1.1	47.1	8.0	0.00	10.0	0.00	99.5
	95	1.1.18	93.5	56.3	2.5	1.5	−14.0	−0.5	1.0	37.2	8.6	0.00	10.0	0.00	96.7
	95	1.1.19	93.1	46.3	2.1	1.3	−23.8	−0.9	1.1	46.3	8.3	0.00	10.0	0.00	98.0
	95	1.1.20	92.0	35.1	1.6	1.0	−33.5	−1.4	0.8	55.3	7.8	0.00	10.0	0.00	100
POC	95	Ø	91.4	43.0	1.9	1.3	−23.3	−1.0	1.1	45.7	6.7	0.04	8.6	0.04	97.7
SDT	95	Ø	93.2	45.4	2.0	1.4	−24.2	−1.0	1.1	47.0	8.2	0.00	10.0	0.00	97.4

DDD: due date determination; U_m: mean utilisation; FGI: finished goods inventory; DEC: delivery compliance; POC: Planned Output Control; WIP_m: mean WIP; $TD_{m,act}$: mean actual delivery time; SCD: shop calendar day; SDT: standard delivery times; TT: throughput time; $TD_{\Delta,act}$: actual delivery time extension; M: mean value; LP_m: mean load percentage; BL_m: mean backlog; $TD_{m,plan}$: mean planned delivery time; SD: standard deviation; No.: experiment number; L: lateness; $TD_{\Delta,plan}$: planned delivery time extension.

Table A5. Results of the simulation study 1.2: basic condition (mean load = 100%).

DDD	LP_m [%]	No.	U_m [%]	WIP_m [#orders]	TT [SCD] M	TT [SCD] SD	BL_m [#orders]	L [SCD] M	L [SCD] SD	FGI [#orders]	$TD_{m,act}$ [SCD]	$TD_{\Delta,act}$ [SCD/SCD]	$TD_{m,plan}$ [SCD]	$TD_{\Delta,plan}$ [SCD/SCD]	DEC [%]
POC	100	1.2.1	91.1	53.9	2.5	1.4	−14.2	−0.5	1.2	36.9	10.8	0.08	12.6	0.07	95.6
	100	1.2.2	91.0	55.0	2.4	1.4	−13.1	−0.6	1.3	36.4	12.9	0.11	14.7	0.10	94.9
	100	1.2.3	95.2	56.0	2.4	1.4	−15.0	−0.6	1.2	39.1	7.4	0.05	8.8	0.05	94.6
	100	1.2.4	88.6	52.9	2.4	1.4	−14.1	−0.6	1.3	36.6	16.7	0.13	19.2	0.13	95.6
	100	1.2.5	90.3	49.6	2.2	1.4	−17.4	−0.8	1.3	40.2	12.2	0.11	14.1	0.10	96.1
	100	1.2.6	92.5	64.1	2.8	1.6	−5.0	−0.2	1.4	30.8	12.0	0.07	13.3	0.07	89.3
	100	1.2.7	90.4	57.4	2.6	1.4	−9.5	−0.4	1.4	32.8	15.3	0.10	16.8	0.08	93.2
	100	1.2.8	90.2	55.3	2.5	1.5	−11.8	−0.6	1.3	35.0	13.9	0.11	16.0	0.11	94.2
	100	1.2.9	88.6	51.5	2.3	1.5	−15.8	−0.7	1.5	39.4	15.2	0.14	17.3	0.13	91.7
	100	1.2.10	90.8	54.7	2.4	1.4	−13.6	−0.6	1.3	37.2	11.2	0.08	13.0	0.08	93.3
SDT	100	1.2.11	95.7	92.4	3.9	2.3	20.5	0.8	1.8	16.7	10.1	0.00	10.0	0.00	69.9
	100	1.2.12	96.2	114.4	4.9	2.3	41.1	1.8	1.9	10.8	11.1	0.02	10.0	0.00	47.3
	100	1.2.13	96.5	95.8	4.1	2.1	22.4	1.0	1.9	17.1	10.3	0.02	10.0	0.00	61.2
	100	1.2.14	95.8	139.0	5.9	3.9	64.5	2.8	3.3	7.5	12.1	0.02	10.0	0.00	43.5
	100	1.2.15	96.0	109.1	4.7	2.8	36.0	1.6	2.4	14.6	10.9	0.02	10.0	0.00	54.3
	100	1.2.16	96.3	111.0	4.7	2.0	37.9	1.6	1.6	7.9	10.9	0.01	10.0	0.00	50.9
	100	1.2.17	97.1	118.3	4.9	2.1	45.4	1.8	1.6	4.9	11.1	0.00	10.0	0.00	46.9
	100	1.2.18	95.3	152.1	6.5	3.5	78.0	3.4	3.0	5.6	12.7	0.03	10.0	0.00	27.7
	100	1.2.19	95.6	122.3	5.3	3.1	48.5	2.2	2.7	15.6	11.5	0.03	10.0	0.00	39.5
	100	1.2.20	95.8	77.5	3.3	1.8	5.1	0.2	1.2	21.9	9.5	0.00	10.0	0.00	85.3
POC	100	Ø	90.9	55.0	2.4	1.4	−12.9	−0.6	1.3	36.4	12.8	0.10	14.6	0.09	93.8
SDT	100	Ø	96.0	113.2	4.8	2.8	39.9	1.7	2.4	12.3	11.0	0.01	10.0	0.00	52.6

DDD: due date determination; U_m: mean utilisation; FGI: finished goods inventory; DEC: delivery compliance; POC: Planned Output Control; WIP_m: mean WIP; $TD_{m,act}$: mean actual delivery time; SCD: shop calendar day; SDT: standard delivery times; TT: throughput time; $TD_{\Delta,act}$: actual delivery time extension; M: mean value; LP_m: mean load percentage; BL_m: mean backlog; $TD_{m,plan}$: mean planned delivery time; SD: standard deviation; No.: experiment number; L: lateness; $TD_{\Delta,plan}$: planned delivery time extension.

Table A6. Results of the simulation study 1.3: basic condition (mean load = 105%).

DDD	LP_m [%]	No.	U_m [%]	WIP_m [#orders]	TT [SCD] M	TT [SCD] SD	BL_m [#orders]	L [SCD] M	L [SCD] SD	FGI [#orders]	$TD_{m,act}$ [SCD]	$TD_{\Delta,act}$ [SCD/SCD]	$TD_{m,plan}$ [SCD]	$TD_{\Delta,plan}$ [SCD/SCD]	DEC [%]
POC	105	1.3.1	91.9	57.8	2.6	1.5	−11.7	−0.4	1.4	35.6	14.8	0.12	16.8	0.11	92.3
	105	1.3.2	91.9	59.6	2.7	1.5	−9.4	−0.3	1.4	33.9	16.4	0.15	18.4	0.14	90.5
	105	1.3.3	93.8	59.8	2.6	1.6	−10.2	−0.4	1.5	36.2	13.7	0.12	15.6	0.11	88.9
	105	1.3.4	88.9	57.6	2.7	1.6	−9.3	−0.4	1.4	33.2	20.9	0.17	23.6	0.17	89.6
	105	1.3.5	91.4	56.6	2.5	1.5	−12.5	−0.5	1.3	36.5	16.0	0.16	18.3	0.14	92.5
	105	1.3.6	92.5	66.6	3.0	1.6	−2.5	0.0	1.5	29.6	17.0	0.13	18.4	0.11	83.6
	105	1.3.7	92.1	63.6	2.8	1.5	−5.9	−0.2	1.5	31.8	18.2	0.14	20.1	0.11	88.1
	105	1.3.8	91.7	62.1	2.7	1.5	−6.5	−0.3	1.4	31.7	16.7	0.15	19.1	0.15	89.5
	105	1.3.9	90.5	53.2	2.4	1.5	−14.5	−0.7	1.4	38.5	17.9	0.17	20.3	0.15	93.0
	105	1.3.10	91.9	56.7	2.5	1.4	−12.4	−0.5	1.3	36.5	14.7	0.12	16.8	0.12	92.1
SDT	105	1.3.11	96.4	198.4	8.2	4.0	122.8	5.1	3.5	3.2	14.4	0.04	10.0	0.00	17.4
	105	1.3.12	96.3	229.5	9.4	4.4	152.5	6.3	4.2	3.2	15.6	0.07	10.0	0.00	15.4
	105	1.3.13	96.6	211.8	8.6	4.1	134.9	5.5	4.0	4.0	14.8	0.06	10.0	0.00	20.1
	105	1.3.14	95.8	259.8	10.6	5.3	181.5	7.4	4.9	2.3	16.7	0.07	10.0	0.00	11.5
	105	1.3.15	96.2	223.6	9.2	4.9	146.9	6.1	4.6	3.0	15.4	0.07	10.0	0.00	19.2
	105	1.3.16	96.3	229.8	9.4	4.0	153.0	6.3	3.8	1.0	15.6	0.06	10.0	0.00	13.2
	105	1.3.17	97.2	232.8	9.6	3.6	156.6	6.5	3.4	1.2	15.8	0.05	10.0	0.00	6.6
	105	1.3.18	95.3	268.0	11.0	5.3	190.3	7.9	5.0	3.1	17.2	0.08	10.0	0.00	12.4
	105	1.3.19	95.9	232.1	9.5	5.3	155.0	6.4	5.0	7.3	15.7	0.08	10.0	0.00	24.4
	105	1.3.20	96.5	183.6	7.6	3.4	107.6	4.5	3.0	3.3	13.7	0.04	10.0	0.00	20.7
POC	105	Ø	91.7	59.4	2.6	1.5	−9.5	−0.4	1.4	34.4	16.6	0.14	18.7	0.13	90.0
SDT	105	Ø	96.3	226.9	9.3	4.6	150.1	6.2	4.3	3.2	15.5	0.06	10.0	0.00	16.1

DDD: due date determination; U_m: mean utilisation; FGI: finished goods inventory; DEC: delivery compliance; POC: Planned Output Control; WIP_m: mean WIP; $TD_{m,act}$: mean actual delivery time; SCD: shop calendar day; SDT: standard delivery times; TT: throughput time; $TD_{\Delta,act}$: actual delivery time extension; M: mean value; LP_m: mean load percentage; BL_m: mean backlog; $TD_{m,plan}$: mean planned delivery time; SD: standard deviation; No.: experiment number; L: lateness; $TD_{\Delta,plan}$: planned delivery time extension.

Table A7. Results of the simulation study 2.1: potentials (combination with ConWIP order release; EODD sequencing; mean load = 95%).

DDD	LP_m [%]	No.	U_m [%]	WIP_m [#orders]	TT [SCD] M	TT [SCD] SD	BL_m [#orders]	L [SCD] M	L [SCD] SD	FGI [#orders]	$TD_{m,act}$ [SCD]	$TD_{\Delta,act}$ [SCD/SCD]	$TD_{m,plan}$ [SCD]	$TD_{\Delta,plan}$ [SCD/SCD]	DEC [%]
POC	95	2.1.1	93.9	49.2	2.1	1.3	−37.8	−1.7	1.0	60.2	2.5	0.00	5.0	0.00	99.8
	95	2.1.2	95.7	50.7	2.1	1.1	−44.0	−1.9	0.9	66.8	2.6	0.00	5.3	0.00	100
	95	2.1.3	95.1	49.4	2.1	1.2	−40.9	−1.7	0.9	63.8	2.5	0.00	5.0	0.00	100
	95	2.1.4	94.0	62.9	2.7	1.9	−50.0	−2.3	1.8	72.9	4.9	0.00	8.0	0.01	98.9
	95	2.1.5	95.2	50.6	2.1	1.3	−47.8	−2.1	0.9	70.5	2.8	0.00	5.6	0.00	100
	95	2.1.6	95.6	48.8	2.0	1.2	−45.9	−2.0	0.9	68.6	2.5	0.00	5.2	0.00	100
	95	2.1.7	95.2	50.3	2.1	1.3	−50.3	−2.2	1.2	73.0	2.7	−0.01	5.6	−0.01	100
	95	2.1.8	94.3	62.4	2.7	1.3	−38.4	−1.9	1.7	60.9	4.1	0.00	6.8	0.02	99.9
	95	2.1.9	94.5	51.8	2.3	1.2	−55.1	−2.4	1.2	77.5	2.7	0.00	5.9	0.00	100
	95	2.1.10	94.0	42.3	1.9	1.3	−46.7	−2.0	0.9	69.1	2.2	0.00	4.9	0.00	100
SDT	95	2.1.11	93.8	49.7	2.1	1.0	−147.8	−6.7	1.0	169.6	2.5	0.00	10.0	0.00	100
	95	2.1.12	95.7	52.4	2.2	0.8	−146.9	−6.5	0.9	169.0	2.7	0.00	10.0	0.00	100
	95	2.1.13	95.2	50.3	2.2	0.9	−152.0	−6.6	0.9	174.2	2.5	0.00	10.0	0.00	100
	95	2.1.14	94.5	62.8	2.7	1.9	−109.8	−4.7	1.5	132.1	4.5	0.00	10.0	0.00	100
	95	2.1.15	95.1	51.1	2.2	1.0	−143.2	−6.4	1.2	165.5	2.8	0.00	10.0	0.00	100
	95	2.1.16	95.5	49.5	2.1	0.9	−149.9	−6.6	1.0	172.1	2.6	0.00	10.0	0.00	100
	95	2.1.17	95.3	51.1	2.1	1.0	−145.5	−6.5	1.2	167.7	2.7	−0.01	10.0	0.00	100
	95	2.1.18	94.4	62.5	2.7	1.3	−117.1	−5.1	1.0	139.4	4.1	0.00	10.0	0.00	100
	95	2.1.19	94.5	53.0	2.3	0.9	−147.9	−6.4	1.0	170.1	2.8	0.00	10.0	0.00	100
	95	2.1.20	94.0	42.2	1.9	0.9	−158.3	−7.0	0.9	180.1	2.2	0.00	10.0	0.00	100
POC	95	Ø	94.7	51.8	2.2	1.4	−45.7	−2.0	1.2	68.4	3.0	0.00	5.7	0.00	99.9
SDT	95	Ø	94.8	52.5	2.2	1.1	−141.8	−6.3	1.3	164.0	2.9	0.00	10.0	0.00	100

DDD: due date determination; U_m: mean utilisation; FGI: finished goods inventory; DEC: delivery compliance; POC: Planned Output Control; WIP_m: mean WIP; $TD_{m,act}$: mean actual delivery time; SCD: shop calendar day; SDT: standard delivery times; TT: throughput time; $TD_{\Delta,act}$: actual delivery time extension; M: mean value; LP_m: mean load percentage; BL_m: mean backlog; $TD_{m,plan}$: mean planned delivery time; SD: standard deviation; No.: experiment number; L: lateness; $TD_{\Delta,plan}$: planned delivery time extension.

Table A8. Results of the simulation study 2.2: potentials (combination with ConWIP order release; EODD sequencing; mean load = 100%).

					TT [SCD]			L [SCD]							
DDD	LP_m [%]	No.	U_m [%]	WIP_m [#orders]	M	SD	BL_m [#orders]	M	SD	FGI [#orders]	$TD_{m,act}$ [SCD]	$TD_{\Delta,act}$ [SCD/SCD]	$TD_{m,plan}$ [SCD]	$TD_{\Delta,plan}$ [SCD/SCD]	DEC [%]
POC	100	2.2.1	96.1	62.9	2.7	1.5	−29.0	−1.3	1.5	52.4	6.7	0.01	8.9	0.01	98.2
	100	2.2.2	96.8	62.9	2.7	1.3	−36.3	−1.5	1.4	59.5	7.3	0.03	9.5	0.03	99.8
	100	2.2.3	96.9	63.0	2.6	1.3	−22.0	−0.9	1.1	45.5	6.3	0.03	8.0	0.02	99.2
	100	2.2.4	94.2	63.0	2.7	2.0	−48.4	−2.1	1.9	71.4	10.0	0.05	13.2	0.06	97.4
	100	2.2.5	96.4	63.0	2.7	1.3	−41.5	−1.8	1.3	64.4	7.0	0.04	9.6	0.04	100
	100	2.2.6	97.0	62.9	2.6	1.4	−29.4	−1.2	1.5	53.2	6.8	0.02	8.9	0.02	97.3
	100	2.2.7	97.1	63.0	2.6	1.4	−34.5	−1.4	1.5	58.1	7.6	0.02	9.7	0.01	99.6
	100	2.2.8	94.1	62.9	2.7	1.5	−33.1	−1.5	1.6	55.8	9.7	0.06	12.3	0.07	99.0
	100	2.2.9	95.5	61.9	2.6	1.5	−53.5	−2.2	1.5	76.6	6.9	0.04	10.1	0.05	98.6
	100	2.2.10	96.4	62.9	2.7	1.4	−25.4	−1.2	1.3	48.7	6.0	0.01	8.0	0.02	99.5
SDT	100	2.2.11	96.1	63.0	2.7	1.5	−63.0	−2.6	1.6	86.0	6.5	0.01	10.0	0.00	100
	100	2.2.12	96.9	63.0	2.7	1.2	−53.1	−2.1	2.1	76.5	7.1	0.03	10.0	0.00	99.8
	100	2.2.13	97.2	63.0	2.6	1.3	−75.5	−3.0	2.0	98.9	6.2	0.03	10.0	0.00	99.7
	100	2.2.14	94.5	63.0	2.7	2.0	9.4	0.6	3.5	36.9	9.9	0.05	10.0	0.00	64.8
	100	2.2.15	96.5	63.0	2.7	1.3	−55.2	−2.2	2.5	79.7	7.0	0.04	10.0	0.00	95.4
	100	2.2.16	96.9	62.9	2.6	1.4	−54.9	−2.2	1.7	78.6	7.0	0.02	10.0	0.00	98.8
	100	2.2.17	97.3	63.0	2.6	1.3	−41.5	−1.8	1.8	65.0	7.4	0.02	10.0	0.00	99.4
	100	2.2.18	94.2	62.9	2.7	1.5	0.4	0.2	3.7	46.9	9.5	0.06	10.0	0.00	66.1
	100	2.2.19	95.3	61.8	2.6	1.5	−49.3	−1.8	3.3	77.0	7.4	0.05	10.0	0.00	86.1
	100	2.2.20	96.2	63.0	2.7	1.4	−73.0	−3.0	1.5	96.0	6.2	0.02	10.0	0.00	100
POC	100	Ø	96.0	62.8	2.7	1.5	−35.3	−1.5	1.5	58.6	7.4	0.03	9.8	0.03	98.9
SDT	100	Ø	96.1	62.8	2.7	1.5	−45.6	−1.8	2.8	74.1	7.4	0.03	10.0	0.00	91.0

DDD: due date determination; U_m: mean utilisation; FGI: finished goods inventory; DEC: delivery compliance; POC: Planned Output Control; WIP_m: mean WIP; $TD_{m,act}$: mean actual delivery time; SCD: shop calendar day; SDT: standard delivery times; TT: throughput time; $TD_{\Delta,act}$: actual delivery time extension; M: mean value; LP_m: mean load percentage; BL_m: mean backlog; $TD_{m,plan}$: mean planned delivery time; SD: standard deviation; No.: experiment number; L: lateness; $TD_{\Delta,plan}$: planned delivery time extension.

Table A9. Results of the simulation study 2.3: potentials (combination with ConWIP order release; EODD sequencing; mean load = 105%).

					TT [SCD]			L [SCD]							
DDD	LP_m [%]	No.	U_m [%]	WIP_m [#orders]	M	SD	BL_m [#orders]	M	SD	FGI [#orders]	$TD_{m,act}$ [SCD]	$TD_{\Delta,act}$ [SCD/SCD]	$TD_{m,plan}$ [SCD]	$TD_{\Delta,plan}$ [SCD/SCD]	DEC [%]
POC	105	2.3.1	96.1	62.9	2.7	1.4	−25.9	−1.1	1.4	49.2	11.1	0.06	13.3	0.06	97.7
	105	2.3.2	96.9	62.9	2.7	1.3	−31.9	−1.3	1.5	55.6	11.8	0.08	14.2	0.08	98.6
	105	2.3.3	96.9	62.9	2.6	1.4	−22.4	−0.9	1.3	46.5	10.9	0.08	12.8	0.07	96.8
	105	2.3.4	94.1	62.9	2.7	2.0	−43.6	−1.9	1.9	67.2	14.4	0.10	17.9	0.11	96.0
	105	2.3.5	96.5	63.0	2.7	1.4	−37.8	−1.6	1.4	60.9	11.7	0.09	14.3	0.08	99.8
	105	2.3.6	96.4	62.9	2.7	1.5	−21.6	−0.9	1.6	46.7	12.0	0.07	13.9	0.07	94.3
	105	2.3.7	97.6	62.7	2.6	1.4	−20.8	−0.8	1.3	45.4	11.6	0.06	13.6	0.05	96.2
	105	2.3.8	94.3	62.9	2.7	1.5	−26.9	−1.2	1.6	50.5	13.9	0.11	16.8	0.11	97.3
	105	2.3.9	95.4	62.9	2.7	1.7	−45.9	−2.0	1.6	69.2	11.8	0.10	14.9	0.09	98.0
	105	2.3.10	96.3	63.0	2.7	1.5	−27.7	−1.2	1.4	51.3	10.5	0.06	12.9	0.07	96.6
SDT	105	2.3.11	96.2	63.0	2.7	1.5	48.3	2.0	4.0	30.8	11.3	0.06	10.0	0.00	40.1
	105	2.3.12	97.1	63.0	2.6	1.3	57.8	2.3	4.6	34.7	11.6	0.08	10.0	0.00	41.4
	105	2.3.13	97.1	63.0	2.6	1.4	41.2	1.6	4.6	37.6	10.9	0.08	10.0	0.00	55.9
	105	2.3.14	94.4	63.0	2.7	2.0	125.0	5.3	6.0	19.0	14.5	0.10	10.0	0.00	27.6
	105	2.3.15	96.7	63.0	2.7	1.4	58.2	2.4	5.1	35.4	11.7	0.09	10.0	0.00	51.3
	105	2.3.16	97.1	62.9	2.6	1.4	58.5	2.4	4.3	28.9	11.7	0.07	10.0	0.00	41.4
	105	2.3.17	97.5	63.0	2.6	1.4	66.0	2.7	4.1	26.2	12.0	0.07	10.0	0.00	41.7
	105	2.3.18	94.1	62.9	2.7	1.6	112.4	4.7	6.2	26.2	14.0	0.11	10.0	0.00	34.9
	105	2.3.19	95.3	62.9	2.7	1.7	65.0	2.7	5.8	42.6	12.0	0.10	10.0	0.00	39.6
	105	2.3.20	96.2	63.0	2.7	1.4	39.3	1.6	4.0	33.5	10.9	0.07	10.0	0.00	45.4
POC	105	Ø	96.0	62.9	2.7	1.5	−30.4	−1.3	1.6	54.3	12.0	0.08	14.4	0.08	97.1
SDT	105	Ø	96.2	62.9	2.7	1.5	67.2	2.8	5.1	31.5	12.1	0.08	10.0	0.00	41.9

DDD: due date determination; U_m: mean utilisation; FGI: finished goods inventory; DEC: delivery compliance; POC: Planned Output Control; WIP_m: mean WIP; $TD_{m,act}$: mean actual delivery time; SCD: shop calendar day; SDT: standard delivery times; TT: throughput time; $TD_{\Delta,act}$: actual delivery time extension; M: mean value; LP_m: mean load percentage; BL_m: mean backlog; $TD_{m,plan}$: mean planned delivery time; SD: standard deviation; No.: experiment number; L: lateness; $TD_{\Delta,plan}$: planned delivery time extension.

Table A10. Results of the simulation study 3.1: robustness (ConWIP order release; EODD sequencing; mean load = 100%).

					TT [SCD]			L [SCD]							
DDD	LP_m [%]	No.	U_m [%]	WIP_m [#orders]	M	SD	BL_m [#orders]	M	SD	FGI [#orders]	$TD_{m,act}$ [SCD]	$TD_{\Delta,act}$ [SCD/SCD]	$TD_{m,plan}$ [SCD]	$TD_{\Delta,plan}$ [SCD/SCD]	DEC [%]
POC	100	3.1.1	92.8	62.9	3.5	1.8	−36.9	−2.3	2.0	55.1	12.8	0.05	16.7	0.07	97.4
	100	3.1.2	94.9	62.9	3.4	1.5	−1.0	0.0	1.6	24.0	11.0	0.06	12.4	0.06	84.4
	100	3.1.3	95.3	62.9	3.3	1.4	−2.8	−0.2	1.6	25.2	9.5	0.04	10.8	0.03	86.5
	100	3.1.4	91.8	62.9	3.5	1.7	−45.6	−3.5	2.5	63.6	16.1	0.08	21.7	0.11	98.7
	100	3.1.5	93.8	62.9	3.4	1.6	−21.0	−1.6	2.0	40.3	10.5	0.05	13.4	0.05	94.4
	100	3.1.6	95.1	62.8	3.3	1.5	−15.7	−0.6	1.8	36.7	10.4	0.03	12.2	0.02	84.7
	100	3.1.7	94.6	62.9	3.4	1.5	−19.7	−0.8	1.9	39.5	12.1	0.04	14.0	0.02	87.8
	100	3.1.8	92.8	62.9	3.5	1.5	−14.5	−1.6	2.4	34.6	13.8	0.08	17.3	0.10	92.1
	100	3.1.9	94.4	62.3	3.4	1.5	−59.0	−3.0	1.9	77.2	11.3	0.06	15.5	0.06	99.5
	100	3.1.10	93.9	62.9	3.4	1.5	−22.3	−1.6	1.7	40.8	9.3	0.03	12.2	0.04	97.5
SDT	100	3.1.11	92.5	62.9	3.5	1.6	41.8	3.7	4.7	24.0	12.7	0.06	10.0	0.00	32.4
	100	3.1.12	94.5	62.9	3.4	1.5	13.7	2.5	4.5	30.4	11.5	0.06	10.0	0.00	42.1
	100	3.1.13	95.5	62.9	3.3	1.4	−18.9	0.4	3.2	40.0	9.4	0.03	10.0	0.00	69.3
	100	3.1.14	91.9	62.9	3.5	1.6	81.5	7.1	6.3	11.7	16.1	0.08	10.0	0.00	18.7
	100	3.1.15	94.0	62.9	3.4	1.5	−0.9	1.6	4.3	38.2	10.6	0.05	10.0	0.00	56.4
	100	3.1.16	94.7	62.8	3.3	1.3	9.5	1.4	2.7	23.4	10.4	0.03	10.0	0.00	45.3
	100	3.1.17	95.0	62.9	3.4	1.4	42.2	3.0	3.4	17.0	12.0	0.04	10.0	0.00	34.9
	100	3.1.18	92.4	62.9	3.5	1.5	53.4	5.6	6.6	21.7	14.6	0.09	10.0	0.00	35.2
	100	3.1.19	94.9	62.2	3.4	1.4	0.6	1.7	4.2	32.7	10.7	0.05	10.0	0.00	40.8
	100	3.1.20	93.3	62.8	3.4	1.4	0.0	1.0	3.0	27.1	10.0	0.03	10.0	0.00	56.8
POC	100	Ø	93.9	62.8	3.4	1.6	−23.9	−1.5	2.3	43.7	11.7	0.05	14.6	0.06	92.3
SDT	100	Ø	93.9	62.8	3.4	1.5	22.3	2.8	4.9	26.6	11.8	0.05	10.0	0.00	43.2

DDD: due date determination; U_m: mean utilisation; FGI: finished goods inventory; DEC: delivery compliance; POC: Planned Output Control; WIP_m: mean WIP; $TD_{m,act}$: mean actual delivery time; SCD: shop calendar day; SDT: standard delivery times; TT: throughput time; $TD_{\Delta,act}$: actual delivery time extension; M: mean value; LP_m: mean load percentage; BL_m: mean backlog; $TD_{m,plan}$: mean planned delivery time; SD: standard deviation; No.: experiment number; L: lateness; $TD_{\Delta,plan}$: planned delivery time extension.

Table A11. Results of the simulation study 3.2: robustness (ConWIP order release; EODD sequencing; mean load = 105%).

					TT [SCD]			L [SCD]							
DDD	LP_m [%]	No.	U_m [%]	WIP_m [#orders]	M	SD	BL_m [#orders]	M	SD	FGI [#orders]	$TD_{m,act}$ [SCD]	$TD_{\Delta,act}$ [SCD/SCD]	$TD_{m,plan}$ [SCD]	$TD_{\Delta,plan}$ [SCD/SCD]	DEC [%]
POC	105	3.2.1	92.4	62.9	3.5	1.7	−25.5	−1.6	1.9	44.2	18.7	0.11	22.4	0.12	95.1
	105	3.2.2	95.1	62.9	3.4	1.6	−0.9	0.1	1.8	25.7	16.5	0.11	18.1	0.10	74.7
	105	3.2.3	95.5	62.9	3.3	1.5	−1.7	0.0	1.7	25.2	15.1	0.08	16.5	0.08	77.0
	105	3.2.4	91.7	62.9	3.5	1.7	−40.9	−2.9	2.2	58.8	21.5	0.14	27.3	0.17	98.2
	105	3.2.5	93.9	62.9	3.4	1.6	−13.3	−1.2	2.0	33.0	15.9	0.10	18.9	0.10	93.0
	105	3.2.6	94.9	62.8	3.3	1.5	−7.7	−0.3	1.9	30.1	16.8	0.08	18.6	0.07	83.2
	105	3.2.7	94.5	62.9	3.4	1.5	−10.4	−0.5	1.9	32.4	18.4	0.09	20.4	0.07	84.3
	105	3.2.8	93.2	62.9	3.5	1.6	−12.8	−1.0	2.0	33.1	19.2	0.13	22.9	0.15	89.2
	105	3.2.9	94.8	62.9	3.4	1.5	−53.9	−2.5	1.9	72.3	16.2	0.10	20.5	0.10	98.4
	105	3.2.10	93.3	62.9	3.4	1.5	−10.7	−1.1	1.9	30.7	16.1	0.09	19.1	0.10	92.3
SDT	105	3.2.11	92.7	62.9	3.5	1.8	131.8	9.3	7.8	15.3	18.3	0.11	10.0	0.00	20.8
	105	3.2.12	94.6	62.9	3.4	1.6	103.6	8.0	7.6	15.7	17.0	0.11	10.0	0.00	26.2
	105	3.2.13	95.2	62.9	3.3	1.4	76.9	6.4	6.4	15.8	15.4	0.09	10.0	0.00	22.3
	105	3.2.14	91.8	62.9	3.5	1.6	175.6	12.7	9.5	9.3	21.7	0.14	10.0	0.00	14.2
	105	3.2.15	93.6	63.0	3.4	1.6	92.1	7.4	7.6	18.4	16.4	0.11	10.0	0.00	24.5
	105	3.2.16	94.7	62.9	3.3	1.4	100.9	7.3	6.0	9.3	16.3	0.08	10.0	0.00	25.4
	105	3.2.17	94.8	62.9	3.4	1.4	139.5	9.1	6.8	8.5	18.1	0.09	10.0	0.00	21.2
	105	3.2.18	92.7	62.9	3.5	1.5	140.7	10.6	9.4	14.4	19.6	0.14	10.0	0.00	18.4
	105	3.2.19	94.8	62.9	3.4	1.4	91.1	7.4	7.5	21.4	16.4	0.11	10.0	0.00	25.5
	105	3.2.20	93.4	62.9	3.4	1.5	82.5	6.5	6.2	17.6	15.5	0.09	10.0	0.00	22.9
POC	105	Ø	93.9	62.9	3.4	1.6	−17.8	−1.1	2.1	38.5	17.5	0.10	20.5	0.11	88.5
SDT	105	Ø	93.8	62.9	3.4	1.5	113.5	8.5	7.8	14.6	17.5	0.11	10.0	0.00	22.1

DDD: due date determination; U_m: mean utilisation; FGI: finished goods inventory; DEC: delivery compliance; POC: Planned Output Control; WIP_m: mean WIP; $TD_{m,act}$: mean actual delivery time; SCD: shop calendar day; SDT: standard delivery times; TT: throughput time; $TD_{\Delta,act}$: actual delivery time extension; M: mean value; LP_m: mean load percentage; BL_m: mean backlog; $TD_{m,plan}$: mean planned delivery time; SD: standard deviation; No.: experiment number; L: lateness; $TD_{\Delta,plan}$: planned delivery time extension.

Table A12. Results of the simulation study 3.3: robustness (ConWIP order release; EODD sequencing; mean load = 110%).

DDD	LP_m [%]	No.	U_m [%]	WIP_m [#orders]	TT [SCD] M	TT [SCD] SD	BL_m [#orders]	L [SCD] M	L [SCD] SD	FGI [#orders]	$TD_{m,act}$ [SCD]	$TD_{\Delta,act}$ [SCD/SCD]	$TD_{m,plan}$ [SCD]	$TD_{\Delta,plan}$ [SCD/SCD]	DEC [%]
POC	110	3.3.1	92.6	62.9	3.5	1.8	−21.8	−1.4	2.0	41.1	23.3	0.16	27.4	0.17	93.0
	110	3.3.2	95.3	62.9	3.4	1.6	6.8	0.6	1.7	19.0	21.2	0.16	23.1	0.15	68.4
	110	3.3.3	95.2	62.9	3.4	1.5	0.9	0.3	1.9	23.0	20.3	0.14	22.2	0.13	69.2
	110	3.3.4	91.7	62.9	3.5	1.7	−38.8	−2.5	2.1	56.9	26.3	0.19	32.7	0.22	98.5
	110	3.3.5	93.5	62.9	3.4	1.7	−6.4	−0.9	2.2	28.8	21.2	0.16	24.4	0.15	85.8
	110	3.3.6	95.0	62.8	3.3	1.5	2.5	0.1	1.8	21.5	21.3	0.13	23.1	0.11	78.3
	110	3.3.7	94.7	62.9	3.4	1.5	−9.2	−0.5	1.9	31.3	22.8	0.15	25.4	0.12	82.3
	110	3.3.8	92.3	62.9	3.5	1.6	2.7	0.0	1.8	22.0	24.9	0.20	28.7	0.20	78.9
	110	3.3.9	95.3	62.9	3.4	1.6	−49.3	−2.2	2.0	68.0	21.0	0.15	25.4	0.14	94.9
	110	3.3.10	93.7	62.9	3.4	1.5	−7.2	−0.6	1.8	28.2	20.5	0.14	23.8	0.14	89.9
SDT	110	3.3.11	92.5	62.9	3.5	1.8	220.5	14.2	10.6	12.1	23.2	0.16	10.0	0.00	17.7
	110	3.3.12	94.5	62.9	3.4	1.6	196.6	13.0	10.4	10.7	22.0	0.16	10.0	0.00	17.2
	110	3.3.13	95.5	62.9	3.4	1.4	167.7	11.2	9.1	11.6	20.2	0.14	10.0	0.00	16.3
	110	3.3.14	91.9	62.9	3.5	1.7	262.7	17.1	12.1	7.0	26.1	0.19	10.0	0.00	13.1
	110	3.3.15	93.8	62.9	3.4	1.7	185.2	12.4	10.4	12.4	21.4	0.16	10.0	0.00	19.6
	110	3.3.16	94.8	62.8	3.3	1.4	187.9	12.0	8.8	5.9	21.0	0.13	10.0	0.00	14.1
	110	3.3.17	95.0	62.9	3.4	1.5	227.2	13.9	9.7	6.4	22.9	0.15	10.0	0.00	14.9
	110	3.3.18	92.5	62.9	3.5	1.6	232.0	15.3	12.3	11.9	24.3	0.19	10.0	0.00	16.7
	110	3.3.19	95.0	62.9	3.4	1.5	177.4	11.8	9.9	16.4	20.8	0.15	10.0	0.00	19.6
	110	3.3.20	93.3	62.8	3.4	1.5	174.6	11.5	9.1	12.0	20.5	0.14	10.0	0.00	19.2
POC	110	Ø	93.9	62.9	3.4	1.6	−12.0	−0.7	2.2	34.0	22.3	0.16	25.6	0.15	83.9
SDT	110	Ø	93.9	62.9	3.4	1.6	203.2	13.2	10.5	10.6	22.2	0.16	10.0	0.00	16.8

DDD: due date determination; U_m: mean utilisation; FGI: finished goods inventory; DEC: delivery compliance; POC: Planned Output Control; WIP_m: mean WIP; $TD_{m,act}$: mean actual delivery time; SCD: shop calendar day; SDT: standard delivery times; TT: throughput time; $TD_{\Delta,act}$: actual delivery time extension; M: mean value; LP_m: mean load percentage; BL_m: mean backlog; $TD_{m,plan}$: mean planned delivery time; SD: standard deviation; No.: experiment number; L: lateness; $TD_{\Delta,plan}$: planned delivery time extension.