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Adaptation of logistic operating curves to one-piece flow processes

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Abstract

Purpose – To provide a model for precise logistic controlling of one-piece flow processes and for the description of the interactions between logistic performance measures. The developed method can help manufacturing enterprises to control their production processes and therewith to exploit existing rationalization potentials in their production.

Design/methodology/approach – The Institute of Production System and Logistics adapted the logistic operating curve for schedule reliability and the logistic operating curve for mean throughput time to describe the behaviour of one-piece flow processes. This model-based method depicts the correlation between the delivery reliability and mean WIP level of single manufacturing systems and enables a goal-oriented modelling as well as a controlling of single manufacturing processes.

Findings – The derivation, calculation, and fields of application of the logistic operating curves for one-piece flow processes, that give a functional relationship between mean WIP, mean throughput time and schedule reliability, are presented in this paper. Moreover, the paper presents how the logistic performance measures can be adjusted to target values.

Originality/value – This paper offers practical help to manufacturing enterprises confronted with the task of evaluation and optimization of manufacturing processes within the framework of production controlling. Moreover, the developed method enables manufacturing enterprises to identify bottleneck work systems where action can be taken to optimize their schedule situation and thereby improve the delivery reliability of an entire manufacturing department.

Keywords Production planning and control, Production management, Distribution management, Delivery

Paper type Research paper

Introduction

The logistic performance measure delivery reliability plays a decisive role for enterprise success in the increased global competition for market share (Lödding, 2005; Wiendahl, 2002). In particular the importance of delivery reliability can be noticed at the forging industry. The reason is, that enterprises of this industry sector sell 70 percent of their goods to automobile manufacturers (Hirschvogel, 2001) and act as suppliers in just-in-time and just-in-sequence networks (Wiendahl and Ruta, 1999). Increasing expectation of the automobile industry concerning shorter delivery times and higher observance of delivery reliability (Boston Consulting Group, 2001) affect direct the forging industry (Barnett, 2000). According to the study of the Boston Consulting Group, costumers expect shorter delivery times in the future. Furthermore, the study proves that a differentiation about the product features is not sufficient anymore for being competitive, but the logistic performance measures delivery time and delivery reliability moved into the foreground under the aspect of the customer

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orientation (Elders *et al.*, 2003; Tracht and Reinsch, 2002; Spath *et al.*, 2001). For example, leading car manufacturers, Daimler Chrysler, BMW, Skoda etc., intend not to exceed a range of five days for all products between commanding data and delivery. Therefore the forging industry is exposed to an enormous pressure of time and is forced to realize the expected logistic performance concerning delivery times and delivery reliability.

In the production, high level of schedule reliability of single work systems is a prerequisite for accomplishing high level of delivery reliability (Lödding *et al.*, 2002). However, among WIP-level, throughput time, and utilisation schedule reliability is only one of several competing performance measures. A logistical orientation of a manufacturing enterprise with regard to the logistic performance measures only makes sense when their interactions are analyzed. For example, from an economic point of view besides short throughput times and high schedule reliability, high utilization and low work in process are important. There is no possibility for manufacturing enterprises to reach all of the four logistic objectives to the highest grade. A conflict exists between the logistic measures work in process (WIP), utilization, throughput time, and schedule reliability (see Figure 1).

Ensuring high utilization level of work systems requires high WIP level, but high WIP level induces long throughput times. As a result, the probability of order sequence modifications increases and consequently the schedule reliability decreases. This conflict between logistic objectives is commonly known as the "dilemma of operation planning" (Gutenberg, 1973). Thus, for an economic reasonable compromise with regard to the demanded delivery time and delivery reliability an integrated consideration of the logistic performance measures – work in process, utilization, throughput time and schedule reliability – is necessary.

In order to control this dilemma it is essential to analyze and to quantify the interdependencies between the logistic performance measures. Moreover, it is important to understand how the logistic performance measures can be adjusted to

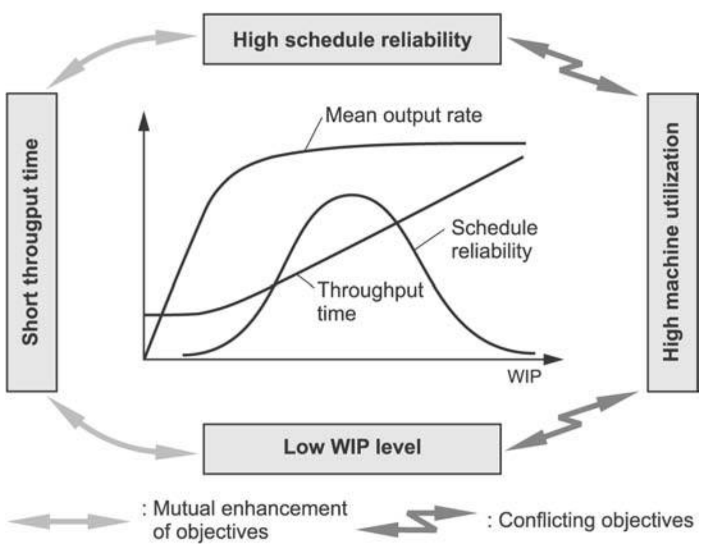

Figure 1. Logistic performance measures and the dilemma of operation planning

target values. For this purpose, the Institute of Production System and Logistics at the University of Hannover developed the theory of logistic operating curves (Wiendahl, 1995). These curves represent an approach for modelling and controlling of the logistic performance of single work systems which process orders under terms of classical lots. These curves describe how mean output rate, mean throughput time and mean schedule reliability of a work system change with the WIP level. The logistic operating curves for mean throughput time and mean output rate can be determined easily by the use of an approximation equation based on the production program, the operation sheets, the lot sizes, and basic capacity information. In addition, the shape of the logistic operating curve can be determined on the basis of Little's Law (Spearman and Hopp, 2000). The calculation of the logistic operating curves is accurately described in Nyhuis and Wiendahl (2002). Thus, enterprises are able to calculate the WIP level offering which offers the best compromise between throughput time, utilization and schedule reliability of a work system. This procedure is called logistic objective trade-off.

However, the logistic operating curves have not been applied so far to forging systems or processes because these systems are characterized by one-piece flow. For this reason, the Institute of Production System and Logistics (IFA) adapted the logistic operating curve for schedule reliability (LOCsr) and the logistic operating curve for mean throughput time (LOCtt) to describe the behaviour of one-piece flow processes, as they exist in a forging manufacturing department or a forging process chain for example. This research work is the one of several topics of the Collaborative Research Centre 489 ("Process chain for the production of precision forged high performance components") which is funded by the Deutsche Forschungs-gemeinschaft.

The derivation, calculation, and fields of application of LOCtt and LOCsr for one-piece flow processes, that gives a functional relationship between the mean WIP, mean throughput time and schedule reliability, is presented in this paper.

Adaptation of the logistic operating curve for mean throughput time to one-piece flow principle

The one-piece flow principle means that single parts are transferred between different operations instead of complete lots. This enables short throughput times and therefore a quick response to changing market requirements. Compared to processing orders under terms of classical lots manufacturing enterprises can realise a higher service level at a lower WIP level as in one-piece flow processes. However, uncomplex and implementable models for an integrated logistic design of one-piece flow processes are missing so far. Thus, throughput times of one-piece flow processes are normally determined by the use of complex simulations. For this reason the knowledge about logistic modelling of one-piece flow processes is less compared to classical lot-wise flow processes. The logistic operating curves for classical lot-wise flow processes describe the interdependencies between the logistic performance measures WIP level, throughput time, utilization and schedule reliability of work systems which process orders under the terms of classical lots (Nyhuis and Wiendahl, 2002). Therefore, it is obvious to adapt the logistic operating curves for classical lot-wise flow processes to one-piece flow processes. This adaptation was made on the basis of a forging process chain (see Figure 2) of a German components supplier who manufactures forging parts for the automobile industry. However, the results are universal valid for other industries. The analysis of the feedback data of the manufacturing department shows that the schedule reliability with respect to the planned schedule was 26 percent. This situation requires a high WIP-level in order to meet the arranged due dates.

The process in the multi-stage forging system starts with the cutting to length of raw material. Afterwards, the parts are heated up for the forging process. Subsequently, the forging process takes place. In a final step, the parts are heat treated before any further processing. All of these forging subsystems are interlinked by one-piece flow. In order to develop a logistic operating curve for mean throughput time for one-piece flow processes, the order time has to be defined. The order time describes the time-span which passes between initiating the forging system setup and completing the processing of the last part of an order at the last subsystem of the forging system. The order time of the multi-stage forging system for an order can be calculated as follows:

$$TO_{opf} = \frac{t_s + (LS - 1) \cdot t_p}{60} \quad (1)$$

where:

TO_{opf}: order time of the forging system (hrs)

t_s: setup time of the forging system (min)

LS: lot-size (unit)

t_p: process time of one unit (min/unit)

In some way, the four subsystems are combined in and modelled as one forging system. This method allows the application of the existing logistic operating curves to one-piece flow processes. The logistic operating curves for one-piece flow can be calculated like the existing logistic operating curves for lot-wise flow by the use of the defined order time (Nyhuis and Wiendahl, 2002). The logistic operating curves for one-piece flow was evaluated by several simulation experiments on the basis of real data of the German forging industry.

Figure 3 shows the comparison of the simulated and the calculated logistic operating curves for mean output rate and throughput time of a one-piece flow process.

It can be seen that the calculated logistic operating curves traces the simulated data points very well. The calculated mean relative deviation of the simulated and calculated data points of the logistic operating curves for one-piece flow processes was below 2 percent. This accuracy can be assessed as sufficient for everyday

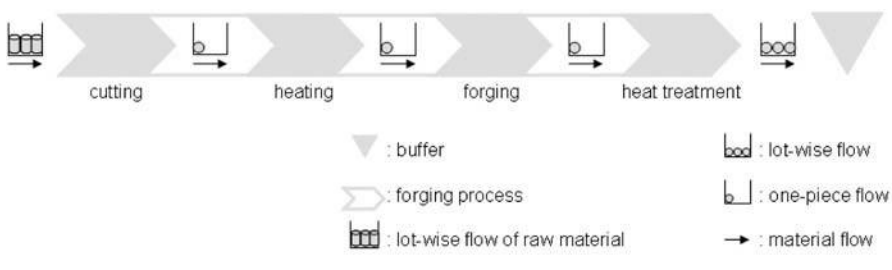

Figure 2.
Forging process chain

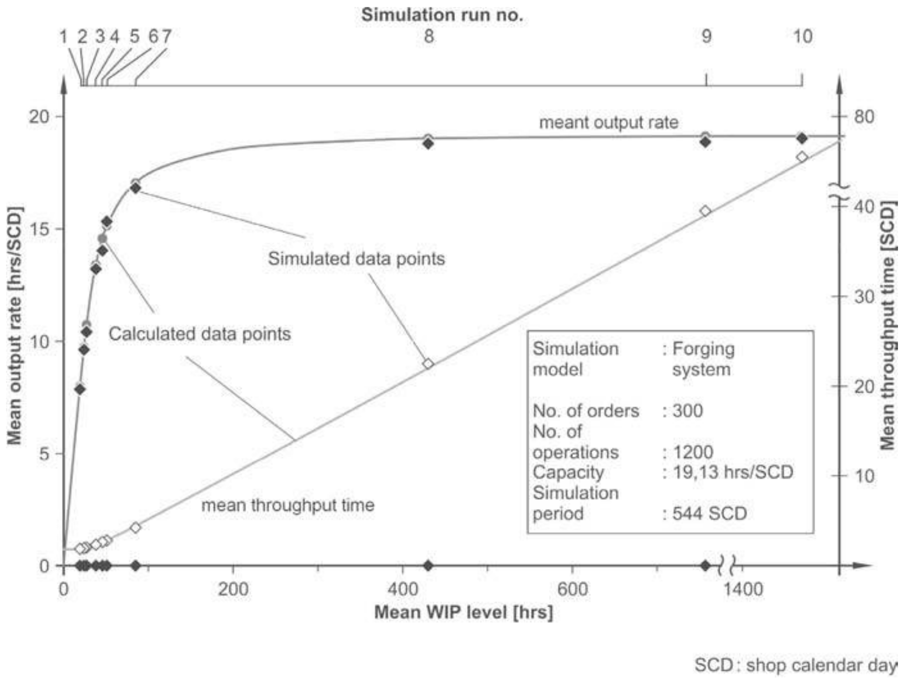

Figure 3.
Comparison of the simulated and the calculated data points of the logistic operating curves for one-piece flow processes

production management issues and proves the correctness of the approach. The simulation experiments therefore prove the correctness of the adapted approximation equations.

Definition of adherence to schedules and schedule reliability

Based on the logistic operating curves for mean output rate and mean throughput time for one-piece flow processes the missing logistic operating curve for schedule reliability has to be developed in order to allow an integrated logistic modelling of one-piece flow processes.

Before deducting the logistic operating curve for schedule reliability, it is important to explain the essential definitions and connections of adherence to schedules and schedule reliability in this chapter as they are different described in the international literature. Furthermore, they are employed differently in the practice. Numerous practical investigations of the Institute of Production Systems and Logistics (IFA) carried out within the framework of the Collaborative Research Centre 489 show that in particular the term schedule reliability is confused with the term adherence to schedules.

The schedule reliability describes the ratio of orders that are completed at a single work system within a defined schedule tolerance and the total number of completed orders at this work system:

$$SR = \frac{\sum_{i=1}^{n} O_{i,on}}{n} * 100\% \tag{2}$$

where:

- SR: schedule reliability (%)
- $O_{i,on}$: on schedule completed order (−)
- i: variable (−)
- n: amount of completed orders (−)

The schedule reliability reflects the company viewpoint (see Figure 4). On economic grounds, manufacturing enterprises are aligned to avoid completing orders before or behind the schedule date.

In addition, the schedule reliability influences the process ability of a work system (Pfeifer, 2001). For the definition of the schedule reliability, a schedule tolerance is to be determined with regard to a schedule-date to be met. Orders completed within the schedule tolerance are defined "on schedule". The schedule tolerance can be distributed symmetrically or asymmetrically around this schedule date (see Figure 5).

On the one hand, the schedule reliability is influenced by the distance between the mean value of the output due-date distribution and the schedule date to be met, on the other hand from the width of schedule tolerance and the width of output due-date distribution (see Figure 5).

Apart from the schedule reliability, from company viewpoint the adherence to schedules can be additionally defined from market point of view (see Figure 4). The adherence to schedules describes the ratio of orders that are completed at a single work

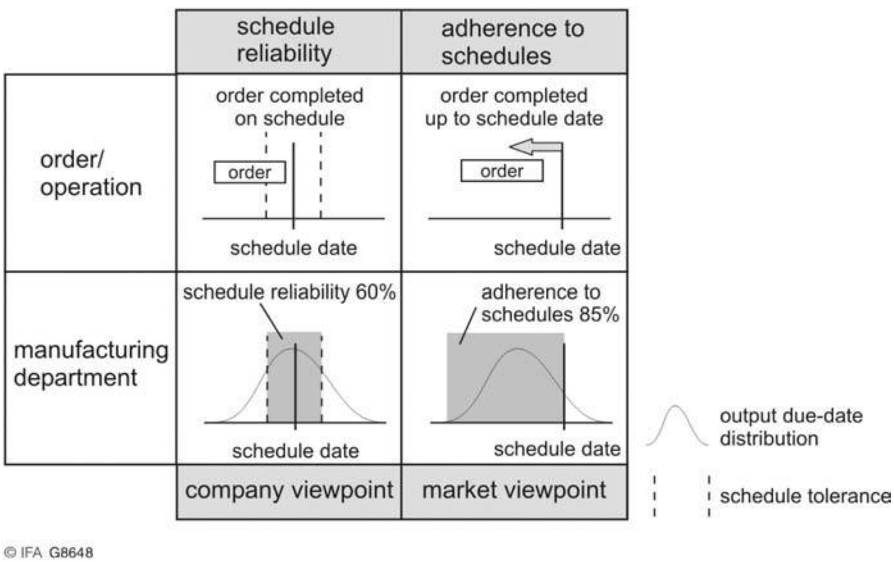

Figure 4. Definition of schedule reliability and adherence to schedules

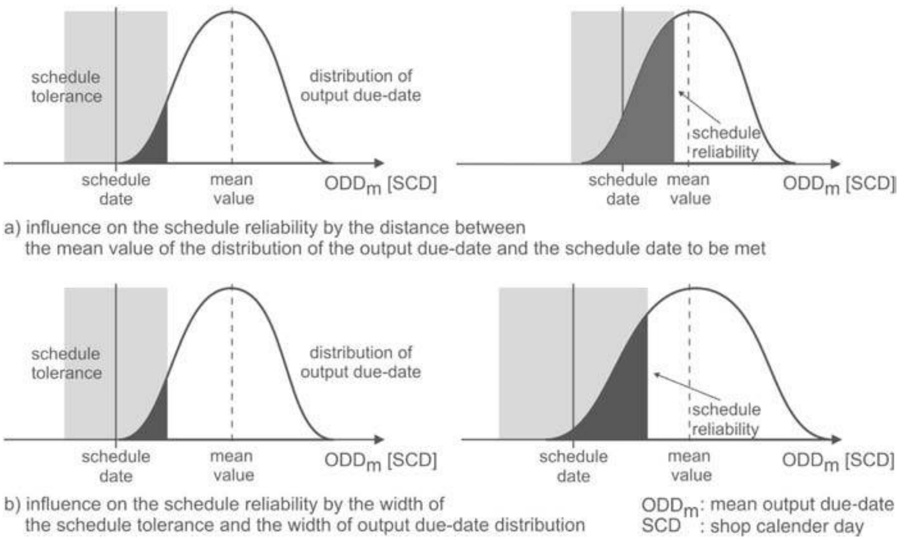

Figure 5.
Influence on the schedule reliability

system up to the schedule date and the total number of completed orders at this work system:

$$AS = \frac{\sum_{i=1}^{n} O_{i,up}}{n} * 100\% \qquad (3)$$

where:

AS: adherence to schedules (%)

$O_{i,up}$: up to schedule date completed orders (−)

Oi: completed orders (−)

i: variable (−)

n: amount of completed orders (−)

From the market point of view, only late completed orders reduce the adherence to schedules. The adherence to schedules is used as a logistic performance measure within the scope of production controlling regarding the schedule dates agreed with the customers. However, within the field of production the schedule reliability is used as evaluation measure in order to avoid unnecessary work in process level (WIP level). The schedule reliability of a single work system influences in combination with the schedule behaviour of the remaining work systems, which are integrated in the order process, the schedule reliability of manufacturing departments and the delivery date deviation to the customer (Yu, 2001).

Derivation of the logistic operating curve for schedule reliability for one-piece flow

The derivation of an approximation equation of the schedule reliability for single work systems of manufacturing departments is realized by the use of a deductive, experimental process model. The development of the process model, which was successfully used by the derivation of logistic operating curves (Nyhuis and Wiendahl, 2002), is based on the following steps:

(1) derivation of an ideal logistic operating curve for schedule reliability (ILOCsr) for ideal one-piece flow processes;

(2) extension of the ILOCsr in order to describe the schedule reliability of real one-piece flow manufacturing processes (development of the logistic operating curve for schedule reliability, LOCsr); and

(3) evaluation of the LOCsr by the use of simulation.

The derivation of the ideal logistic operating curve for schedule reliability (ILOCsr) is enabled by assumption of ideal process conditions. Thus, the relevant system behaviour can be described quite simply – in this case, the scope is defined by the ideal assumptions. The following features characterize this ideal state:

- no input due-date deviation;
- dispatching sequence of orders based on using first-in-first-out (FIFO);
- no distribution of planned and actual throughput times; and
- no distribution of planned and actual process times.

First, a mean planned throughput time is determined by a schedule method and the appropriate mean planned WIP level by the use of the logistic operating curves for one-piece flow processes (see Figure 3). Under ideal conditions, the schedule reliability of this work system only depends on the relative mean due-date deviation, which results from the difference of the mean planned and mean actual throughput times. Provided that the mean planned and the mean actual throughput time are identical (relative mean due-date deviation = 0) respectively that the mean planned and mean actual WIP level are equal, the schedule reliability of this work system amounts 100 percent under the indicated limiting conditions. An ILOCsr for a single work system can be seen in Figure 6(a). If the mean actual WIP level and the mean planned WIP level are identical, the schedule reliability reaches 100 percent, at all other mean actual WIP levels the schedule reliability amounts 0 percent (see Figure 6(a)). With usage of a schedule tolerance, a field of the ILOCsr arises in which the schedule reliability amounts 100 percent (see Figure 6(b)).

In that case, an order is completed on schedule, if the actual mean WIP level is between the upper and lower limit of the mean planned WIP level. In all other cases, the schedule reliability amounts 0 percent. The transitions of the schedule reliability from 0 percent to 100 percent are defined by the upper respectively lower limit of the schedule tolerance.

The assumption of no distribution of planned and actual throughput time for derivation of ILOCsr is not reachable in the manufacturing practice. Among others, this is shown by the wide distribution of output due-date deviation. Consequently, the course of the ILOCsr deviates from the real schedule reliability situation of the manufacturing department. Therefore, a real logistic operating curve for schedule

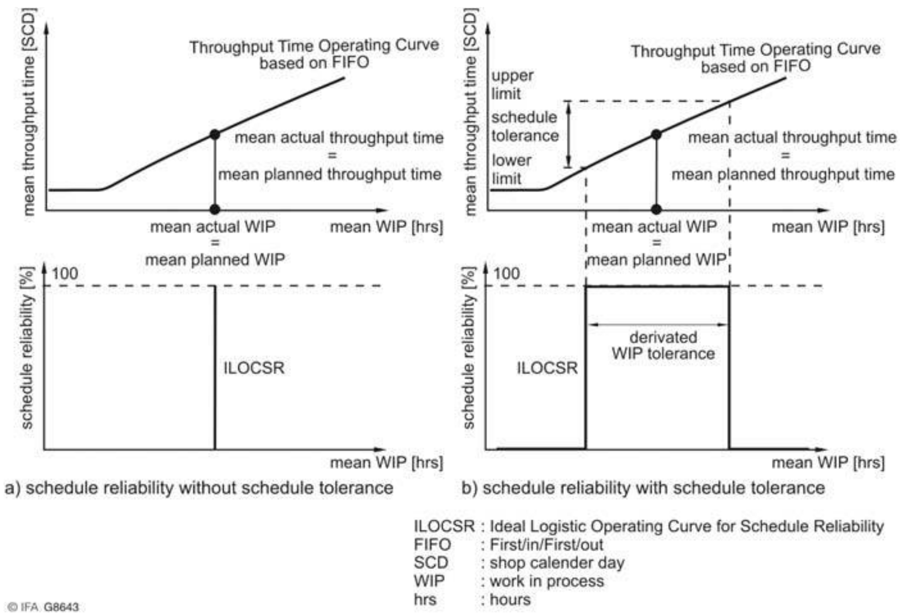

Figure 6.
Derivation of the ideal logistic operating curve for schedule reliability for one-piece flow processes

reliability (LOCsr) for one-piece flow processes is developed in this chapter, which is based on the ILOCsr and describes the real schedule reliability situation of a one-piece flow process of a manufacturing department.

The distribution of the inter-operation time (amount of waiting time and transit time (Nyhuis and Wiendahl, 2002)) between two work systems is the starting point for these considerations (see Figure 7). Under the assumption that the actual and planned operation time (ratio of order time and daily capacity (Nyhuis and Wiendahl, 2002)) are identical (no distribution of the process) and the planned inter-operation time is constant, the output due-date deviation respectively the LOCsr only depends on the distribution of the actual inter-operation time distribution.

The determination of a mean planned throughput time (e.g. 6 shop calendar days) and a schedule tolerance (e.g. +/− 1 shop calendar day) is the first step for the definition of the real schedule reliability of a single work system. The actual mean inter-operation time (e.g. 4.5 shop calendar days) as well as the distribution function of the inter-operation time (cumulative percentage) can be determined by the distribution of the actual inter-operation time. Starting from the schedule tolerance as well the upper and lower limits as the corresponding upper and lower probabilities for the inter-operation time can be determined. The schedule reliability results in the difference of the upper (85 percent) and lower (22 percent) probability of the distribution function of the inter-operation time (see Figure 7). The schedule reliability amounts 63 percent in the example. Under the assumption, that actual and planned WIP level are identical (see Figure 7), this value corresponds to the practical maximum schedule reliability at the same time. The practical maximum schedule reliability defines the value of the schedule reliability, which a single work system cannot exceed with the given logistic conditions and the defined schedule tolerance. Actual and planned WIP levels are often not identical in the manufacturing

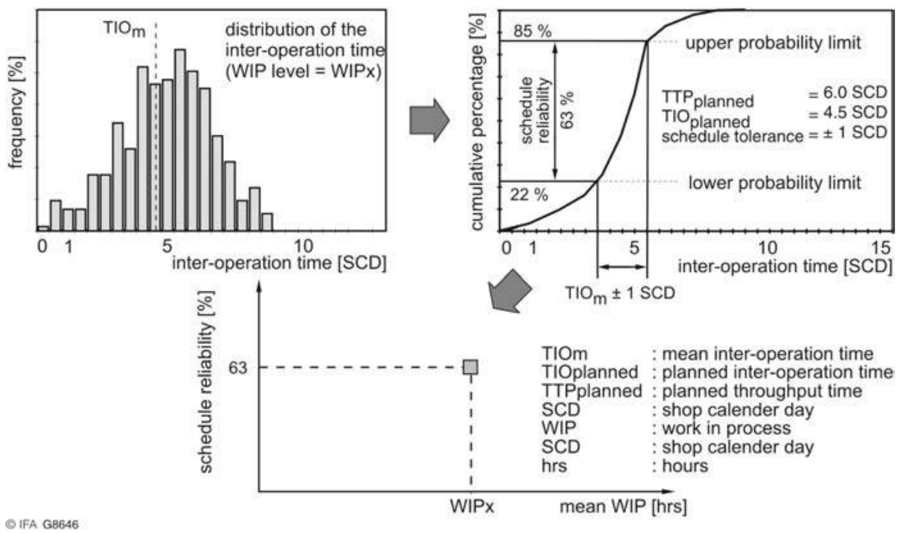

Figure 7.
Definition of schedule reliability by the use of inter-operation time distribution

practice. Therefore, it is necessary to determine the practical maximum schedule reliability of a single work system by analyzing the distribution of the inter-operation time at different mean WIP levels. The goal is to get a complete mathematic description of the practical maximum schedule reliability depending on the mean WIP level (LOCsr). In this regard, simulation experiments with varied mean WIP levels of a single work system show that the corresponding inter-operation distribution functions run parallel to each other (see Figure 8).

This means that the standard deviations of the inter-operation time are nearly identical apart from the field of a high mean WIP level (> 92.7 hrs). However, this field is not relevant in the manufacturing practice because from the economic point of view a low mean WIP level is aimed for in order to reduce the costs in the

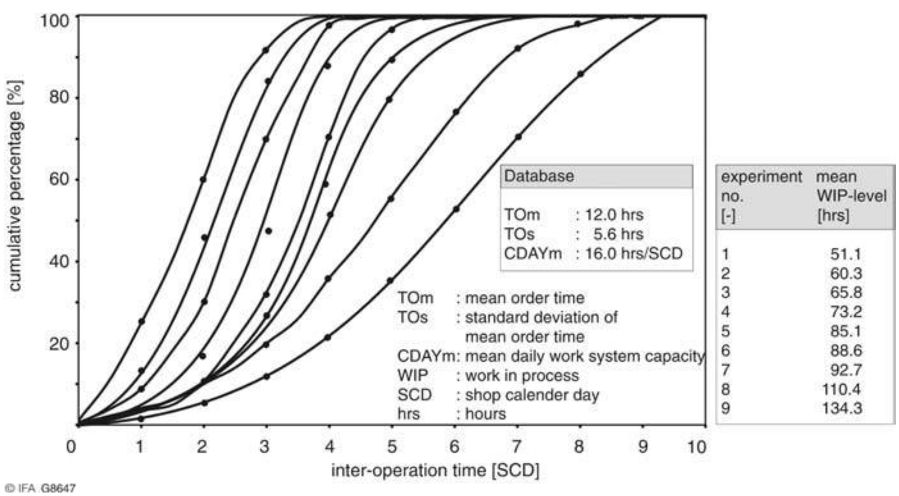

Figure 8.
Inter-operation time depending on WIP level

manufacturing department. Furthermore, the distribution of the inter-operation time of a single work system is a normal distribution in general (Ludwig, 1996), under the assumption of using the dispatching sequence FIFO. The practical maximum schedule reliability of a single work system can then be calculated like the probabilities of a normal distributed random variable x with a mean value μ and a standard deviation σ by the use of the distribution function (u) of the standard normal distribution (Yu, 2001; Winston, 1997):

$$P(LL \leq x \leq UL) = \phi\left(\frac{UL - \mu}{\sigma}\right) - \phi\left(\frac{LL - \mu}{\sigma}\right) \tag{4}$$

where:

P: probability (%)

LL: lower interval limit (−)

UL: upper interval limit (−)

μ: mean value (−)

σ: standard deviation (−)

(u): distribution function of the standard normal distribution (−)

Through the introduction of the corresponding logistic parameters in equation (4) follows for the approximation equation of the LOCsr:

$$SR(WIP(t)) = \phi\left(\frac{UL - TIO_m(WIP(t))}{TIO_S}\right) - \phi\left(\frac{LL - TIO_m(WIP(t))}{TIO_S}\right) \tag{5}$$

where:

SR: schedule reliability (%)

LL: lower interval limit (−)

UL: upper interval limit (−)

TIO_S: standard deviation of inter-operation time (SCD)

TIO_m: mean inter-operation time (SCD)

WIP: work in process level (hrs)

t: variable $(0 \leq t \leq 1)$ (−)

The upper and lower interval limits define the interval within an order is determined as “on schedule”. Because of the result that the distribution of the inter-operation time by using the dispatching sequence FIFO is independent of the WIP level, the standard deviation of inter-operation time can be determined on the basis of any actual distribution of the inter-operation time. By the use of the characteristic curve theory developed by Nyhuis (Nyhuis and Wiendahl, 2002) the mean throughput time and with it the mean inter-operation time can be calculated as follows:

$$TIO_m(t) = TT_m(t) - TOP_m \tag{6}$$

where:

$TIO_m(t)$: mean inter-operation time (SCD)

$TT_m(t)$: mean throughput time (SCD)

TOP_m: mean operation time (SCD)

t: variable $(0 \leq t \leq 1)$ (−)

For the evaluation of the approximation equation of the LOCsr, several simulation runs were carried out where the mean WIP level was varied specifically. All other parameters remain unchanged during the simulation experiments. For every simulation run the mean WIP level and the schedule reliability are measured. The mean relative deviation of the calculated data points from the simulated ones was below 5 percent.

The LOCsr for one-piece flow processes offers the possibility to describe the correlation of schedule reliability and mean WIP level of a single one-piece flow process of a manufacturing department. LOCsr enable a goal-oriented modelling as well as a controlling of single manufacturing processes.

Applicability of the operating curve for schedule reliability for one-piece flow processes

The LOCsr for one-piece flow processes allows a quantitative and qualitative description of the logistic connection between the mean WIP and the schedule reliability of single work systems. This enables manufacturing enterprises to identify bottleneck work systems where action can be taken to optimize their schedule situation and thereby improve the delivery reliability of the entire manufacturing department. Although for the derivation of the LOCsr it is assumed that no input due-date deviation is existing, it represents an ideal basis for verifying the process ability of a manufacturing enterprise. Thus, the LOCsr is suited for the evaluation of manufacturing process within the framework of a production controlling. It shows which schedule reliability can be achieved with the present structural conditions. In addition, the LOCsr combined with the other operations curves set up by Nyhuis (Nyhuis and Wiendahl, 2002) enables an economic reasonable logistic compromise between the different logistic performance measures (von Cieminski *et al.*, 2001). Therewith it is possible to determine logistic rationalization potentials and to model production processes. Subsequently the different possible applications of the LOCsr are introduced in the following part.

An instrument, with which the orientation of the corporate activities towards the enterprise success is supported, is the production controlling. On condition of, that the LOCsr can be derived, their possible field of application within the production controlling extends from the target declaration over the process visualization and evaluation up to the potential analyses (see Figure 9).

The schedule reliability defines the process ability of a single work system (Pfeifer, 2001). The reason is that the process ability describes if a process is able to reach the demanded schedule. Thus, by the use of the LOCsr the quality of the process ability can be evaluated by estimating the maximum schedule reliability with the existing structural constraints (see Figure 9(a)). Dependent on the specific work system

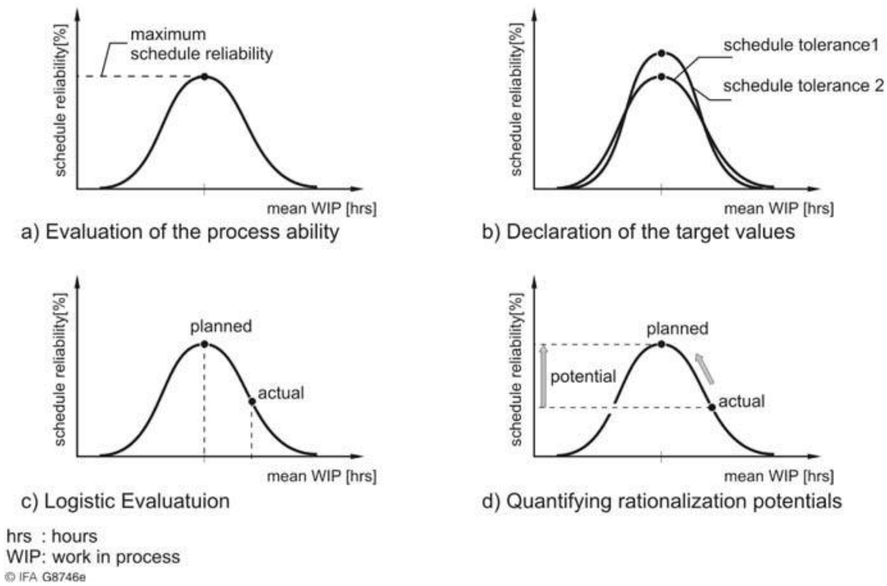

Figure 9.
Possible applications of the real LOCsr for one-piece flow processes

conditions, target values can be declared for the schedule tolerance or schedule reliability. In Figure 9(b) it can be seen for example that a determined schedule tolerance led to corresponding schedule reliability and vice versa. If the schedule reliability is quantified, a logistic evaluation of the actual state can be made according to the planned state (see Figure 9(d)). Finally, the LOCsr can be used in order to quantify rationalization potentials.

Logistic objective trade-off

The contradiction between a high schedule reliability, short throughput times and low WIP on the one hand and a high utilization on the other hand is a problem in the manufacturing practise. As mentioned before, the logistic operating curves offer an effective support for solving that problem. By the use of the logistic operating curves, a so called "logistic objective trade-off" can be realized. Logistic objective trade-off of processes means the definition of a value of a logistic performance measure and the derivation of the concluding remaining logistic performance measures in consideration of their interactions (Figure 10).

The LOCsr enables the first time a model-based logistic objective trade-off regarding all logistical performance measures. Thus, for realizing the schedule reliability, which is demanded by the market, the needed values for the throughput time, WIP, and utilization can be determined.

In analogy, a procedure to improve the schedule reliability in the manufacturing department can be built up by the use of the LOCsr (see Figure 11).

First, the logistic operating curves and the initial state operating point must be built up. Second, the decrease of the WIP is often the next step to increase the schedule reliability. Thus, it is the task of the production control to decrease the existing WIP in order to be able to achieve the maximum of the schedule reliability

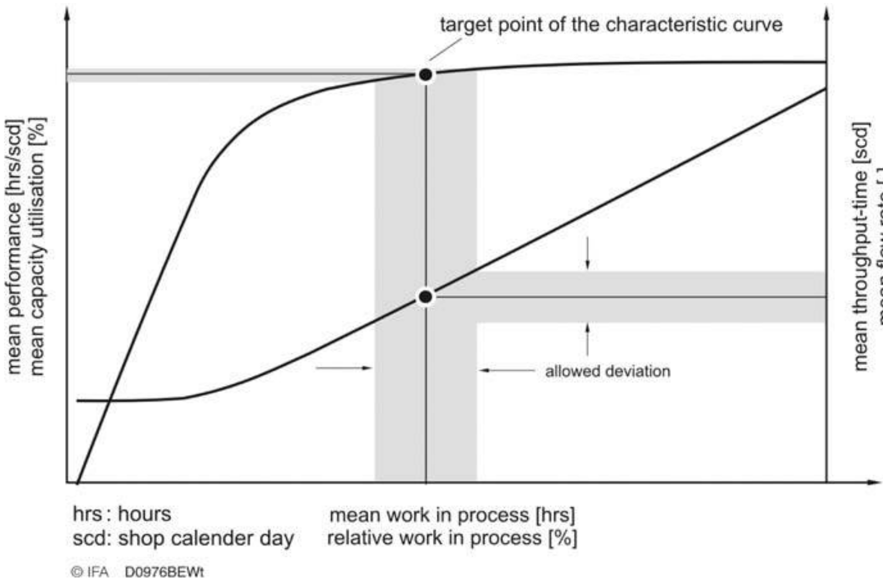

Figure 10.
Logistic objective trade-off with logistic operation curves

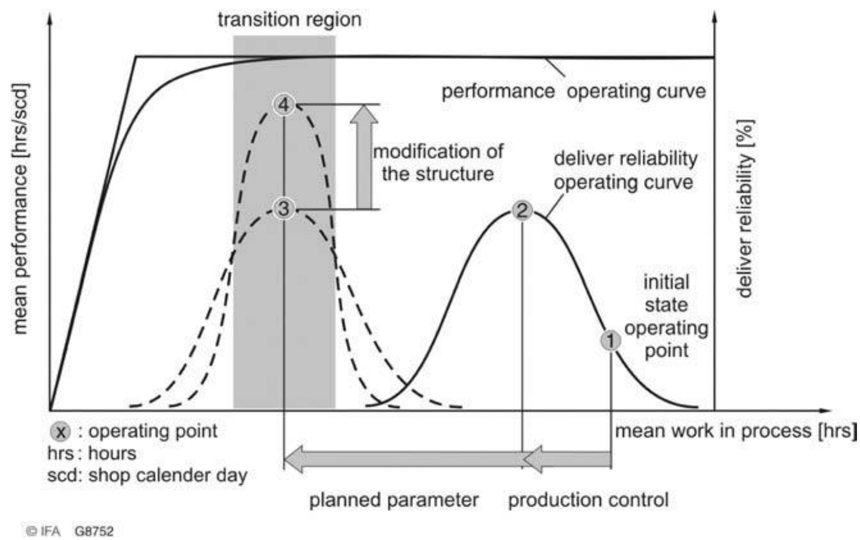

Figure 11.
Steps to the improvement of the schedule reliability in a manufacturing department

(see Figure 11, operating point 2). By the use of the logistic operating curves, in a further step it can be decided whether the targeted WIP level is in the transition region (adequate field) of the logistic operating curve. Through a shift of the operating point in this field (objective trade-off) an goal-oriented tuning of the logistic performance measures throughput time, utilization, WIP and schedule reliability can be realized (see Figure 11, operating point 3). In a next stage further potentials can be created (for example capacity flexibility) through a modification of the structure (see Figure 11, operating point 4).

Practical use of the work to industry

The logistic operating curves for one-piece flow processes improve the understanding of the interdependencies of the logistic performance measures. The paper shows that a goal-oriented variation of the WIP-level is the key for realizing short delivery times and high delivery reliability. Conditional on adaptation of the existing models to one-piece flow processes the application of logistic operating curves is enhanced from job shop manufacturing to serial productions. Implementing the presented results in a production planning and control system, enterprises are able to optimize the logistic performance of their manufacturing departments. Furthermore, the results can be used for the development of cost account methods in order to evaluate logistic costs.

Conclusion

The strategic importance of short delivery times and high delivery reliability is undisputed. Manufacturing enterprises that are able to supply their customers faster, more surely, and more economically have better chances in the global competition. In this context, the adaptation of the logistic operating curve for mean throughput time to the one-piece flow principle allows an integrated logistic description of one-piece flow processes. Thus, the theory of the logistic operating curves is enhanced from the focus on the lot-wise flow to the one-piece flow principle for the first time. With that description, a precise logistic controlling of one-piece flow processes, e.g. forging systems is possible. Furthermore, through the model based description of the interactions between the logistic performance measures, manufacturing enterprises have the possibility to model production processes and therewith to exploit existing rationalization potentials in their production within the framework of an integrated logistic objective trade-off of one-piece flow systems, e.g. forging systems.

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