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Logistic Target Achievement In Scope Of The Lead Time Syndrome Of Manufacturing Control

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*Validation Of The Syndrome
And Development Of A Methodology To Avoid It In Practice*

by

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Abstract

The aim of production planning and control is to ensure the achievement of the logistic targets while maintaining productivity and quality targets. If order due dates are missed, a common intuitive reaction of production planners is to adjust planned lead times. How often and to what extent updates are reasonable has previously been unclear because, while trying to improve the logistic target achievement, planned lead time adjustments may actually cause an opposite effect, which is known as the Lead Time Syndrome of Manufacturing Control (LTS). Although the LTS was described as early as 1977, the cause-and-effect relationships in the LTS still have not been sufficiently investigated. Thus, this thesis has the overall target of investigating the influence of the LTS of manufacturing control on logistic target achievement by firstly validating the LTS line of argumentation by Mather and Plossl (1977) and secondly developing a roadmap to mitigate the LTS in practice. For the validation initially a mathematical model of LTS interactions by means of the Funnel Model and statistics is presented, which also enables determining the main triggers of the LTS. The insights are then validated and extended in a control theoretic model of the LTS and transferred into strategies to avoid or dampen the LTS. Finally, the derived propositions are evaluated and confirmed in a case study of a job-oriented manufacturing process. To develop a roadmap in the second step, the questions of *when, how often, and on which value should planned lead times be adjusted* are addressed. The results are finally transferred into a methodology to avoid the LTS in practice. In summary, this thesis validates the LTS line of argumentation and shows the relevance of the problem in today's manufacturing systems. The roadmap finally transfers the results from theory into practice to support planners in the process of decision-making and prevent accidentally wrong adjustments that might lead to a decrease in performance.

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List of Abbreviations

a	actual
c	capacity [h/SCD]
COV	covariance
CV	coefficient of variation
d	delay [SCD]
DR	due date reliability [%]
ERP	Enterprise Resource Planning
FR	Flow Rate [-]
h	hours
j	period of investigation / averaging period
k	current period
k_c	magnitude of response of capacity adjustments [-]
k_p	magnitude of response of planned lead time adjustments [-]
KDD	Knowledge Discovery in Databases
L	lateness [SCD]
Low/Up	lower/upper limit of due date tolerance [SCD]
LS	lot size [units]
LTS	Lead Time Syndrome
m	mean
MRP	Material Requirements Planning
$MRP II$	Manufacturing Resource Planning
n	adjustment period length [SCD]
n_{actual}	actual adjustment period length [SCD]
$n_{suitable}$	suitable adjustment period length that avoids the LTS [SCD]
N	number of simulation runs
p	planned
P	simulation periods
PPC	Production Planning and Control
R	range [SCD]
$ROUT$	output rate [h/SCD]
SCD	shop calendar day
sd	standard deviation
tio	interoperation time [SCD]
tl	lead time [SCD]
top	operation time [SCD]

tp	processing time [min/unit]
ts	setup time [min]
VAR	variance
WC	work content [h]
w_e	work output deviation [h]
w_i	work input [h]
WIP	work in process [h]
w_o	work output [h]

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*“If people don’t understand the problem,
they won’t understand the solution”
(Wight 1984)*

1 Introduction

1.1 Problem, Motivation, and Research Question

The shifting priorities of customers and the increasing competitive pressure in terms of, e.g., reductions in costs, shorter product life cycles, consistent high quality, increasing complexity, and the integration of new technologies have led to continuous changes and challenges in manufacturing systems¹ (Schönsleben 2012; Wiendahl 2014). This introductory section gives initially a brief overview of some of the mentioned problems in manufacturing. This includes a lack of logistic awareness of production planners for the interdependencies and interactions of the logistic targets, the often observed poor quality of planned lead times, and finally the increasing complexity of production² networks. These problems are able to reduce logistic performance, which can lead to countermeasures by production planners such as planned lead time adjustments in order to increase it. However, such countermeasures can lead into the Lead Time Syndrome of manufacturing control (LTS). Thus, this section introduces the LTS line of argumentation, shows the topicality of this syndrome, and finally presents the guiding research question of this thesis to investigate it.

Targets and a lack of logistic awareness

Uncertainties, fluctuations, and too high work in process levels are only a few reasons for a low proportion of orders that are produced on time and thus result in a low due date reliability. Due date reliability is one of the four targets of manufacturing control, which are short lead times, low work in process levels, high capacity utilization, and high due date reliability (Nyhuis 2009b; Wiendahl 2014). However, these targets are contradicting. The trade-off between logistic targets became known by the name ‘dilemma of operations planning’, which stated that short lead times and high capacity utilization cannot be achieved simultaneously (Gutenberg 1951). A high capacity utilization requires a high work in process level, which also leads to long lead times. While the focus in logistics was on high capacity utilization in the past, it shifted more and more to low lead times and high due date reliability (Koether 2008). Thereby, the increasing complexity of networked production systems and the missing awareness of production planners for the

¹ Manufacturing is defined as “a series or interrelated activities and operations involving the design, materials selection, planning, production, quality assurance, management and marketing of the products of the manufacturing industries.” (CIRP 1990) as cited in (Bellgran 2010).

² Production is defined as “the act or process (or the connected series of acts or processes) of actually physically making a product from its material constituents, as distinct from designing the product, planning and controlling its production, assuring its quality.” (CIRP 1990) as cited in (Bellgran 2010).

interdependencies and interactions of the logistic targets often leads to problems while trying to improve them, as decisions based on intuition and experience are likely to be wrong (Wiendahl 2005; Schönsleben 2012). The problems that arise with these decisions are described next.

Poor quality of planned lead times

In order to improve the logistic target achievement, production planners often take precautions. These are taken to deal with uncertainties that arise for example in demand predictions or disturbances in supply chains and production systems (Lindau 1995; Kingsman 1997; Vollmann 2005; Hopp 2008; Riezebos 2009). In this context, Lindau (1995) observed that safety stocks (71.4%), safety capacities (92.9%), safety lead times (78.6%), and overplanning (64.3%) are most commonly used in planning systems. Moreover, orders are, e.g., accelerated (85.7%) or subcontracted (92.9%) manually. If planned lead times increase due to these safety actions, also the standard deviation of lead times increases (Nyhuis 2009b). This is due to the increasing probability of disturbances, such as sequence deviations of planned schedules (Patig 1999). These disturbances lead to deviations between planned and actual lead times, thus result is a reduction in due date reliability. As a consequence, planners often tend to set planned lead times too long in the effort to increase due date reliability once again (Wight 1984; Plossl 1988; Lindau 1995). Thereby, Production Planning and Control (PPC) systems often lack the support to define and maintain planned values (Nyhuis 2010). This leads to a poor quality of planned lead times, which is observed even in more sophisticated PPC-systems (Nyhuis 2010).

Increasing complexity

The complexity of production networks makes it according to Wiendahl and Schönsleben impossible for planners to anticipate effects of variable adjustments correctly (Wiendahl 2005; Schönsleben 2012). However, the complexity of manufacturing systems increased drastically in the past decades (Hu 2008). For example, product variety, as one indicator for complexity, increased from 84 car models in 1973 to 142 models in 1989 (MacDuffie 1996). Today, the BMW 7 series can already be configured in 10^{17} variants (Hu 2008; Roy 2011). Thus, planners have to deal with uncertainty about current system states, future demands, disturbances and many more, which can lead to misinterpretations or overreactions. A common example is given by the ‘Beer Distribution Game’ in which planners have to estimate parameter settings for a linear distribution system (Sterman 1989). One of the observed outcomes is that the participants attributed the observed fluctuations to external events rather than to their own actions, thus leading to renewed inadequate adjustments. In short, the so-called ‘bullwhip effect’, which led to poor system performance, was observed (Moscoso 2011; Sterman 1989).

The Lead Time Syndrome of Manufacturing Control

The lack of logistic understanding, the poor quality of planned lead times, and the increasing complexity of production networks can lead to a low logistic

performance as described by the Lead Time Syndrome (LTS) of manufacturing control. Mather and Plossl (1977) were the first to describe the phenomenon of the LTS. Their line of argumentation was a logical deduction of a likely occurring cascade of problems that reinforce themselves. Thus, they named this chain reaction *the vicious cycle*, which is presented below (Mather 1977; Plossl 1988).

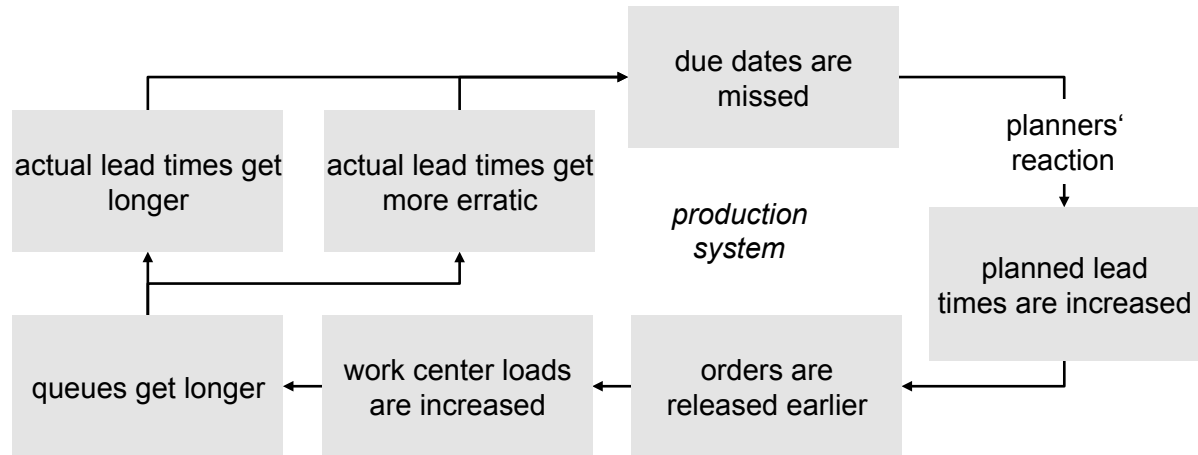


Figure 1.1 Lead Time Syndrome of manufacturing control (based on (Mather 1977; Wiendahl 1997a))

The LTS starts with the initial observation of production planners that due date reliability is on a low level. As prior planned lead times were apparently set too short to produce in time, it seems sensible for production planners to increase the planned lead times to allow more time for product completion. Due to the predominantly applied backward scheduling, orders are released earlier. Thus, some orders that were initially planned to be released in later periods are now released in the current period, which leads to a sudden increase in current workloads of the work stations. With an increasing workload and constant capacities, the work in process (WIP) levels increase and also both mean and standard deviation of the actual lead times increase. Finally, this circle of mistakes leads to an even lower due date reliability (in comparison with the initial situation), although the aim of production planners was to improve it with a planned lead time adjustment. Thus, the decreased due date reliability once again demands improvement measures. Eventually, the number of tardy orders increases and expediting of selected orders leads to an increased number of rush orders (which are highly prioritized orders) that lead to high sequence perturbations. This once again causes an increasing lead time standard deviation and wasted production capacity, e.g., due to increased set up times. In theory this leads to a vicious circle, which continues until mean and standard deviation of lead times reach a very high level (Mather 1977; Plossl 1988; Wiendahl 1997a; Wiendahl 2005).

Topicality

Although the phenomenon of the LTS was first described in 1977, the problem described by the LTS is still just as valid now as it was back then. As stated above, the LTS was observed in systems using backward scheduling (Mather 1977; Wiendahl 2005). At that time, simple, not computer-aided, scheduling techniques

such as forward or backward scheduling were the prevailing technologies to meet logistic targets. As backward scheduling provides the latest possible time slot to produce in time (Schönsleben 2012), a lower inventory level is aspired to (Kumar 2006). In spite or because of its simplicity, backward scheduling is still a very common approach in practice. For example, if ERP software like SAP is used for scheduling, classical backward scheduling is used (Balla 2006). The missing support in determining plan values and a lack of PPC-Controlling to monitor the logistic target achievement often lead into the situation described by the LTS, as the intuitive reaction of planners is to adjust planned lead times instead of, e.g., controlling capacities (Plossl 1988; Higgins 1996b; Wiendahl 2005; Nyhuis 2010). However, on one hand the emergence of the LTS in practice was merely discussed by fictive examples (see (Mather 1977; Selçuk 2007; Hopp 2008)), but not confirmed by means of descriptive analysis such as case studies. On the other hand, the cause-and-effect relationships in the LTS still have not been sufficiently investigated.

Focus areas and guiding research question of this thesis

The presented conceptual description of the LTS by Mather and Plossl did not include a formal analysis of the described effects. Furthermore, the LTS “is a particularly illustrative example of how little is known about the actual interdependencies between manipulated and observed variables“ (Wiendahl 2005). This quotation shows that it is still an open question regarding how the planned lead time adjustment affects other logistic key figures and in particular the resulting due date reliability. For example, if planned lead time adjustments lead to an increase in lead time standard deviation as proposed by the LTS. Thus, the first focus area of this thesis is the validation of the LTS line of argumentation, which includes a derivation of the impact of planned lead time adjustments on the resulting due date reliability. The resulting insights into the interactions of the logistic variables that lead to the LTS drawbacks (i.e. decrease in due date reliability) then enable a derivation of strategies to avoid or dampen the impact of the LTS and thus to increase logistic performance of a company.

The reaction of planners to adjust planned lead times specifies the main reason why the chain reaction described by the LTS is able to lead to a vicious cycle. Due to the lack of knowledge about the correlations between the logistic targets, the planners tend to define too long planned lead times and to adjust them too often in terms of the given system states. This leads into a system state with long and erratic lead times that are accompanied by a low due date reliability. The lack of support of PPC systems in defining and maintaining planned lead times amplifies this effect. Thus, the second focus area of this thesis is to answer the question of how can possibly wrong decisions of planners to adjust planned lead times be avoided, which includes the question of how they should react to avoid the LTS in practice.

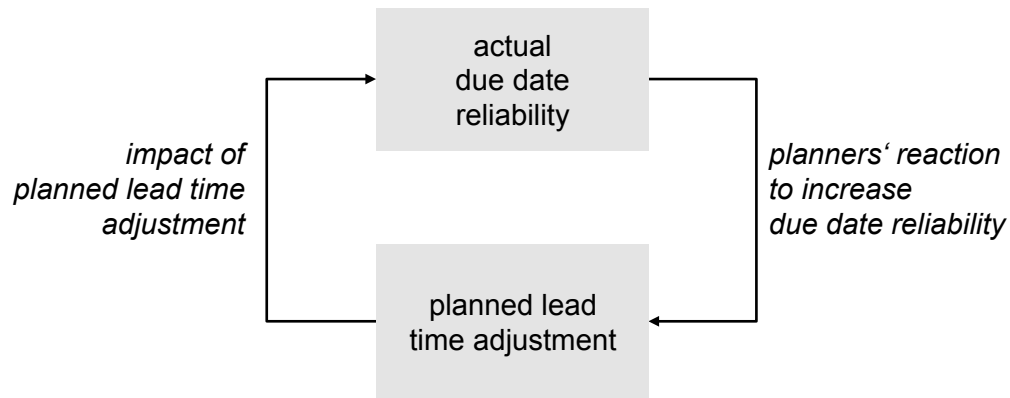


Figure 1.2 Two focus areas to investigate the LTS

Figure 1.2 assigns these two focus areas into the condensed version of the LTS. It shows that the central questions in terms of the LTS investigation are, *how does a planned lead time adjustment affect due date reliability*, and *how can possibly wrong decisions of planners to adjust planned lead times be avoided?* These questions are combined in the following guiding research question of this thesis:

Guiding research question:

How does the LTS affect the logistic target achievement of manufacturing control and which methodologies can planners apply to avoid it?

This guiding research question is approached in this thesis by six objectives that are presented in the next section and serve as milestones for the investigation of the LTS. The initial focus lies on the understanding of the LTS, which is required to derive reasonable and comprehensible strategies to avoid it. This approach is supported by the quotation of Wight (1984), who is regarded as one of the inventors of Manufacturing Resource Planning (MRP II):

“If people don’t understand the problem, they won’t understand the solution”
(Wight 1984)

1.2 Objectives and Methodology

This thesis has the overall target to investigate the influence of the LTS of manufacturing control on the logistic target achievement. The derived new insights then enable to merge the derived strategies into a roadmap that determines how to mitigate the LTS in practice. Several objectives have to be defined to investigate the focus areas that were mentioned above. These serve as milestones for the investigation of the LTS. They are presented below with a brief description of the approach and methods used to work on them. A detailed reasoning for the choice of each of the defined methods is presented when they are first introduced in this thesis.

Objective one: Validate the line of argumentation of the Lead Time Syndrome.

Objective two: Reveal interactions that trigger the Lead Time Syndrome.

To validate the LTS line of argumentation presented by Mather and Plossl (1977), initially each step of the LTS has to be investigated individually to prove the correctness of the underlying logic. Therefore, methods from statistics and logistic equations that are based on the Funnel Model (Nyhuis 2009b) are applied to derive the LTS interactions mathematically. This mathematical model then enables the identification of main relationships that lead to a reduced performance as measured in due date reliability, thus to reveal interactions that trigger the LTS.

Objective three: Validate the derived interactions of the mathematical investigation of the Lead Time Syndrome.

Objective four: Define strategies to avoid the Lead Time Syndrome.

The derived interactions and identified triggers of the LTS in the mathematical approach have to be validated, which is done using a control theoretic simulation model. Moreover, a control theoretic model enables the targeted manipulation of parameter settings, and thus a more detailed investigation of LTS triggers. This provides the basis to define strategies to damp or to avoid the LTS.

Objective five: Evaluate and confirm the derived propositions in a real system.

Both initial approaches are subject to assumptions and limitations. Thus, a final evaluation and confirmation of the derived propositions is needed to prove the applicability of the research results on problems in practice. Data collected from a manufacturing system provides the data for a case study in which two system states are evaluated. A scenario in which planners set values based on their gut feelings (worst case of LTS) and a second scenario in which a planning system enables justified adjustments.

Objective six: Develop a roadmap of strategies to avoid the Lead Time Syndrome.

The investigation of the impact of planned lead time adjustments on the resulting due date reliability provides the fundamental basis for developing a roadmap that defines strategies for how to avoid the LTS in practice for different environmental conditions. This roadmap defines *when, how often, and on which value* to adjust planned lead times. To determine the question of when to adjust planned lead times, an additional control theoretic investigation is needed in this context to test if *capacity control* serves as an alternative to *planned lead time control*³ for specific parameter settings. Also, for the question of how often to adjusted planned lead times a methodology is presented to define a suitable adjustment period length, which also proposes a strategy for situations in which planned lead times have to be adjusted more frequently. Finally, for the question of on which value to adjust planned lead times to maintain high system performance an extension of the

³ The method to adjust planned lead times will be referred to as planned lead time control in this thesis.

Logistic Positioning approach is presented, which is based on the Funnel Model theory.

The presented six key objectives serve as milestones for the investigation of the LTS and the derivation of strategies to avoid it in practice. The following section presents the outline of this thesis, which is based on these milestones.

1.3 Approach and Thesis Outline

For the investigation of the LTS this thesis is subdivided into seven main chapters, including this introductory chapter. The outline is structured according to the objectives presented in the previous section to answer the guiding research question. Thereby, Table 1.1 maps the relationships between the main chapters, the applied methods and the objectives of this thesis.

II. State of the Art and Definitions

Chapter two starts by laying out the theoretical dimensions of the research. Therefore, initially the relevant definitions of fundamental logistic key figures in the scope of the LTS are presented. This also includes the introduction of the Logistic Operating Curve theory, which is commonly used to describe production processes and to determine their operating states. Then, a brief overview of the evolution of Production Planning and Control (PPC) is given to show the context in which the LTS emerges. This includes the Aachen PPC model, Enterprise Resource Planning, a model of manufacturing control, and, finally, a model that links PPC, control theory, and the LTS. Besides the theoretic foundations, previous research on the LTS also is presented. Finally, these are brought together in the definition of the research gap.

III. Mathematical Modeling of Lead Time Syndrome Interactions and Triggers

Chapter three is concerned with validating the LTS line of argumentation by means of a mathematical model using statistical methods and logistic functions that are based on the Funnel Model. Thus, the impact of planned lead time adjustments on the resulting due date reliability is quantified. Then, using the derived interactions, situations are outlined that support the emergence of the LTS, and reasons for a diminishing or low due date reliability are determined.

IV. Control Theoretic Derivation of Lead Time Syndrome Interactions and Triggers

The interactions and triggers of the LTS derived in the mathematical investigation are validated in Chapter four using a control theoretic investigation. Therefore, initially a control theoretic simulation model with planned lead time control as control strategy is developed and validated. Then, cause-effect relationships between planned lead time adjustments and a decreasing due date reliability are evaluated for varying parameter settings. Finally, the simulation results are transferred into strategies to damp or, if possible, avoid the LTS.

V. Single Case Study: Evaluation of LTS Effects and Confirmation of Propositions

Chapter five presents the results of a descriptive case study of a manufacturing company. This evaluates and illustrates the effects of the LTS interactions in a real system to confirm the derived propositions. Therefore, initially the underlying manufacturing process is presented in detail, including the reasons for choosing the specific unit of analysis (i.e., a real manufacturing process) and the process of data validation. Then, observations of two different periods of investigation are presented. The first illustrates the worst case steady state of the LTS, while the second enables the observation of effects of planned lead time adjustments in a running manufacturing system, and thus observation of the impacts of the LTS on the resulting due date reliability.

VI. Development of a Roadmap to Face the Lead Time Syndrome

In chapter six, methodologies are developed to dampen or avoid the LTS. Therefore, the theoretical results from chapter three to chapter five are transferred into practice by finding answers to each of the following questions: *When, how often, and on which value should planned lead times be adjusted.* To answer the first question it is tested if capacity control is a better manufacturing control strategy as compared to planned lead time control. For the second and the third question, the research results from the previous chapters are transferred into a methodology of how often and on which value to adjust planned lead times. The research results are finally merged in a roadmap to deal with the LTS in practice.

VII. Conclusion

The final chapter of this thesis gives a summary of the presented research results and includes a critical discussion of its limitations, transferability and generalizability. Finally, implications for science and practice and areas for further research on the LTS are identified.

Table 1.1. Applied methods, approach, and objectives of this thesis.

Methods	Approach	Objectives
	Introduction	
	Chapter 2 State of the Art <ul style="list-style-type: none"> ▪ introduce fundamentals of production logistics ▪ discuss other research on the LTS ▪ identify research gap 	
<ul style="list-style-type: none"> ▪ Funnel Model ▪ Statistics 	Chapter 3 Mathematical Investigation <ul style="list-style-type: none"> ▪ mathematical LTS derivation ▪ determine main LTS triggers 	1. validation of LTS line of argumentation 2. derivation of LTS interactions
<ul style="list-style-type: none"> ▪ Simulation 	Chapter 4 Control Theoretic Investigation <ul style="list-style-type: none"> ▪ develop a control theoretic model ▪ model validation ▪ control theoretic investigation of LTS interactions 	3. validation of LTS interactions 4. derivation of strategies to avoid LTS
<ul style="list-style-type: none"> ▪ Case Study 	Chapter 5 Descriptive Case Study <ul style="list-style-type: none"> ▪ choice and description of a case ▪ observation of a worst case LTS situation ▪ observation of planned lead time adjustments in a running system with PPC 	5. evaluation and confirmation of derived propositions
<ul style="list-style-type: none"> ▪ Simulation ▪ Funnel Model 	Chapter 6 Roadmap Development <ul style="list-style-type: none"> ▪ test of capacity control as alternative to planned lead time control ▪ determine how often and on which value to adjust planned lead times 	6. roadmap to avoid LTS
	Conclusions	

2 State of the Art and Definitions

This chapter gives an overview of the fundamental concepts for the investigation of the LTS and presents the current state of research. Therefore, Section 2.1 introduces the definitions of logistic key figures in scope of the investigation of the LTS and presents the targets of manufacturing control. As these targets are conflicting, the theory of the Logistic Operating Curves is presented, which is well established in scientific and specialist literature in the German-speaking region to describe production processes and to determine their operating states. Section 2.2 gives a brief overview of the evolution of PPC with a focus on tasks and key elements of commonly used models. Section 2.3 presents previous research on the LTS interactions. The presented overview of the research fundamentals and research on the LTS is finally brought together in the definition of a research gap in Section 2.4.

2.1 Definition of the Targets of Manufacturing Control

For the investigation of the LTS, a description and definition of fundamental logistic key figures and variables affected by the LTS (see Figure 1.1) is essential. These fundamentals are based on the relevant literature in the field of manufacturing. Two main models have been established in scientific literature (Nyhuis 2009b): Little's Law (see, e.g., (Conway 1967)) and the quite similar Funnel Model (see, e.g., (Kettner 1981)). While the first is implemented, e.g., in queuing theory (see, e.g., (Erlang 1909; Gross 2008)) or clearing functions (see, e.g., (Karmarkar 1989; Missbauer 2011; Armbruster 2012)), the latter is implemented, e.g., in throughput diagrams and the Logistic Operating Curves (see, e.g., (Wiendahl 1995; Wiendahl 1997a; Nyhuis 2009b)). The Funnel Model is well established in the German-speaking region to describe production processes and has been chosen in this work to investigate the LTS. This section introduces briefly key definitions and refers to the cited publications for more detailed explanations. To investigate the LTS initially the term 'lead time' has to be defined in the context of the LTS in Section 2.1.1, as a wide range of definitions and terms are given in literature. Section 2.1.2 introduces the targets of manufacturing control upon which the impact of the LTS on the logistic target achievement becomes quantifiable. This also includes the definition of due date reliability, which is the final variable in the line of argumentation of the LTS that is monitored by production planners. Finally, Section 2.1.3 presents the Funnel Model and the Logistic Operating Curves, which are commonly used to describe production processes.

2.1.1 Definition and Components of Lead Time

The terms ‘throughput time’ and ‘lead time’ are often used synonymously (Plossl 1988). As the *Lead Time Syndrome* is being investigated, the term *lead time* is used in this work for simplification. The lead time is defined as the time period that an order requires to get through a work system after arrival (Plossl 1988).

Part (a) of Figure 2.1 depicts the operation-related ‘throughput element’ for a more detailed definition (Wiendahl 1997a). This throughput element defines the lead time as the time period between the end of the predecessor and the end of the order processing at the respective operation. For an initial work system the order release defines the moment of the end of the process predecessor. After processing, each order waits to be transported to the next operation, then transported, and finally waits to be processed. The sum of these three elements defines the interoperation time. The operation time is the sum of the set up and processing time. The lead time is the sum of the interoperation time and the operation time. In a job shop production operation times can differ significantly. Thus, Bechte introduced the two-dimensional throughput element (see part (b) of Figure 2.1), which includes the work content in the dimension of hours on the vertical axis (Bechte 1984).

To enable a comparison of work systems and calculate standardized values in job shop production, the calculated time periods have to exclude non-working days such as weekends or holidays. Therefore, all calculations are processed in the time format of shop calendar days (SCD), which sequentially numbers all working days (Nyhuis 2009b).

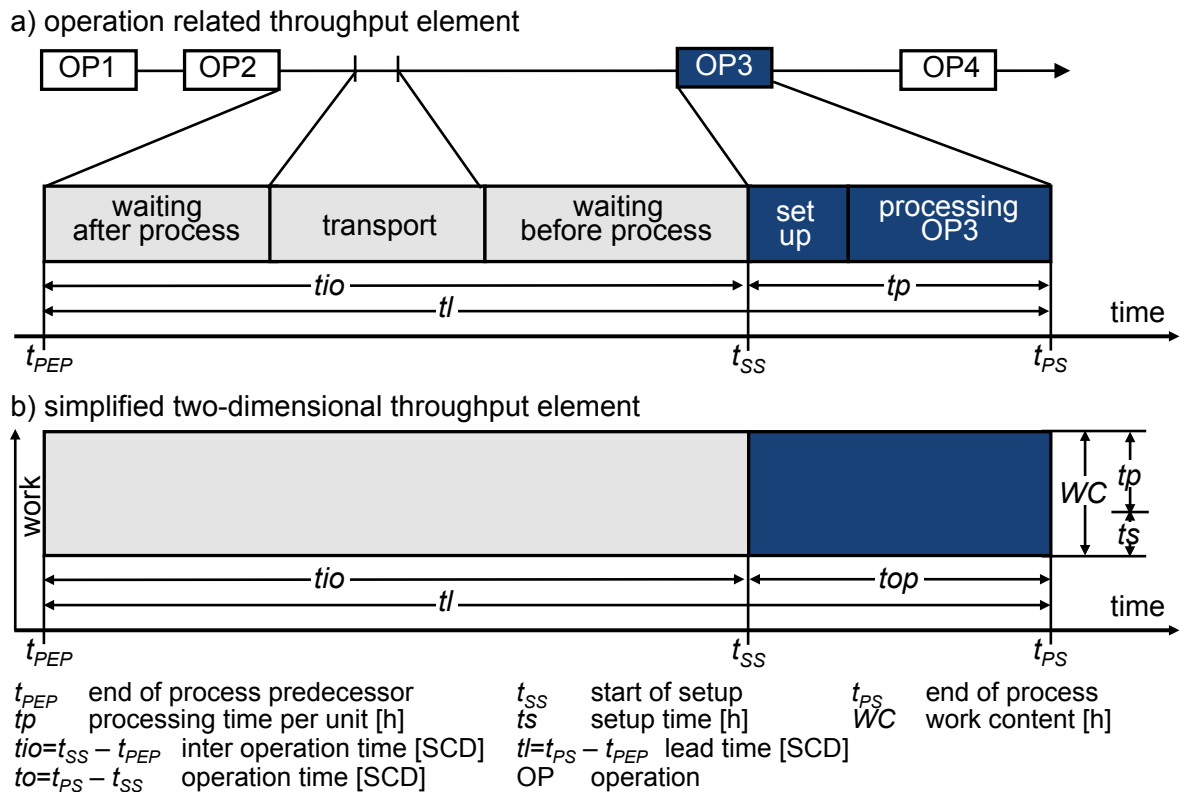


Figure 2.1 Lead time components and throughput element (Wiendahl 1997a)

Equation 2.1 shows the correlation between operation time and work content. Thereby, the work content results from the sum of the setup time for each lot and the product of lot size and processing time per piece.

$$top = \frac{WC}{ROUT_{max}} = \frac{ts + LS \cdot tp}{ROUT_{max} \cdot 60}$$

Equation 2.1

top	operation time [SCD]
WC	work content [h]
$ROUT_{max}$	maximum possible output rate [h/SCD]
ts	setup time [min]
tp	processing time [min/unit]
LS	lot size [units]

It can be assumed that the interoperation time of an order is independent from the individual operation time (for operation time independent order scheduling) (Ludwig 1995). In practice, the interoperation times can comprise between 90% and 98% of total lead times⁴ (Plossl 1988; Wiendahl 1995; Hyer 2002; Nyhuis 2009b). In addition, only interoperation times are affected by changing WIP levels (increased waiting time), hence directly affecting lead times. Therefore, a separated consideration of interoperation and operation times is unnecessary in terms of the investigation of the LTS and referred to as lead time in the following, unless stated otherwise.

2.1.2 Targets of Manufacturing Control and their Trade-off

The logistic performance determines the success of a manufacturing company and contributes significantly to its competitiveness in the market (Hon 2005; Enslo 2006). Therefore, this section introduces key figures to measure logistic performance, which allows to assess the quality of production planning decisions and hence to quantify the deteriorating effects of the LTS.

The performance of manufacturing systems can be defined as the level of achievement of logistic targets. Nyhuis and Wiendahl (2009) defined the targets of production logistics as short lead times and high due date reliability from the customer perspective and low WIP levels and high capacity utilization from the company perspective. Figure 2.2 shows the described target system with economic efficiency as overarching objective, hence minimizing costs per unit. The WIP level is defined as the sum of orders that are processed or waiting to be processed. A low WIP level means low tied-up capital of unfinished goods, requires less storage areas and hence minimizes non-value-adding material handling costs. The minimal delivery time of a customer order is given by the lead time, the time period from order release to finished product. Therefore, short lead times satisfy the customers' wish of short delivery times while enabling a higher level of process flexibility.

⁴ Exemplary Nakao calculated an average lead time of 44 SCDs and an average element operation time of 20 minutes in manufacturing injection molding molds for cellular phones (Nakao 2002).

Moreover, a consequence of short lead times is a reduced lead time variability which increases due date reliability (Yu 2001; Nyhuis 2009b) (see also Section 3.3.1). Due date reliability is defined as the number of orders produced within a due-date tolerance in proportion to the total number of produced orders. A high due date reliability reduces possible costs of both tardy and too early deliveries. If orders are finished too early, inventory costs or quality problems of sensitive goods (e.g., corrosion) may arise. If orders are delivered too late, contract penalties and dissatisfied customers can lead to unpredictable costs. The probability with which a manufacturing system is producing goods at a given point in time is given by the capacity utilization. A higher capacity utilization increases the output per time unit, hence reducing costs per unit (Nyhuis 2009b).

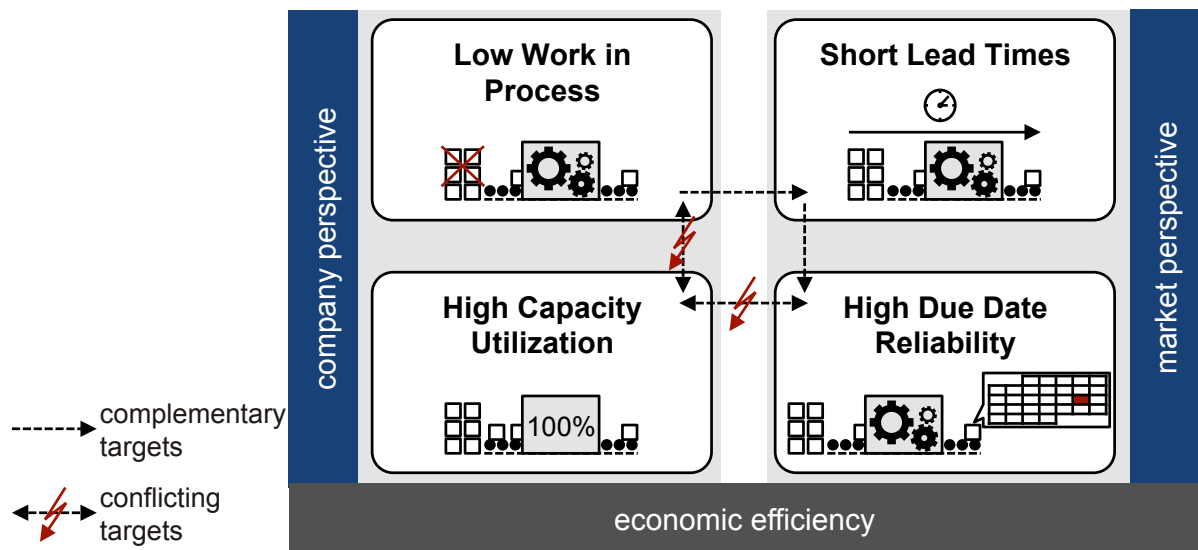


Figure 2.2 Targets of manufacturing control and their trade off (based on (Wiendahl 1997a))

To quantify the performance obtained by a manufacturing system, this work concentrates on the target achievement calculation of these four quantitative targets. Other qualitative targets⁵, such as flexibility or quality are not examined, but are directly affected by the presented target system, like in the case of economic efficiency. However, the targets of manufacturing control are conflicting, which became known as the ‘Dilemma of Operations Planning’ (Gutenberg 1951). It states that short lead times and high capacity utilization cannot be achieved simultaneously. To ensure ‘appropriate’ capacity utilization a higher work in process level is necessary, which induces longer lead times. With increasing lead times, process disturbances such as rush orders get more likely. This leads to an increased lead time variability, thus a lower due date reliability. Due to this conflict of targets, the optimization of all targets at the same time is unattainable. Thus, if planners focus on high capacity utilization all other target achievements deteriorate. Manufacturing traditionally desired high capacity utilization, but with increasing importance of punctuality and speed, the emphasis shifted to the other targets in

⁵ See also (Schönsleben 2012) for more possible key performance indicators.

the past decade (i.e., high due date reliability, short lead times, and low WIP levels) (Wiendahl 1995; Koether 2008)(see also the movement of ‘lean thinking’ (Womack 1996; Hopp 2004)). This shifting focus makes the investigation of the LTS interactions even more important as it leads to a decreasing logistic performance and in particular to a decreasing due date reliability.

Figure 2.2 also shows the complementary or conflicting links between these targets. In this context, an increase in capacity utilization should lead to a smallest possible increase of WIP and lead time to increase competitiveness⁶ (Beeg 2004). Figure 2.2 also shows the complementary link between the targets lead time and due date reliability, which is given by the lateness. Three types of lateness are distinguished in literature (Dombrowski 1988; Yu 2001; Nyhuis 2009b): input lateness, output lateness and relative lateness (see Figure 2.3). Positive input lateness indicates that the order input is later than it was planned. Positive output lateness is given for situations in which the order completion date is later than the planned output date. The relative lateness of an order can be defined as the difference between the actual lead time and the planned lead time (Nyhuis 2009a):

$$L = tl_a - tl_p$$

Equation 2.2

tl	order lead time [SCD]
L	relative lateness [SCD]
a	actual
p	planned

Positive relative lateness implies longer actual lead times than originally planned. Thus, the presented approach focuses on the defined relative lateness, as the LTS line of argumentation puts emphasis on lead time effects, which is abbreviated ‘lateness’ in this work, unless stated otherwise. Moreover, it can be assumed for simplicity that planned and actual order release dates match, hence leading to an input lateness of zero. Figure 2.3 shows that relative lateness and output lateness are equal in this described case (see also (Nyhuis 2009b)).

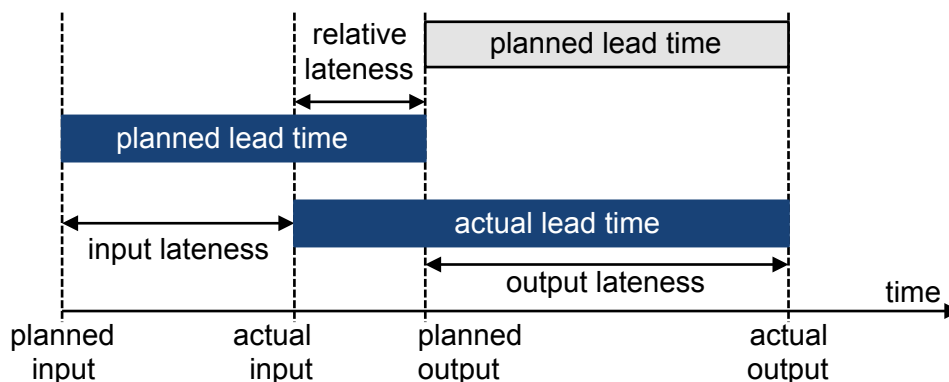


Figure 2.3 Definition of Lateness (based on (Dombrowski 1988; Yu 2001))

⁶ This correlation is represented by a variability factor *alpha*, which corresponds to work input variability, inter-arrival variability, equipment breakdown variability, etc. (Beeg 2004; Fayed 2007). See also Section 2.1.3 for the correlation of capacity utilization, lead time and WIP level.

A given lateness distribution of finished orders provides the data for calculating the resulting due date performance of a manufacturing system a posteriori. Three main key figures are defined in the literature to measure the performance of how due dates are met (Lödding 2013; Windt 2011): Schedule adherence, on-time production and due date reliability. The first can be defined as percentage of orders produced in a reference period that have a negative lateness or a lateness of zero ($L \leq 0$). Thus, all orders that are produced too late ($L > 0$) lead to a decreasing schedule adherence. On-time production is defined as the percentage of orders that are produced with a lateness of zero (Lödding 2013; Schönsleben 2012). These orders are produced neither too late, nor too early. Finally, due date reliability defines a less strict tolerance period in which orders are considered to be on time (Yu 2001). Figure 2.4 depicts the different definitions of due date performance in histograms of an exemplary lateness distribution of a manufacturing system. Part (c) shows that only orders with a resulting lateness in between the exemplary upper/lower tolerance period limits of ± 1 SCD are considered to have met the due date and hence lead to an increasing due date reliability.

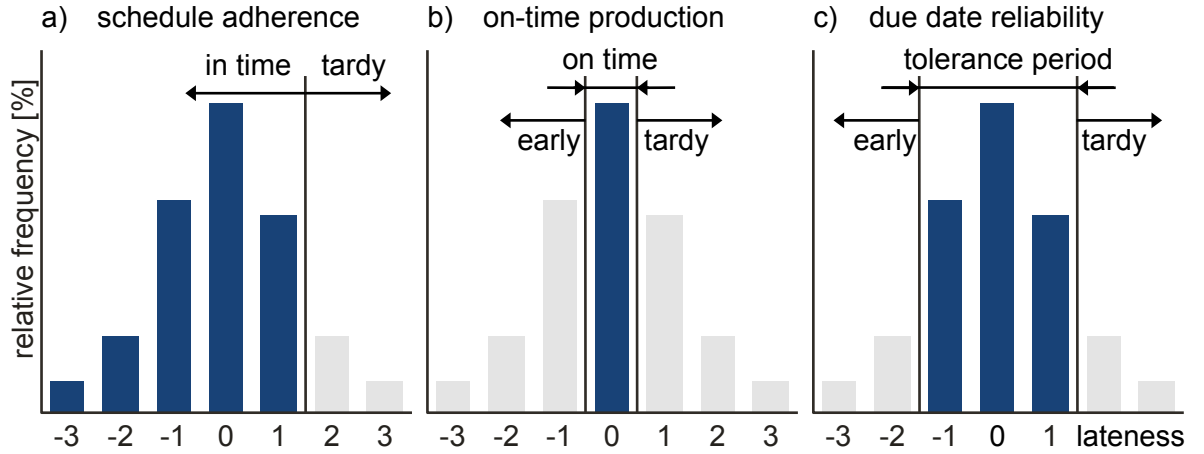


Figure 2.4 Definitions of due date performance in a histogram (acc. to (Lödding 2013))

According to this definition, the resulting due date reliability is calculated in Equation 2.3 as ratio of the number of orders produced with a lateness in between the tolerance period limits to the total number of orders (Yu 2001; Lödding 2012).

$$DR = \frac{\text{number of orders with } Low \leq L \leq Up}{\text{total number of orders}} \cdot 100$$

Equation 2.3

DR	due date reliability [%]
L	lateness [SCD]
Low/Up	lower/upper limit of due date tolerance [SCD]

To increase due date reliability, the variance of lead times has to be decreased to maximize the number of orders within the tolerance period. Furthermore, the mean lateness is lowest and the due date reliability is highest, if the difference between planned and actual lead times narrows. According to the LTS (see Section 1.1), a planned lead time adjustment finally leads to a change of the mean lead time and the lead time standard deviation. Due date reliability thereby reflects the impact of

this adjustment on the due date performance best. The definition of due date reliability is more restrictive than schedule adherence (far too early orders lead to a decrease in due date reliability), but due to the scalable tolerance period more flexible than on-time production. Therefore, the value of the due date reliability has been chosen as the measure of due date performance in this work.

2.1.3 Logistic Targets in the Funnel Model and Logistic Operating Curves

The previous section showed that the optimization of all targets of manufacturing control at the same time is unattainable. They are conflicting and lead to the necessity that planners have to position their production system according to their individual target preferences. This section presents the Funnel Model and the resulting Logistic Operating Curves, which visualizes and quantifies the trade-offs and thereby supports planners in the decision-making of how to position their manufacturing processes. Both models are well-proven in the field of manufacturing (and well established in the German-speaking region) for analyzing manufacturing systems (see, e.g., (Wiendahl 1995; Wiendahl 1997a; Nyhuis 2009b)).

The Funnel Model by Bechte is a model that describes the current situation of a work system from a logistic point of view (Bechte 1984). The fundamental idea is to transfer the production network into a model of linked funnels with a current WIP level and incoming and outgoing orders at each system or funnel. Part (a) of Figure 2.5 shows such a funnel with incoming and outgoing orders.

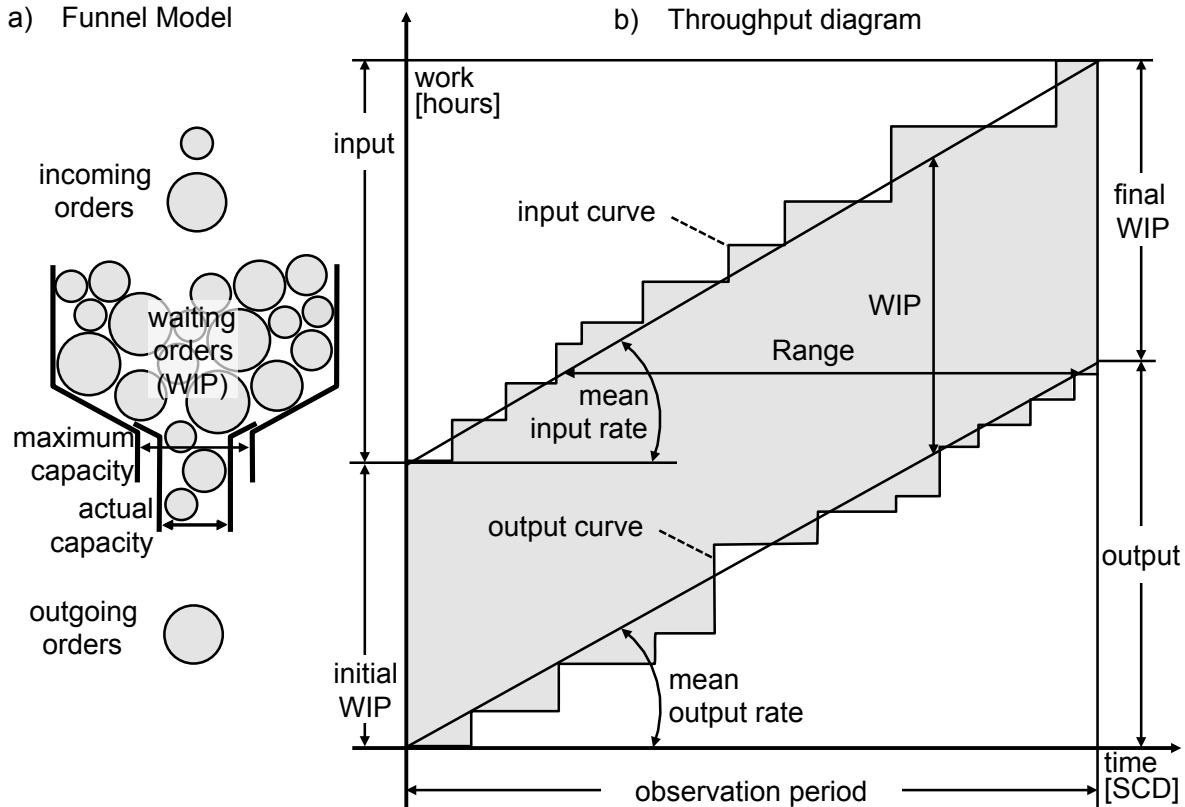


Figure 2.5 Funnel Model and throughput diagram (Bechte 1984; Wiendahl 1997a)

The sum of all orders in the funnel represents the WIP level, whereby the amount of work of each order is represented by its diameter. The current capacity is given by the funnel opening, which is limited by the maximum capacity. Accumulating the work content of incoming and outgoing orders over time plots the throughput diagram in part (b) of Figure 2.5. The initial WIP level at the beginning of the observation period defines the starting point of the input curve on the ordinate. The WIP level is defined for each point in time as the vertical distance between the input and output curve. Dividing the sum of the resulting WIP levels by the observation period length gives the mean WIP value. The horizontal distance between the input and output curve defines the Range, thus how long an incoming order waits on average to be processed if there are no sequence deviations. Range is therefore a ‘forward-looking’ value that corresponds to the lead time of an incoming order, if orders are processed according to the First-In-First-Out principle (Wiendahl 1997a). The output during the reference period is defined by the accumulated sum of the work of outgoing orders. Dividing the cumulated output by the observation period calculates the mean output rate. The capacity utilization can be calculated by comparing the mean output rate with the maximum possible output rate. The trigonometric correlation between range, WIP, and output rate leads to the following equation, which is referred to as the ‘Funnel Formula’ (Bechte 1984).

$$R_m = \frac{WIP_m}{ROUT_m}$$

Equation 2.4

R_m	mean range [SCD]
WIP_m	mean work in process level [h]
$ROUT_m$	mean output rate [h/SCD]

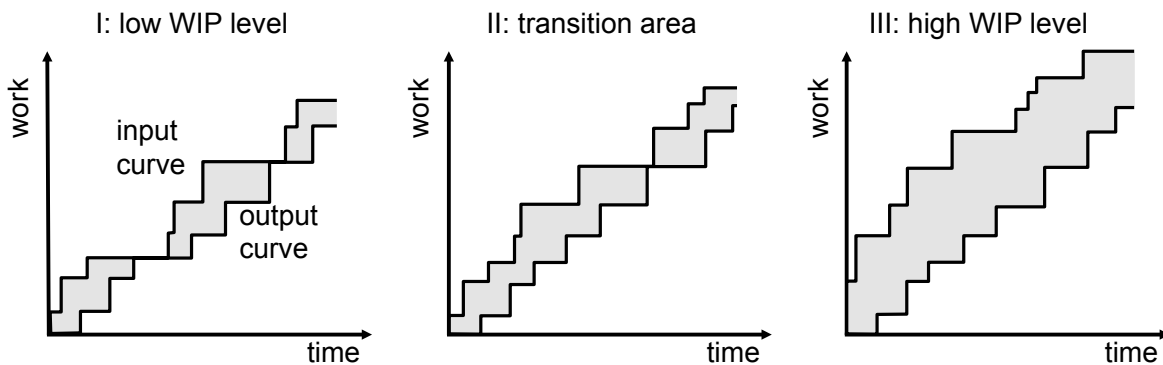
Moreover, planned input and planned output dates can be included into the throughput diagram to visualize and monitor the due date performance (Nyhuis 2009b). Exemplary, if the planned output curve is located on the right side of the actual output curve, orders are produced too early (Yu 2001). The throughput diagram thus enables the qualitative and time-related description of dynamic correlations (Wiendahl 1997a; Bechte 1984).

As shown, all four targets (WIP, lead time, capacity utilization, and due date reliability) of a logistic system can be visualized in an (extended) throughput diagram. However, interdependencies between these logistic targets are not describable (Nyhuis 2009b). A tool to visualize them is given by the model of the *Logistic Operating Curves* by Nyhuis and Wiendahl: Part (a) of Figure 2.6 shows three simplified throughput diagrams that represent different work system operating states with respect to their WIP levels. These operating states are transferred in a condensed form into the Logistic Operating Curves in part (b) of Figure 2.6, describing the output rate, lead time, and range for each operating state as a function of the corresponding WIP level. The output rate curve shows that the output rate of a system does not change any more when the WIP level exceeds a certain level. For each moment enough work is waiting to be processed, thus

eliminating idle times. For lower WIP levels idle times lead to a decrease of the output rate. Above a critical WIP level, the lead time curve increases proportionally to the WIP level. The incline follows immediately from the Funnel Formula. The minimum, irreducible, and WIP independent lead time is given by the sum of the mean setup, processing, and transportation time. According to the Funnel Formula, the range curve is given by the ratio of WIP and output rate (Nyhuis 2009b).

It has to be pointed out that the actual operating state of a manufacturing system is given by one operating point in the Logistic Operating Curves. Thus, under equal conditions (e.g. same maximum capacity and order structure) the operating curves are able to represent the resulting system behavior for different WIP levels (Nyhuis 2009b). In further research on the Logistic Operating Curves equations were derived to calculate the operating states. These equations are able to calculate systems' behavior for steady state situations⁷ and are referred to as 'logistic equations' in this work.

a) exemplary operating states of work systems



b) transfer of operating states into Logistic Operating Curves

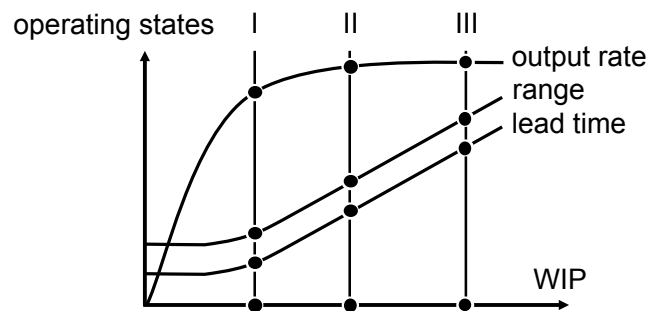


Figure 2.6 Derivation of Logistic Operating Curves from different operating states (Nyhuis 2009b)

The Logistic Operating Curves show that it is impossible to maintain an operating point with an optimal target achievement for each of the logistic targets. Also, the definition of an 'optimal' operating state is impossible. To ensure appropriate capacity utilization a higher work in process level is necessary, which induces longer lead times. Thus, the Logistic Operating Curves visualize the

⁷ Underlying process characteristics that influence the objectives remain the same during the reference period (e.g., maximum capacity) (Nyhuis 2009b).

‘Dilemma of Operations Planning’ (Gutenberg 1951) and quantify the effect of a changing WIP on the lead time and the output rate (Nyhuis 2007; Nyhuis 2009b). They provide a tool for visualizing interdependencies and make the decision-making process more transparent with regard to the consequences of focusing on a specific target, while without this tool control decisions were based on gut feelings or experience. Hence, the strategic and operational targets of the company (from the company and market perspective (see Figure 2.2)) define the target operating point for each work system along with the corresponding WIP level, lead time, and output rate. This procedure is called ‘Logistic Positioning’. It directly offers the possibility to check if the target operating points are feasible. As shown in Figure 2.7, a target capacity utilization level defines the output rate or rather a tolerance field. If the corresponding tolerance fields of lead time and WIP are not achievable at the given environmental conditions, measures have to be undertaken to generate new logistic potentials. Exemplary, such measures can be harmonized operation times, reduced waiting times between processes, or an increase of the maximum capacity (Nyhuis 2009b).

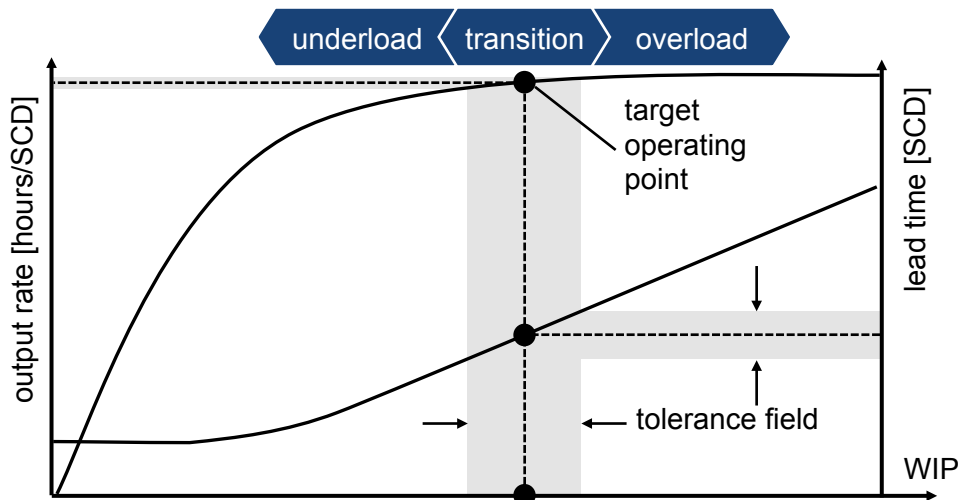


Figure 2.7 Logistic Positioning by Logistic Operating Curves (Nyhuis 2009b)

The Logistic Positioning leads to an operating point that is located in one of the above described operating states with a low or a high WIP level. Thus three operating positions can be defined: underload, transition, and overload (Nyhuis 2009b). If a system has an operating point that is located in the overload area, another increase of WIP would only lead to an increasing lead time without affecting the output rate any more. However, the powerful application of the Logistic Operating Curves is still not well-known in industry. Therefore, safety lead times and safety stocks are commonly used in order to avoid idle times and maximize the capacity utilization of bottleneck work systems (Lindau 1995). Hence, work systems are unknowingly positioned in the overload area with wasted potential regarding lower lead times and WIP levels for the same output rates (Lödding 2013). For higher WIP levels sequence deviations or rush orders get more likely, which decreases the resulting due date reliability. If planners again add safety stocks

and safety lead times to increase the due date reliability, the LTS is triggered according to the definition presented in Figure 1.1 (Section 1.1).

2.2 Classification of Manufacturing Control into the Concept of Production Planning and Control and Analogies to Control Theory

The lack of knowledge of production planners about the interactions between the logistic targets leads to the LTS of manufacturing control (Wiendahl 1997a). However, adjustment of planned lead times is only one component of Production Planning and Control (PPC). This section will give a brief overview of the evolution of PPC and commonly used models to classify the LTS of manufacturing control in the context of PPC. Thus, Section 2.2.1 initially introduces the Aachen PPC model and Manufacturing Resource Planning (MRPII), which is based on the concept of Material Requirements Planning (MRP). Then, Section 2.2.2 presents the manufacturing control model of Lödding (2008), which links the tasks of manufacturing control to the targets of production logistics. Finally, a model that links control theory and PPC is presented in Section 2.2.3, which also introduces the positive feedback loop of control theory and its similarities to the LTS.

2.2.1 Models and History of Production Planning and Control

The core task of PPC is to “allocate items, processes and resources to orders in terms of time and volume” (Wiendahl 2006). Thereby, PPC primarily focuses on controlling and continuously improving processes within a company (Schuh 2006). The Aachen PPC model was developed to structure the main functions of PPC and is well established in the German-speaking region (Luczak 1999; Schuh 2006). Figure 2.8 shows the developed model, which is based on the Y-model of Scheer and the PPC-model of Hackstein (Jäger 2000; Scheer 1995; Hackstein 1989)⁸.

The Aachen PPC model differentiates between four core tasks, three cross-sectional tasks, and a cross-functional data management (Schuh 2006). *Production program planning* determines in a production program which products are going to be produced in the next planning periods, including type, amount, and due dates. The *production requirements planning* has the task to plan the required resources to fulfill the production program. It includes the determination of required materials for all order components, the definition of planned input and due dates by means of e.g. backwards-scheduling, and the planning of required capacities to produce the orders. The resulting rough planning is further detailed in the *outside supply planning and control* and *in-house production planning and control*. It covers lot-sizing, sequencing, detailed planning, capacity control, and order release for in-house PPC and supplier selection, obtaining and comparing quotations, and lot-sizing for the outside supply planning and control. In contrast to the core tasks that aim to

⁸ See also, e.g., (Vollmann 2005; Hilton 2005; Hopp 2008; Arnold 2008) for more models of PPC.

push forward the completion of orders, the cross-sectional tasks of PPC aim to integrate and optimize PPC. This includes the *coordination* of order processing along the process chain, the *warehouse management* to manage and minimize inventory levels, and *PPC-controlling* to monitor the logistic target achievement. The accuracy and practicability of both core tasks and cross-sectional tasks strongly depends on the accuracy and completeness of the feedback data, which is a task of the *data management* (Schuh 2006; Luczak 1999).

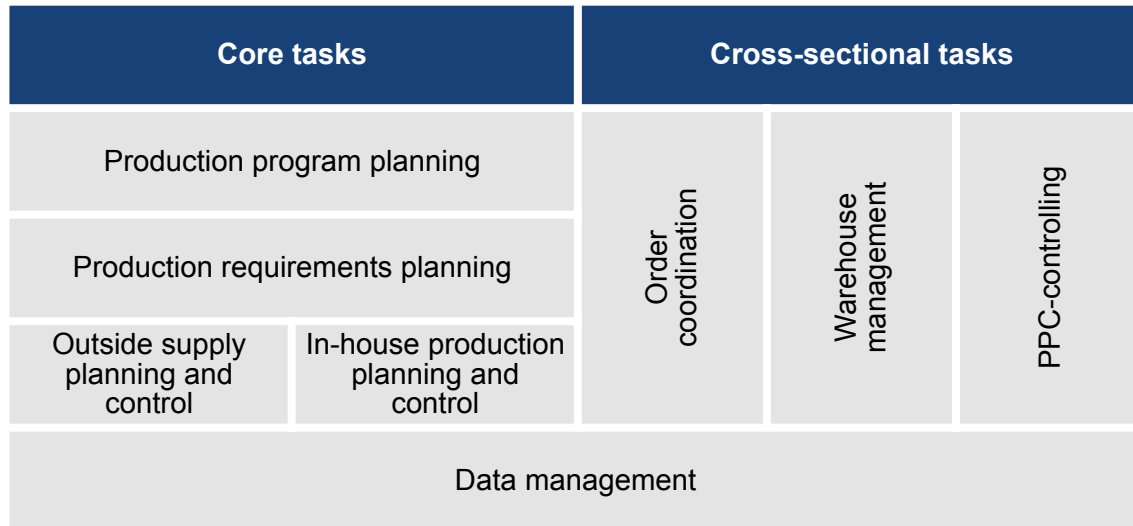


Figure 2.8 Aachen Production Planning and Control Model (Luczak 1999; Schuh 2006)

The majority of today's PPC-systems are based on the concept of Manufacturing Resource Planning (MRPII), which is an extension of the Material Requirements Planning (MRP) (Hopp 2008; Schuh 2006). The following description of MRP and MRPII is based on Hopp and Spearman (2008).

Joseph Orlicky developed the principle of MRP at IBM in the early 1960s. According to Hopp and Spearman (2008) the key insight of MRP was the differentiation between *independent demand* and *dependent demand*. Independent demand is given by the customer demand for final products, thus originates outside the system and is subject to uncertainty. Dependent demand consists of components that are needed for the final products and is therefore known by the bill of material (BOM), which describes the relationship between finished products and their constituent parts. The basic MRP procedure can be described by the following five steps (Hopp 2008):

1. *Netting*: The net requirement is calculated by subtracting the sum of current inventory and the status of outstanding orders (scheduled receipts) from the gross requirement.
2. *Lot sizing*: Orders (jobs) are determined by dividing the net requirements into lots.
3. *Time phasing*: The planned order release time is calculated by subtracting the planned order receipt (due date) by the planned lead time.

4. *BOM explosion*: The gross requirement of all components of the next level in the BOM can be determined by the above calculated planned order release times and lot sizes.
5. *Iterate*: The steps above have to be repeated until all levels on the BOM are processed.

The implementation of MRP into manufacturing systems revealed several problems, from which *capacity infeasibility*, *long planned lead times*, and *system nervousness* were identified as the most severe drawbacks (Hopp 2008): Regardless of actual system loads orders are scheduled in step three according to fixed planned lead times. The underlying production model thus ignores the previously discussed dependence of lead time and WIP levels, an assumption which could only be upheld if infinite capacities are assumed in planning. Since production capacities are usually limited (at least in the short-term) the opposite can lead to infeasibilities in terms of capacity restrictions. The second problem is raised by setting safety lead times and safety stocks, which were set to deal with uncertainties in demands and production (Lindau 1995; Hopp 2008; Vollmann 2005). Here, planners tend to define excessively long planned lead times with the intention of reducing positive lateness. However, the increase in planned lead times inevitably leads to increasing WIP levels, longer actual lead times, and finally to a decreasing due date reliability, thus to the LTS with renewed planned lead time adjustments as introduced in Section 1.1. The last main drawback is given by the resulting ‘nervousness’ of an MRP system after changes in the master production schedule due to changing demands. Due to the fixed lot sizes, these changes could lead to numerous changes in planned order release times and result in highly fluctuating and potentially infeasible MRP plans.

To overcome the problems of MRP additional procedures were developed, which were then incorporated into the concept of Manufacturing Resource Planning (MRP II). Figure 2.9 shows the hierarchy of MRP II presented by Hopp and Spearman (2008), which includes MRP at the center. Thereby, it separates the tasks into *long-range planning* (year to decades), *intermediate-range planning* (week to year), and *short-term control* (hour to week). A fundamental characteristic of the MRP II concept is the feedback of various control tasks, which monitor planned and actual values (Eversheim 2000). However, a lack of PPC-controlling⁹, a missing finite capacity planning, and a lack of support in maintaining plan parameters, such as planned lead times, are often referred to as main drawbacks of the MRP II concept (Higgins 1996b; Eversheim 2000; Stadtler 2005; Nyhuis 2010). Thus, many companies with MRP II had problems maintaining a high logistic target achievement. Moreover, the MRP II concept is subject to assumptions that are primarily valid in mass and large batch production, which makes it less applicable in small-scale and single item production (Eversheim 2000).

⁹ According to (Hautz 1993) PPC-controlling consist of six steps: define targets, set planned values, measure actual values, compare planned and actual values, analyze deviations, and derive measures (as cited in (Schuh 2006)).

The further evolution of the MRP II concept aimed at the integration of the whole company into one Enterprise Resource Planning (ERP) system, thus covering PPC, accounting, personnel etc. into one system (Schuh 2006). More recent approaches are advanced planning systems (APS) that aim at fixing MRP drawbacks by providing, e.g., finite capacity scheduling, warehouse management, or forecasting (Hopp 2008). However, even today's ERP systems often assume infinite capacities and fixed planned lead times (Hopp 2008). Moreover, in order to reduce the workload of the software, they often leave the task of sequencing, capacity control, and order release to the manufacturing control, which has the task to implement the plans despite disturbances (e.g., to meet planned due dates) (Wiendahl 1997a; Wannenwetsch 2006). The manufacturing control model by Lödding (2008) is presented next to clarify the tasks of manufacturing control and to show how they influence the logistic target achievement.

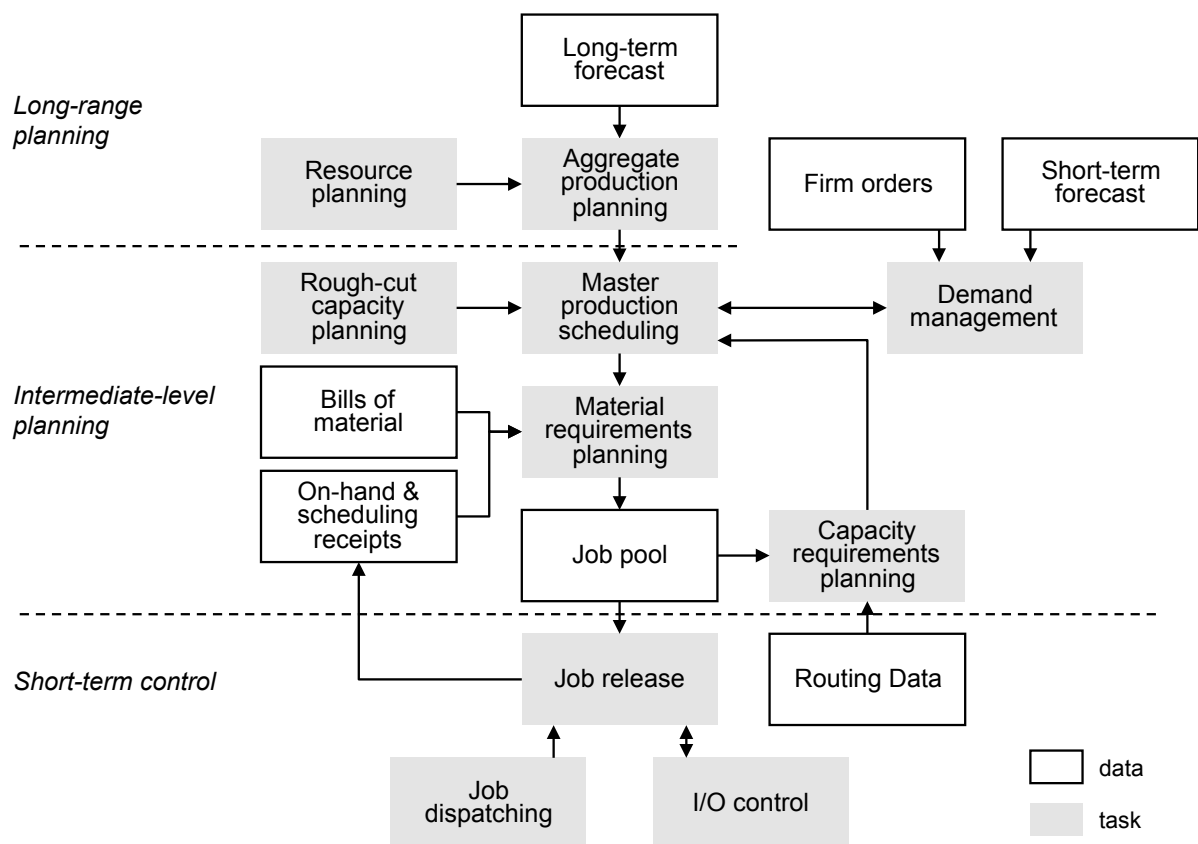


Figure 2.9 Manufacturing Resource Planning (MRP II) hierarchy (Hopp 2008)

2.2.2 A Model of Manufacturing Control

During production, disruptions and unstable demand patterns may result in deviations from the original plans. As defined by Wiendahl (1997) it is the task of manufacturing control to maintain a high logistic target achievement by implementing the plans set by production planning. According to Lödding (2013) manufacturing control consists of the four tasks *order generation*, *order release*, *capacity control*, and *sequencing*. Figure 2.10 shows the developed manufacturing control model (Lödding 2013). The tasks determine the planned and actual values that are defined as *actuating variables*. The differences between two connected

actuating variables result in the *control variables*, which in turn determine the *target values*.

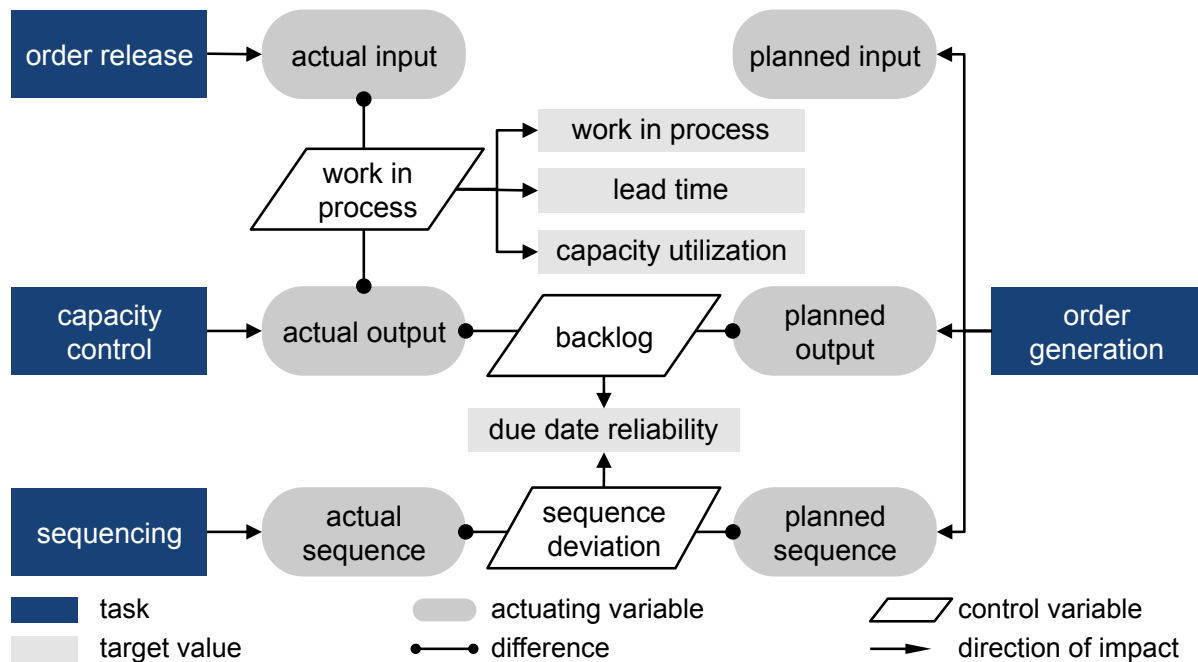


Figure 2.10 Manufacturing Control Model (Lödding 2013)

In more detail, *order generation* is a logical component of production planning, which determines the planned values of input, output, and order sequence. The actual values are determined by the manufacturing control tasks *order release*, *capacity control*, and *sequencing*. *Order release* determines the actual input to the production process by setting the release dates of orders. The actual output is determined by *capacity control*, which controls the working hours and the allocation of workers to work systems and tasks. The *sequencing* finally determines the chronological order in which competing orders are processed at work systems. The difference between *actual input* and *actual output* results in the *work in process* (WIP) level, which is both a control variable and a logistic target. In addition, the WIP level directly influences the logistic targets of *lead time* and *capacity utilization*. The target of *due date reliability* is influenced by the two-control variables *backlog* and *sequence deviation*, which in turn are defined as the difference between actual and planned output and actual and planned sequence. More specifically, if a company produces less output than planned, a certain amount of orders cannot be produced within the planned period, which leads to lateness and therefore affects the schedule adherence. Sequence deviations occur if orders in a workstation queue are not processed according to their planned due dates. Possible reasons can be the grouping of orders that belong to the same setup family, unavailable production resources, unawareness of employees or the use of sequencing rules that do not focus on due dates (Lödding and Kuyumcu, 2011). The model not only maps the correlation between the tasks of manufacturing control and production planning, but also links the tasks to the targets of production logistics (Lödding 2013).

2.2.3 Analogies Between Production Planning and Control, Control Theory, and the Lead Time Syndrome¹⁰

As stated above a fundamental problem of MRP II and ERP systems is the lack of sufficient PPC-controlling and missing support in setting and maintaining parameters such as planned lead times (Eversheim 2000; Schuh 2006). Thus, actual values often differ from planned values and lead to a low logistic target achievement. Therefore, increasing and maintaining a high logistic target achievement with PPC is a classical control problem, as manufacturing parameters (control variables) have to be adjusted continuously according to planned values (reference variables) (Schuh 2006).

Due to the lack of PPC-controlling and the analogies between control theory and PPC, the closed loop of production planning and control was developed by Ludwig (1995), which is depicted in Figure 2.11 (Ludwig 1995; Wiendahl 1997a): It includes company goals (target), which affect the settings of production planning (plan) and the controlling of order fulfillment. Within the loop, the plan provides the planned values for the actual manufacturing process. In a feedback loop, the logistic controlling compares planned and actual manufacturing data that are continuously measured in the manufacturing process (actual). The comparison and interpretation of planned and actual values enables specific adjustments of company targets or production planning and control variables to counteract disturbances.

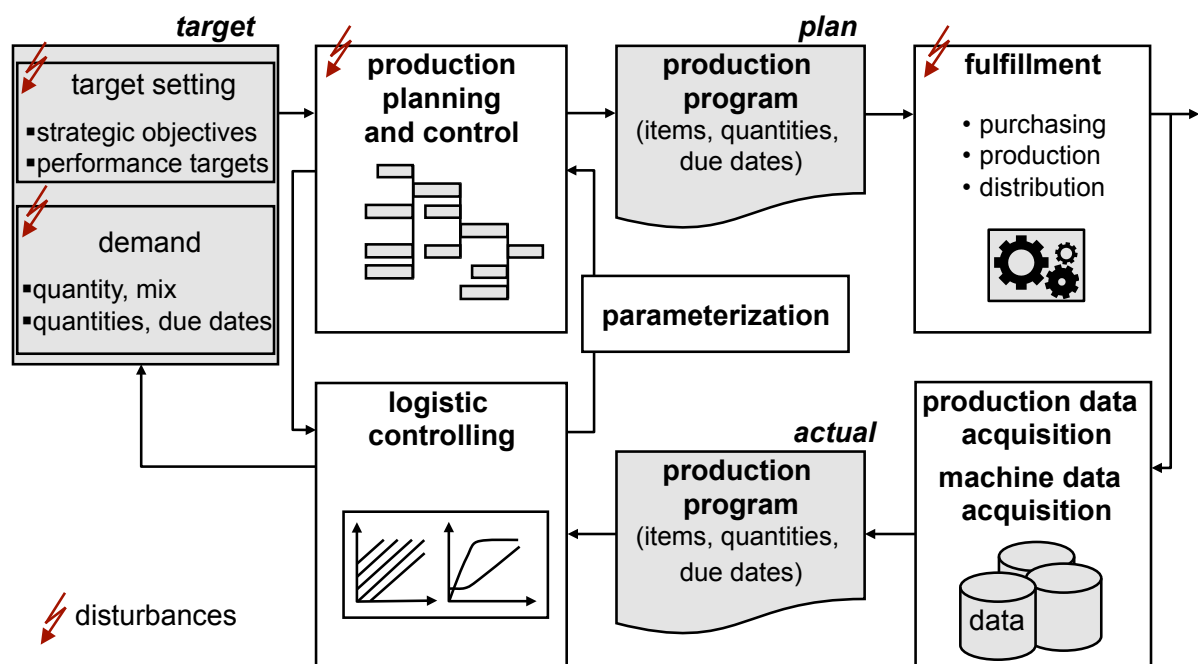


Figure 2.11 Closed loop of production planning and control (Wiendahl 1997a; Ludwig 1995; Schuh 2006)

PPC-controlling is one of the cross-sectional functions in the Aachen PPC model (see Section 2.2.1) and has shown according to Schuh (2006) in theory (Breithaupt 2001; Windt 2001; Ludwig 1995) and practice (Schneider 2002; Breithaupt 2000b;

¹⁰ Parts of this section have been published in similar form in (Knollmann 2013a; Knollmann 2014b)

Westkämper 1998) that its implementation significantly increases logistic target achievement. Moreover, the model suggests that PPC is a classical control problem and can be modeled using control theory. Hence, various models were developed in recent years to analyze and control dynamic manufacturing systems (see, e.g., (Petermann 1996; Duffie 1996; Wiendahl 1997b; Wiendahl 2000; Breithaupt 2000b; Deif 2006; Duffie 2002; Ratering 2003; Duffie 2009; Nyhuis 2009a; Duffie 2010; Jeken 2012) and (Duffie 2014) for a review on control theoretical modeling of PPC).

The analogy between control theory and PPC can also be shown by the similarities between the positive feedback loop of control theory and the LTS of manufacturing control. As shown in Figure 2.11 feedback is frequently used in modern engineering practice because it allows reliable and precise controlling of the system output (Nagrath 2006). However, the dynamic behavior of complex systems often emerges due to feedback. Figure 2.12 shows a simple feedback loop in which system gain and feedback are static, constant gains, and a fraction of the output value is fed back to the input value, which means that the output value influences itself (Graf 1999). The feedback loop is called *positive* if the output value is bigger than it would have been without feedback and *negative* if the output is smaller (Graf 1999). The resulting output of the feedback loop shown in Figure 2.12 is calculated according to Equation 2.5 (Nagrath 2006). Without the fraction of the output that is fed back (*feedback*=0), the output value is calculated according to Equation 2.6.

$$output = \frac{system\ gain}{1 - system\ gain \cdot feedback} \cdot input$$

Equation 2.5

$$output = system\ gain \cdot input$$

Equation 2.6

These equations show that the resulting output is amplified more than without the feedback fraction, if the value of the denominator in Equation 2.5 is between zero and one (Chattopadhyay 2006). The closer the term *system gain* • *feedback* approaches unity, the smaller is the denominator. Hence, the positive feedback loop gain would increase (Jagacinski 2003). Moreover, when system gain and feedback are dynamic (described by differential equations), even small perturbations can lead to unstable behavior in a positive feedback loop. The amplification of the input signal increases exponentially or it oscillates, which depends on the phase shift or the delay of the feedback signal relative to the output (Nagrath 2006). It can be concluded that under the right circumstances positive feedback is possible in systems in which the output signal is fed back to the input signal (Zeigler 2000; Chattopadhyay 2006).

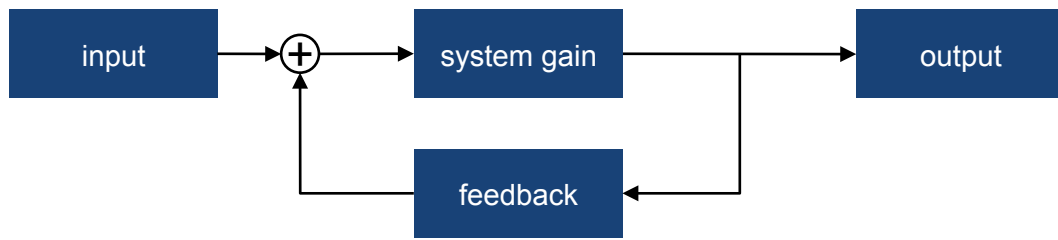


Figure 2.12 Basic feedback loop (Jagacinski 2003; Zeigler 2000)

A common real life example of positive feedback is shown in Figure 2.13. In this simplified model a sound system amplifies the signal of a microphone. If the microphone receives the output signal of the speakers, the signal amplifies itself. This can lead to the well-known deafening sound of audio feedback. In this positive feedback loop the volume increases exponentially until the maximum output power of the amplifier has been reached (Davis 2006).

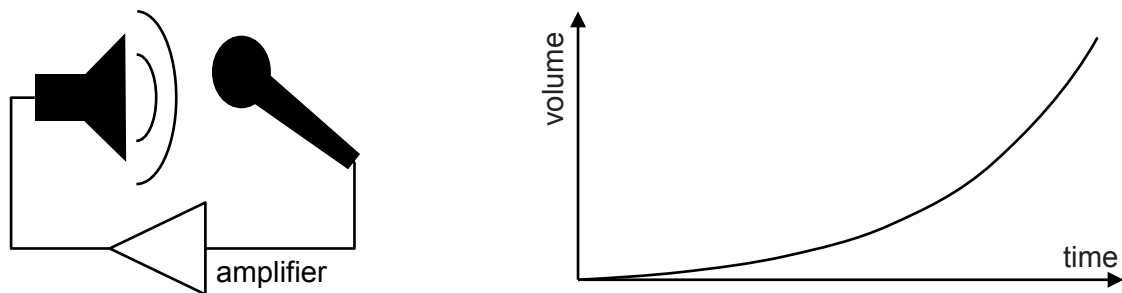


Figure 2.13 Sound system as an example of positive feedback

The described situation of positive feedback has strong similarities to the chain of reactions in the LTS described in Figure 1.1 (Section 1.1). If order release (input) changes due to measures that aim to improve the process due date reliability, the short-term parameter changes in the manufacturing process may trigger the LTS interactions. Thus, the resulting due date reliability (output) strongly depends on the interaction of the manufacturing process and the LTS interactions. Planners observe a decrease in due date reliability due to the short-term amplification and estimate that order release dates have to be changed again by adjusting planned lead times. Therefore, if the LTS interactions are triggered, a positive feedback loop that leads to a lower due date reliability is likely to occur. More specifically, positive feedback occurs because the increased and more variable workload at the work centers of the manufacturing process results in a longer lead time, which triggers earlier order releases and finally leads to an even more increased workload.

The analogies between the LTS and positive feedback as well as PPC and control theory suggest that control theory is a suitable method to confirm and evaluate the LTS interactions. Therefore, Chapter 4 presents a control theoretic investigation of LTS interactions for varying input fluctuations, frequencies and delays of planned lead time adjustments, and decreased magnitudes of planned lead time adjustments.

2.3 Previous Research on the Lead Time Syndrome

The phenomenon of the LTS that was presented in Section 1.1 was firstly described in 1977 (Mather 1977). Only much later a first investigation of the LTS interactions by means of queuing theory was carried out by Selçuk et al. (2006; 2007; 2009), which is presented in Section 2.3.1. Based on these formal studies Fischer, Fransoo, and Moscoso (Fischer 2006; Moscoso 2010; Moscoso 2011) carried out empirical studies of the LTS and planning instabilities in general, which are presented in Section 2.3.2.

2.3.1 Investigation of the Lead Time Syndrome by means of Queuing Theory

The first serious discussions and investigation of particular LTS issues emerged in the research of Selçuk et al. (2006). Their research initially investigated the influence of the update frequency (how often planned lead times are changed) on the performance of hierarchical planning systems. The discrete event simulation study of a two-stage production system provided experimental evidence of the existence of the LTS in a push production system (Selçuk 2006).

Using queuing theory an exact analytical model (two-dimensional Markov process) was developed in further research on the LTS (Selçuk 2009). They found that the LTS increases the process variability and leads to a higher WIP level, thus also to increasing lead times. In this context, Selçuk (2007) argued that the attempt of planners to close the gap between planned and actual lead times by frequent planned lead time adjustments would lead to unstable order release patterns. The author also concluded that the planned lead time variability increases if updates are more frequent and that possible overreactions, which could be triggered due to short-term WIP fluctuations, are smoothed if the frequency is decreased (Selçuk 2007). Thus, they stated that a lower frequency would decrease the lead time variability and hence decrease the impact of the LTS (Selçuk 2009).

However, this research approach was not able to determine a proper update frequency that would lead to the maximum achievable performance while avoiding the LTS, as the impact of the update frequency on the resulting due date performance was not part of the research. Also, the time delay between calculating an adjustment and measuring changed system states was not included in these analytical models, although Deif et al. found that the responsiveness of a system is inversely proportional to information delay (Deif 2006). For a holistic investigation of the LTS, this research approach requires inclusion of the delay component (see Section 3.3.2) and the development of a model for measuring the impact of planned lead time adjustments on the resulting due date performance (see Section 3.1.1).

2.3.2 The Lead Time Syndrome as a Special Case of the Planning Bullwhip

Moscoso et al. (2011) extended the research results of Selçuk et al. (2006; 2007; 2009) presented in the previous section by using a more general approach to study

planning instabilities (Fischer 2006; Moscoso 2010; Moscoso 2011). Their empirical study introduced the term ‘planning bullwhip’ that subsumes any kind of planning instabilities that are generated primarily by planning policies and internal actions such as adjustments of plan values. According to their definition the LTS is a special case of the planning bullwhip (namely the ‘vertical bullwhip’), as it is a result of planning instabilities. They assumed that in the hierarchical planning structures of companies, dynamics are generated by the discrete decisions that are made at each planning level simultaneously, which could deviate from optimal operations, thus causing instabilities. An essential reason for such deficiencies is because of the overreaction of higher planning levels, which tend to constantly change plan parameters to balance out observed deviations on the shop-floor level. In addition, a poor data quality that does not reflect current system states is a potential reason for overreactions. These overreactions of planners can initiate even more deviations, thus leading to a vicious circle causing the ‘planning bullwhip’ as depicted in Figure 2.14 (Moscoso 2011).

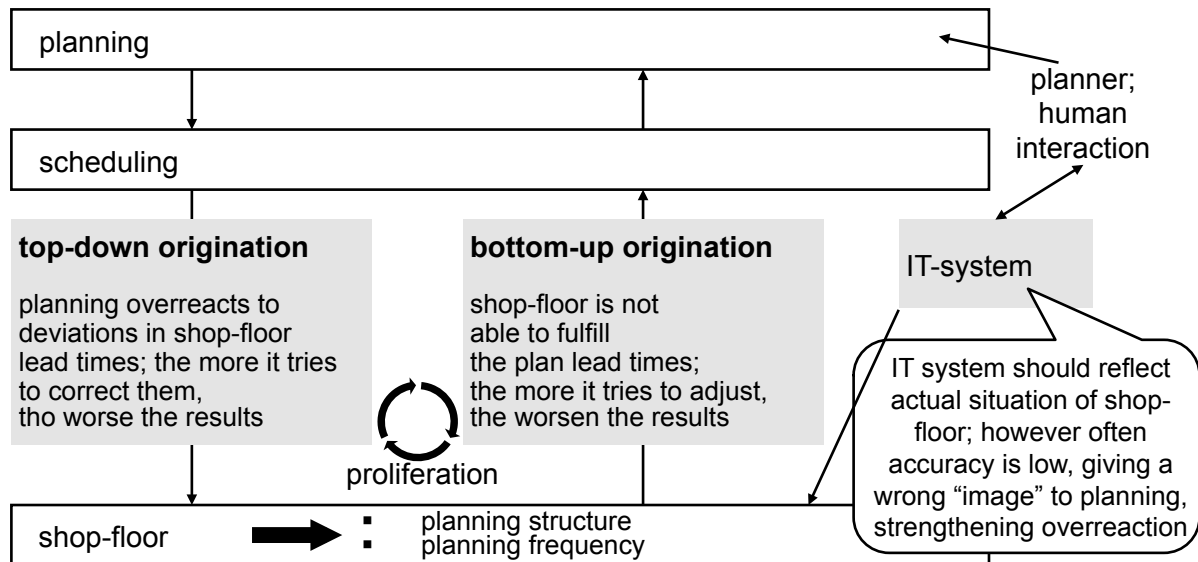


Figure 2.14 Mechanisms underlying origination of planning instabilities (based on (Moscoso 2011))

As a main research outcome, a holistic framework was presented to address root causes of the planning bullwhip (Moscoso 2011). This general framework includes the detection of planning system attributes that possibly can be associated with the emergence of the planning bullwhip. They include, e.g., the number of hierarchies, the planning frequency and the data quality. Moscoso et al. (2011) initially brought together the research on planning instabilities (such as the LTS) and human behavior (such as overreaction). However, their studies did not include a more detailed investigation of human behavior (see Section 7.5); rather their studies remained on a meta-level of human reactions under uncertainty. This also influenced the presented holistic framework to address the planning bullwhip, as it did not include a quantification of resulting impacts or a validation of the attributes. Nevertheless, with the LTS as a special case of the planning bullwhip, their research shows that the investigation of the LTS not only includes a quantification of the

chain reaction after planned lead time adjustments, but also to develop a methodology that supports planners in the process of decision-making. Therefore, the development of a roadmap in Chapter 6 includes the development of a methodology that answers the questions of when, how often, and on which value to adjust planned lead times. Thus, if it is appropriate to adjust planned lead times (see Section 6.1) and if so, at which time intervals (i.e., suitable update frequency) (see Section 6.2) and on which value they should be adjusted (see Section 6.3).

2.4 Research Gap

Although the phenomenon of the LTS was first described in 1977 (Mather 1977) and the occurrence of LTS effects is still just as valid now as it was back then (see Section 1.1 and Section 2.2.1), the cause-and-effect relationships in the LTS still have not been sufficiently investigated (see Section 2.3). Instead, several researchers used the line of argumentation of the LTS to develop measures to overcome selected negative LTS interactions, instead of studying the syndromes interactions themselves. For example Wight described the effect of the ‘phoney backlog’ as a trigger of the LTS (Wight 1984). When customers are forced by a backlog of the manufacturer to order earlier, the lead times increase, thus triggering the LTS. As a measure to avoid the phoney backlog, Wight introduced the MRP II concept, which was presented in Section 2.2.1. In a similar manner, other concepts were introduced to prevent LTS drawbacks. Some examples are logistic positioning using Logistic Operating Curves (see Section 2.1.3) (Nyhuis 2006; Nyhuis 2009b), workload control (Breithaupt 2002; Thürer 2011), input/output control (Tatsiopoulos 1983; Fry 1987), techniques of assembly controlling (Wiendahl 1997a; Lödding 2011), decoupling (Wikner 2005; Skipworth 2006), capacity control and flexibility (Breithaupt 2000a; Begemann 2005; Wiendahl 2005), and controlling instead of forecasting lead times (Tatsiopoulos 1983; Plossl 1988; Kingsman 1989).

Section 2.3.1 shows that previous research on the LTS did not consider the time delay between calculating an adjustment and measuring changed system states. This time delay corresponds to the phase shift of a feedback signal that determines whether positive feedback – and thus the LTS – occurs (see Section 2.2.3). Moreover, the impact of planned lead time adjustments and the influence of the update frequency on the resulting due date performance has not been part of previous research. The lack of knowledge of production planners about the relationships between the logistic targets leads to the LTS of manufacturing control, because they tend to set planned lead times that are too long and to adjust them too often in terms of the given system states. However, Section 2.2.2 and Section 2.3.2 show that in terms of the LTS it is still an open question in theory and in practice how to set suitable planned lead times and how often they should be adjusted. Thus, the investigation of the LTS not only needs to include a quantification of the chain reaction after planned lead time adjustments, but also to

derive a methodology to avoid the LTS in practice by supporting planners in the process of decision-making.

Thus, the first part of this thesis (Chapter 3 – Chapter 5) aims at the validation of the LTS line of argumentation and the derivation of strategies to avoid or dampen the LTS. Therefore, Chapter 3 presents a mathematical modeling of the LTS interactions to determine the main triggers. These interactions are validated in Chapter 4 using a control theoretic model of the LTS and transferred into strategies to avoid or dampen the LTS. Finally, Chapter 5 presents the results of a case study to evaluate and confirm the derived propositions.

The second part of this thesis (Chapter 6) aims at developing a roadmap of strategies to avoid the LTS in practice. Therefore, Chapter 6 presents methodologies to answer the questions of *when, how often, and on which value should planned lead times be adjusted*. These methodologies are finally transferred into a merged roadmap.

3 Mathematical Investigation of Lead Time Syndrome Interactions and Derivation of Impacts on Due Date Reliability¹¹

As shown in Section 2.4, several authors used the LTS line of argumentation to investigate different production planning and scheduling techniques as well as to improve due date reliability. The LTS itself was not part of these investigations. The apparently logical steps in the vicious cycle of the LTS were neither validated nor quantified yet, as shown in Section 2.3. However, the formal description of the above-mentioned logistic targets has made progress in recent years. This offers the opportunity to investigate the LTS using mathematical equations that are based on the Logistic Operating Curve theory (see Section 2.1.3). Thus, the aim of this chapter is modeling of the underlying LTS effects, to validate the LTS line of argumentation and to quantify the impact of the LTS on the logistic target achievement on the one hand and to reveal the main triggers of the LTS on the other. This approach finally enables the derivation of propositions that sum up the main LTS characteristics.

First, the LTS line of argumentation will be derived mathematically in Section 3.1. Using logistic functions, a quantification of the planned lead time adjustment effects will be derived for the first time. These functions as well as the LTS itself are subject to statistical and model based assumptions, which will also be discussed and validated. The presented derivation provides a detailed analysis of underlying variable interactions and enables a targeted investigation of LTS triggers in the subsequent sections. Section 3.2 is concerned with the question how to measure the impact of the LTS on logistic target achievement. Due date reliability will be presented as a suitable performance indicator of the obtained system performance, thus providing an indicator for the impact of possible LTS drawbacks. Section 3.3 outlines environmental conditions that are likely to result in emergence of the LTS. With due date reliability as the performance indicator and indicator of LTS impacts, this section focuses on reasons for a decreasing due date reliability, as well as on reasons for an increasing lead time standard deviation and the impact of the time period after planned lead time adjustments until the system reaches a steady state again. The results and insights from this chapter are finally summarized in Section 3.4.

¹¹ Parts of this chapter have been published in similar form in (Knollmann 2013a; Knollmann 2013b; Knollmann 2013c; Knollmann 2014b).

3.1 Mathematical Modeling of the Lead Time Syndrome

According to the LTS line of argumentation by Mather and Plossl, the adjustment of planned lead times in a production system affects work center loads, queues, lead times, and finally the due date reliability (Mather 1977). Yet there has been no research on the quantification of the planned lead time adjustment on the resulting due date reliability as well as on the validation of the underlying assumptions.

Therefore, a model to validate the logic behind the LTS and to anticipate the resulting due date reliability has been developed. The combination of a calculated due date reliability with a derivation of the LTS through logistic equations enables a quantification of impacts on the logistic target values. These consequences of planned lead time adjustments are described below, following the steps of the LTS. According to Figure 3.1, this section starts with the derivation of an equation that enables the calculation of the actual due date reliability. The small figures at the beginning of the following sections depict which element of the LTS is investigated.

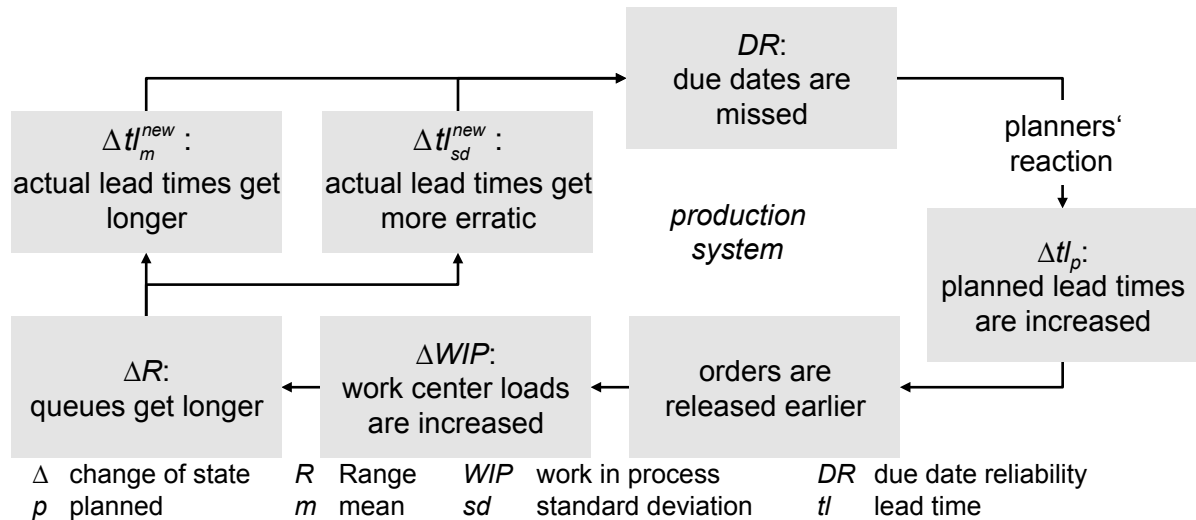
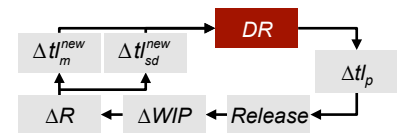


Figure 3.1 Steps of the Lead Time Syndrome (based on (Mather 1977; Wiendahl 1997a))

3.1.1 Initial Situation: Due Dates are Missed

The fundamental idea in the LTS argumentation is that initially production planners or other persons in charge observe a non-satisfying due date reliability. As defined in Section 2.1.2, due date reliability quantifies the ability of a worksystem or a complete production systems to meet agreed due dates. As the planners' aim to maintain high due date reliability, it is a crucial parameter in the LTS. This leads to the following question: How to measure due date reliability? Equation 3.1 (introduced in Section 2.1.2) defines due date reliability as a function of lateness, which is defined as the difference between actual and planned lead times (Lödding 2013; Yu 2001):



$$DR = \frac{\text{number of orders with } Low \leq L \leq Up}{\text{total number of orders}} \cdot 100$$

Equation 3.1

DR	due date reliability [%]
L	lateness [SCD]
Low/Up	lower/upper limit of due date tolerance [SCD]

For the investigation of the LTS this equation is insufficient due to the following shortcomings: (1) it is a past-oriented calculation, which requires a given set of manufacturing data. (2) no information is given about the underlying lateness distribution and (3) a quantifiable, equation-based link to changes of planned or actual lead times is impossible. Hence, an approach to quantify and anticipate the resulting due date reliability will be derived next.

To estimate or forecast the resulting due date reliability when planned or actual lead times are shifting initially a suitable due date reliability function has to be defined that relates it to planning parameters and system performance figures. Figure 3.2 shows a histogram of an exemplary lateness distribution, which seems to be normally distributed. Including a normal probability density function of lateness, the probability of each realization of lateness to fall in certain ranges is represented. Thus, in a simplified model, the distribution of lateness can be assumed to be a Gaussian distribution (see also central limit theorem (Hoang Pham 2006; Kozak 2008)). According to the cumulative distribution function formula of the Normal distribution (Hoang Pham 2006), due date reliability can be calculated as a function of the mean and standard deviation of lateness (Equation 3.2). The integration interval is defined by the upper and lower limit of the tolerance period, framing the share of orders that are considered to be on time.

$$DR = \frac{1}{L_{sd} \cdot \sqrt{2\pi}} \int_{x=\text{lower due date tolerance}}^{\text{upper due date tolerance}} e^{-\frac{1}{2} \left(\frac{x-L_m}{L_{sd}} \right)^2} dx$$

Equation 3.2

m	mean
sd	standard deviation

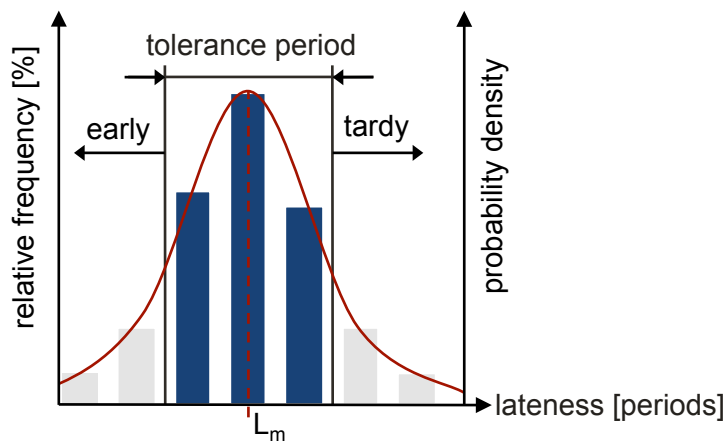


Figure 3.2 Due date reliability as a normal probability density function of lateness

This assumption has to be validated. Whether a sample of values is normally distributed is commonly tested by graphical methods, numerical methods, or formal normality tests (Razali 2011). Graphical methods such as histograms or Q-Q-Plots can easily be misinterpreted and are not sufficient to prove that the normal distribution assumption holds (Razali 2011). However, as shown in Figure 3.2 they are suitable to give a first impression. Numerical methods such as skewness (degree of symmetry) or kurtosis (degree of flatness) are able to describe the shape of a distribution. A standard normal distribution has a skewness of zero and a kurtosis of three (Park 2008). The skewness is positive for left shifted distributions with a longer right tail and the kurtosis is lower than three if the distribution is flatter than a normal distribution. According to Razali and Wah (Razali 2011), the most powerful normality test is the Shapiro-Wilk test (Shapiro 1968), followed by the Anderson-Darling test (Anderson 1954). Both tests calculate a p -value that is suggested to be greater than the critical alpha level of $\alpha > 5\%$. For $p > \alpha$, the null hypothesis can be accepted, thus it can be assumed that the dataset is normally distributed. To test whether it can be accepted that the lateness of orders is normally distributed, a set of manufacturing system feedback data was tested with the described numerical methods and the two formal normality tests. The resulting values of these randomly chosen cases¹² are listed in Table 3.1.

Table 3.1. Validation of the normal distribution assumption of lateness.

A,B,C: Manufacturing process feedback data of a steel manufacturer.

D,E: Feedback data of a manufacturing company in the process industry.

Test/Calculation System	Skewness	Kurtosis	Shapiro-Wilk test (p -value)	Anderson Darling test (p -value)	Measured (actual) due date reliability (acc. to Equation 3.1)	Calculated (anticipated) due date reliability (acc. to Equation 3.2)
A: Manufacturing process with multiple work stations	0,28	3.06	0,42	0,13	49%	45%
B: Bottleneck work station out of the manufacturing process of A	0,11	2.60	0,31	0,08	51%	51%
C: Single work station out of the manufacturing process of A	-0,06	2.56	0,10	0,14	91%	81%
D: Work station 246	0,40	2.98	0,15	0,06	68%	71%
E: Work station 71	0,28	3.27	0,28	0,14	79%	81%

¹² The chosen example cases are able to confirm or rather accept the assumption of a normal distribution. However, due to the limited number of cases, this approach is not able to prove the assumption (see Section 7.2).

For the randomly chosen manufacturing systems all tests result in values that confirm the assumption of a normal distribution. Small deviations from the above stated expectations, e.g., the positive skewness of four out of five cases can be explained by the fact, that negative lateness is naturally limited by the planned lead time ($L_{min} = -tl_p$ with $tl_a = 0$ SCD), whereas the maximum positive lateness is theoretically infinite. However, the goodness of fit can also be seen by comparing the actual measured due date reliability with the anticipated due date reliability based on the normal distribution function of lateness. Nevertheless, this assumption does not hold for all cases. If no planning or controlling is performed, situations may arise in which lateness is not normally distributed (see also case study results in Figure 5.4 of Section 5.2). Concluding, Equation 3.2 provides a suitable anticipation of the resulting due date reliability.

With a planned lead time adjustment in the second step of the LTS, both mean and standard deviation of lateness have to be expressed as functions of lead time to derive an expression of due date reliability as a function of lead times. The actual mean and standard deviation of lateness can be calculated ex post for the last j periods:

$$L_{m,k} = \frac{1}{j} \sum_{i=k-(j-1)}^k L_i = \frac{1}{j} \sum_{i=k-(j-1)}^k [tl_i^a - tl_i^p]$$

Equation 3.3

$$L_{sd,k} = \sqrt{\frac{1}{j-1} \sum_{i=k-(j-1)}^k (L_i - L_{m,k})^2}$$

Equation 3.4

tl	actual lead time
k	current period
j	period of investigation
a	actual
p	planned

However, the logistic operating curve theory by Nyhuis and Wiendahl is only valid for a manufacturing system in a stable, steady state (see Section 2.1.3) (Nyhuis 2009b). For long observation periods Equation 3.3 can be simplified to:

$$L_m = tl_m^a - tl_m^p$$

Equation 3.5

In practice, the length of the actual lead time correlates to the length of the planned lead time. To calculate the variance of the difference of two dependent random variables, the covariance of these variables has to be included into the term of $L_{sd,k}$ (Hoang Pham 2006; Kozak 2008; Shynk 2012):

$$L_{sd} = \sqrt{VAR(tl^a - tl^p)} = \sqrt{VAR(tl^a) + VAR(tl^p) - 2 \cdot COV(tl^a, tl^p)}$$

Equation 3.6

Substituting Equation 3.5 and Equation 3.6 into Equation 3.2 leads to the desired calculation of due date reliability as a function of actual and planned lead times:

$$DR = \frac{1}{\sqrt{VAR(t_l^{act} - t_l^{pl})} \sqrt{2\pi}} \int_{x=lower\ due\ date\ tolerance}^{upper\ due\ date\ tolerance} e^{-\frac{1}{2} \left(\frac{x - (t_l^{act} - t_l^{pl})}{\sqrt{VAR(t_l^{act} - t_l^{pl})}} \right)^2} dx$$

Equation 3.7

Equation 3.7 estimates the impacts of both actual and planned lead time changes on the resulting due date reliability. However, these estimations of resulting due date reliabilities apply only for the assumed steady state situation of a manufacturing system, excluding the short term fluctuations of the variables that possibly lead to the LTS or amplify its effects. Therefore, Equation 3.2 and Equation 3.7 calculate the maximum possible due date reliability for the given system state. In contrast to the initial ex post due date reliability calculation in Equation 3.1, these equations allow forecasting of future scenarios. If, for example, the actual lead time standard deviation is reduced by 10%, due date reliability will be increased by 6%. A further discussion of the advantage of a direct quantification of lateness adjustments is presented in Section 6.3. A qualitative visualization of situations with low due date reliability is shown in Figure 3.3. Using the derived equation to calculate the due date reliability, four scenarios are presented for increasing the resulting due date reliability again.

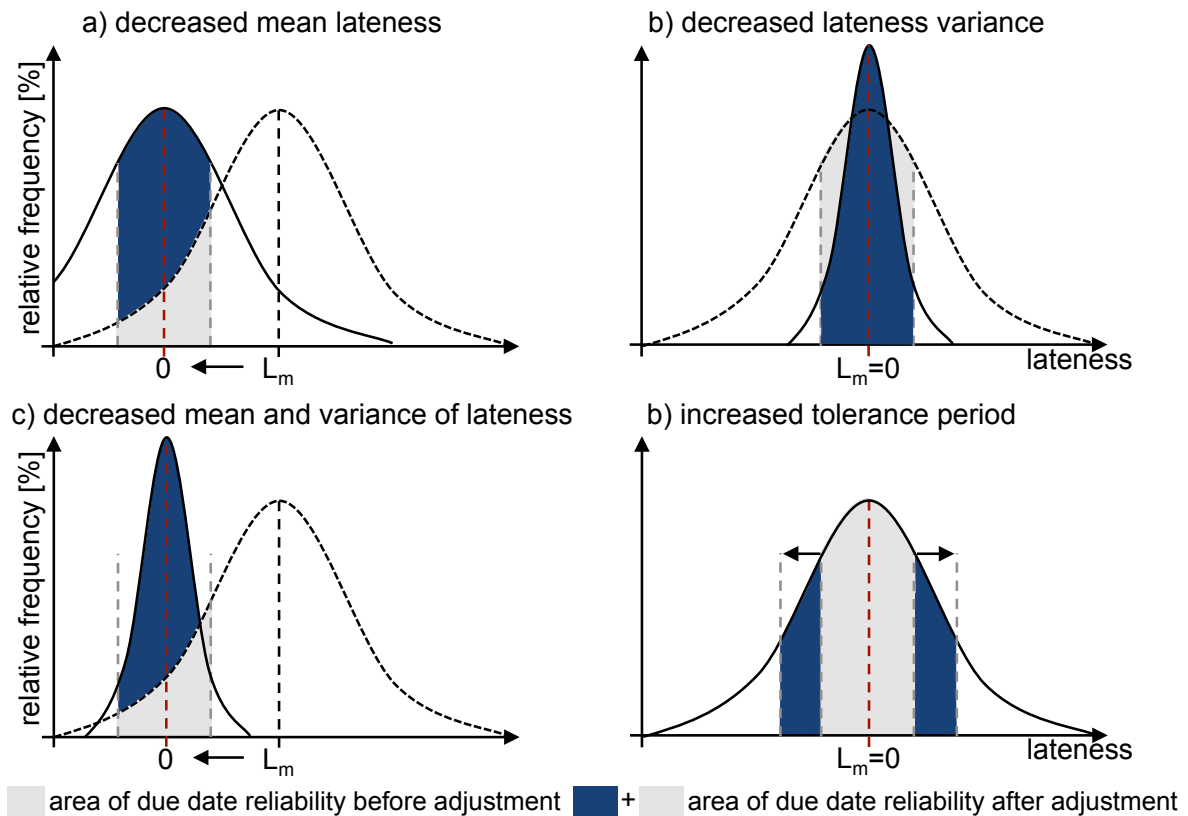


Figure 3.3 Visualization of the influence of various adjustments (a)-(d) on the resulting due date reliability

Equation 3.7 to calculate the due date reliability solely depends on the lateness distribution. In the context of Figure 3.3, this equations leads to the following intuitively obvious observations:

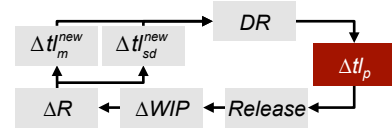
Observation 1: *The higher the lead time standard deviation (for a given due date tolerance), the lower the resulting due date reliability.*

Observation 2: *The lower the absolute mean lateness $|L_m|$, the higher the resulting due date reliability*

As due date reliability diminishes in the final step of the LTS, the resulting lateness or lead time standard deviation have to increase. To determine if this conclusion holds, the impact of a planned lead time adjustment is analyzed in the next section.

3.1.2 Planners' Reaction: Planned Lead Time Adjustment

In order to avoid delays and prevent the propagation of system disturbances production planners often add safety lead times to the originally planned lead times (see Section 1.1) (Lindau 1995). Equation 3.8 shows the resulting new planned lead time¹³. Assuming a reasonable planned lead time adjustment by planners, the question of the optimal magnitude of response arises. According to the definitions of due date reliability and lateness, the maximum increase in due date reliability can be achieved by reducing mean and variance of lateness, as noted in Observation 1 and Observation 2 (see also Figure 3.3). Hence, to minimize the actual lateness, Equation 3.9 defines the level of adjustment Δtl_p as the difference between the moving average of the actual lead time and the previously planned lead time.



$$tl_p^{new} = tl_p^{old} + \Delta tl_p \quad \text{Equation 3.8}$$

$$\Delta tl_p = tl_m - tl_p^{old} \quad \text{Equation 3.9}$$

with

$$tl_{m,k} = \frac{1}{j} \sum_{i=k-(j-1)}^k tl_i \quad \text{Equation 3.10}$$

$$tl_{sd,k} = \sqrt{\frac{1}{j-1} \sum_{i=k-(j-1)}^k (tl_i - tl_m)^2} \quad \text{Equation 3.11}$$

In this approach, the ‘optimal’ planned lead time adjustment is defined as value that would lead to the best possible due date reliability under the given constraints.

¹³ The LTS line of argumentation assumes constant (fixed) system capacities. Hence, the value-adding operation time (set up plus processing times) remains unchanged during changing lead times. Only the interoperation time – the sum of transportation and waiting times – is affected by changing lead times in Equation 3.8. Normally, interoperation times comprise over 95% of total lead times (Plossl 1988; Nyhuis 2009b). Thus, for reasons of simplification, a more in-depth analysis of the lead time elements is unnecessary (see also Section 2.1.1).

However, planners' reactions are rarely based on calculations but rather on a gut feeling. Such adjustments would lead to situations that are in the best case close to the presented optimal solution. Hence, an increasing mean and standard deviation of lateness is even more likely, which would lead to even worse situations. The mathematical modeling concentrates on the question whether the LTS is triggered even in the optimal case. Therefore, if the LTS is triggered in the optimal scenario, all other possible scenarios would lead into it accordingly. The influence of the planned lead time adjustments on the order release and the resulting work center loads are discussed next, which are the subsequent steps in the LTS.

3.1.3 Effects: Order Release Adjustment and Resulting Work Center Load



The LTS was firstly observed in 1977 in systems using backward scheduling (see also Section 1.1 and Section 2.2.1) (Mather and Plossl 1977). Thus, incoming orders are released at a specific date, which is calculated by subtracting the agreed due date from the assumed planned lead time. As a consequence of planned lead time adjustments in Section 3.1.2, Equation 3.12 shows that order release dates automatically shift by the amount of the adjustment.

$$order\ release\ date = due\ date - tl_p^{new} = due\ date - (tl_p^{old} + \Delta tl_p)$$

Equation 3.12

Figure 3.4 shows the resulting simplified throughput diagram of a work system with at least short-term fixed capacities (e.g. a not expandable bottleneck system) and order due dates where planned lead times are adjusted ‘today’. Orders *A-K* in Figure 3.4 have the same work content and disturbances are omitted. Exemplary, the planned lead time increases from four to six shop calendar days (SCD). Hence, all forthcoming orders (*G-K*) are planned backwards with the new planned lead time and released accordingly. Since the orders *G* and *H* would have been released in the past, their earliest possible order release is ‘today’. In this example case, this leads to a short-term increase of the WIP level ‘today’ from four to six orders (not only order *G* is released, but also order *H* and order *I*).

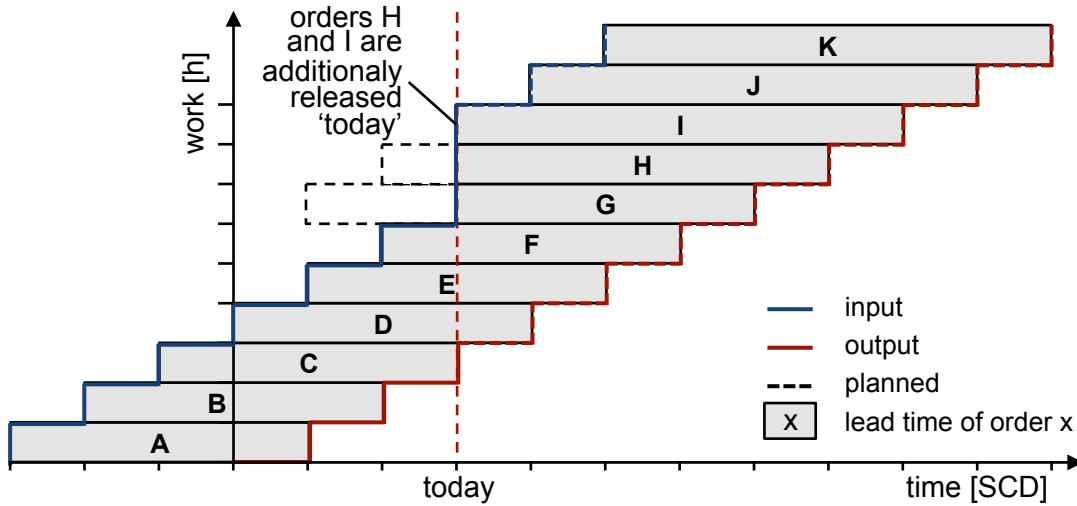


Figure 3.4 Throughput diagram of a work system: effect of earlier order release due to increased planned lead times

The mean WIP level is defined in Equation 3.13 as mean Range multiplied by the mean output rate (Funnel formula) (Nyhuis 2009b). Assuming a steady state, the variables range and lead time match (Nyhuis 2009b). Replacing the Range with the new planned lead time (see Section 3.1.1), Equation 3.14 and Equation 3.15 can be derived to quantify the influence of a planned lead time adjustment on the resulting WIP level. This work deviation can also be calculated in the example of Figure 3.4 ($\Delta t_l = 2\text{SCD}$; each order is assumed to have a work content of 1h): $\Delta WIP = 2\text{SCD} \cdot 1\text{h}/\text{SCD} = 2\text{h}$.

$$WIP_m = R_m \cdot ROUT_m \quad \text{Equation 3.13}$$

$$\Delta WIP = t_l^{new} \cdot ROUT_m - WIP_a \quad \text{Equation 3.14}$$

$$\Delta WIP = \Delta t_l \cdot ROUT_a \quad \text{Equation 3.15}$$

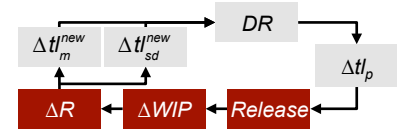
R range [SCD]
 WIP work in process [h]
 $ROUT$ output rate [h/SCD]

When the WIP level changes, the Range changes an amount ΔR :

$$\Delta R = \frac{\Delta WIP}{ROUT_a} \quad \text{Equation 3.16}$$

It can be seen that due to the assumed backward scheduling a planned lead time adjustment directly affects the WIP level and the range. As the variables WIP, range and lead time correlate according to the Logistic Operating Curve theory, the consequences of a changing WIP level on the resulting mean and standard deviation of lead times is quantified next.

3.1.4 Consequences: Resulting Mean and Standard Deviation of Lead Times



The calculated increase of WIP derived in the previous section leads to an increasing actual lead time. The resulting mean and standard deviation of lead times are calculated in Equation 3.17 and Equation 3.18. These equations incorporate the adding of a constant Δtl_p into Equation 3.10 and Equation 3.11. Both values are calculated each period k over the last j periods. A smaller averaging period j is chosen for systems in which a lower response time to fluctuations is desired. Figure 3.5 shows the resulting lead time variables for the example of a one-time increase of the actual lead time in period two. The standard deviation only increases temporarily from period two up to period eight, the duration of the averaging period which is $j-1$ periods (averages include the value in the current period).

$$tl_{m,k}^{new} = \frac{1}{j} \sum_{i=k-(j-1)}^k (tl_i + \Delta tl_{p,i})$$

Equation 3.17

$$tl_{sd,k}^{new} = \sqrt{\frac{1}{j-1} \sum_{i=k-(j-1)}^k [(tl_i + \Delta tl_{p,i}) - tl_m^{new}]^2}$$

Equation 3.18

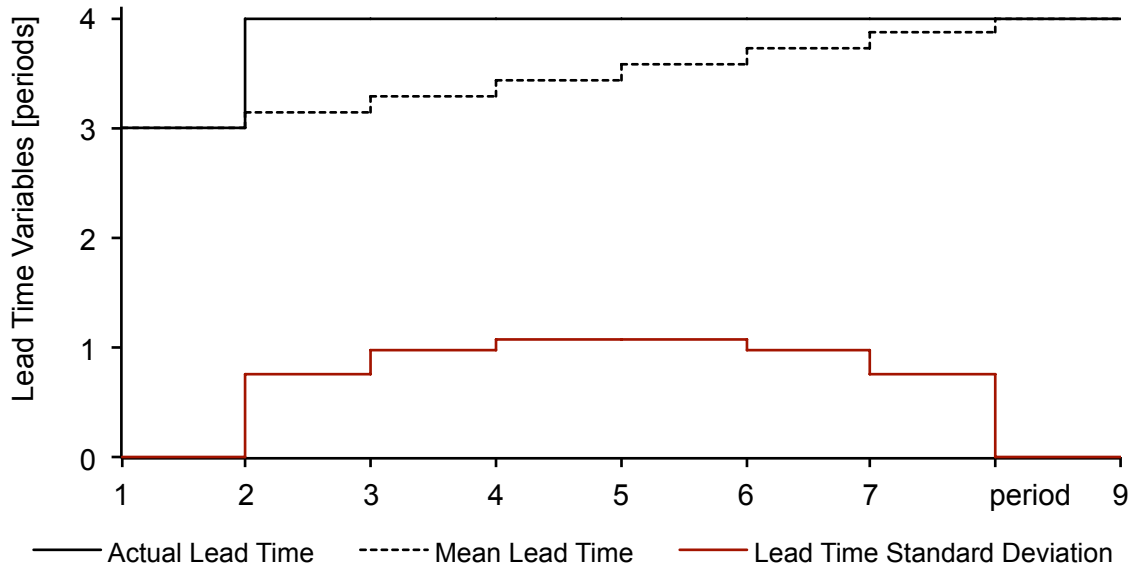


Figure 3.5 Simplified lead time adjustment: resulting mean and standard deviation of lead times at a one-time increase of lead times. $\Delta tl_p=1$ SCD in period 2; $j=7$

The standard deviation calculated in Equation 3.18 can also be expressed in a more general way. Equation 3.19 shows the different elements of the resulting lead time standard deviation after implementing planned lead time adjustments. The covariance term measures if the planned lead time adjustment was performed randomly or statically, or if planned lead times were adjusted in a certain ratio to the actual lead times. Hence, the variance of the resulting new lead time increases, if

planned lead times are adjusted separately for each order and if these adjustments correlate with the actual lead time.

$$tl_{sd}^{new} = \sqrt{VAR(tl_a^{old} - \Delta tl_p)} = \sqrt{VAR(tl_a^{old}) + VAR(\Delta tl_p) + 2 \cdot COV(tl_a^{old}, \Delta tl_p)}$$

Equation 3.19

However, Figure 3.5 also indicates the long-term effect of a single, static planned lead time adjustment, representing the steady state after adjustments. The resulting new mean lead time value is calculated simplified in Equation 3.20, which is the sum of the old lead time (before the adjustment) and the planned lead time adjustment level. The resulting variance of adjustments in Equation 3.19 is zero, as well as the covariance. For this case, the standard deviation returns in the long-term to its old level (Equation 3.21).

$$tl_m^{new} = tl_m^{old} + \Delta tl_p$$

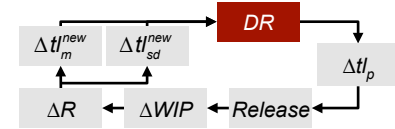
Equation 3.20

$$tl_{sd}^{new} = tl_{sd}^{old}$$

Equation 3.21

The derived equations distinguish between the short-term and the long-term effect of planned lead time adjustments. How they influence the resulting due date reliability is quantified in the next section.

3.1.5 Final Situation: Influence on Due Date Reliability – Closed Loop of Lead Time Syndrome



The preceding effects of a planned lead time adjustment affect the resulting lateness, thus also due date reliability. Surprisingly, the resulting mean lateness in Equation 3.22 remains unaffected. In contrast, however, the lateness standard deviation calculation in Equation 3.23 depends on the variance of the difference of the two resulting values actual lead time and planned lead time. Exemplary, if planned lead times change depending on orders or more than once per averaging period, the standard deviation of lead times rises. As discussed in the previous section, the short term due date reliability worsens due to the short-term increase of lead time standard deviation. This logic implies that the resulting new due date reliability in Equation 3.24 only worsens ($DR^{new} < DR^{old}$), if the lateness standard deviation increases.

$$L_m^{new} = (tl_m^{old} + \Delta tl_p) - (tl_p^{old} + \Delta tl_p) = tl_m^{old} - tl_p^{old} = L_m^{old}$$

Equation 3.22

$$L_{sd}^{new} = \sqrt{VAR(tl_a^{new} - tl_p^{new})} = \sqrt{VAR(tl_a^{old} + \Delta tl_p) + VAR(tl_p^{old} + \Delta tl_p) - 2 \cdot COV(tl_a^{new}, tl_p^{new})}$$

Equation 3.23

$$DR^{new} = \frac{1}{L_{sd}^{new} \cdot \sqrt{2\pi}} \cdot \int_{x=lower\ due\ date\ tolerance}^{upper\ due\ date\ tolerance} e^{-\frac{1}{2}\left(\frac{x-L_m^{new}}{L_{sd}^{new}}\right)^2} dx$$

Equation 3.24

The result of these interdependent equations throughout the steps of the LTS is a vicious cycle with a low due date reliability as its initiator. Hence, the short-term decrease in due date reliability could be misinterpreted by planners. If these planners once again decide to control their system using a planned lead time adjustment, the loop of the LTS would start again. Thus, the presented mathematical approach proves the correctness of the line of argumentation of the LTS. The impact of the LTS depends on the resulting lateness (and lead time) standard deviation. This brings up the question of how to measure the impact of the LTS on the logistic target achievement, which is quantified by the achievement of each of the four targets as described in Section 2.1.2. A definition of a suitable performance indicator is presented in the next section.

3.2 Due Date Reliability as Indicator for the Impact of the Lead Time Syndrome on the Logistic Target Achievement

The mathematical model of the LTS quantifies the impact of a planned lead time adjustment on each of the four targets of production logistic. However, monitoring each of the four targets in parallel to derive interactions that lead to the LTS or to quantify impacts of, e.g., planned lead time adjustments is not feasible for all analyses (e.g., see the control theoretic investigation in Section 4.2). Therefore, this section presents and justifies the use of due date reliability as the performance indicator for system performance, which provides a single indicator surrogate for the impact of the LTS on overall systems' performance. For this purpose, initially the interactions between the four targets are presented, which suggest that due date reliability is sufficient to reflect the emergence of LTS drawbacks. This assumption then enables the determination of two characteristics that lead in the scope of the LTS to a reduction of the due date reliability, thus triggers of the LTS that are analyzed in detail in the subsequent sections.

The influence of a planned lead time adjustment on each logistic target was derived in the previous section. To describe the relationships between the targets initially the assumptions of capacity utilization in the scope of the LTS are presented. In the mathematical model full capacity utilization is assumed, because for reasons of simplification the maximum available capacity is fixed in the presented approach. This proposition is valid, as it is assumed in the long-term that the WIP level is high enough to ensure (close to) full capacity utilization, which is approximately the case for an operating point that has a WIP level greater than the so called ideal minimum WIP level (see Section 2.1.3). With a fixed output rate, Equation 3.25 shows that the resulting change in WIP level solely depends on the

adjustment level of the planned lead time, which is also the case for the resulting lead time (see Equation 3.20). As explained in Section 3.1.3, the values *lead time* and *range* match in the long-term. The previous assumptions modify the so called Funnel Formula, resulting in Equation 3.26 (Nyhuis 2009b). The equation shows that only the lead time variable has to be observed to quantify the influence of the LTS on each of these tree targets, as the values *WIP* and *lead time* are linearly dependent from each other and the output performance is constant.

$$WIP^{new} = WIP^{old} + \Delta WIP = WIP^{old} + \Delta tl_p \cdot ROU_a$$

Equation 3.25

$$tl_m = \frac{WIP_m}{ROU_{max}}$$

Equation 3.26

According to the mathematical definition of lead time and lateness in Section 2.1.2, the resulting lead time performance is reflected by the variable lateness. With due date reliability as a function of lateness (see Section 3.1.1), the variable due date reliability combines all four targets for the given assumptions, thus being able to indicate the obtained system performance. Therefore, the impact of planned lead time adjustments and thus the influence of the LTS on the logistic target achievement is represented by the resulting due date reliability. This simplification is in line with the continuing goal of production planners to meet due dates and the logic of the LTS with due date reliability as its initial and final step. The previous paragraph showed that the variable due date reliability can be utilized as indicator for the impact of adjustments on logistic performance. These findings can be summed up as follows:

Due date reliability as performance indicator:

Due date reliability estimates the obtained system performance and enables quantification of the influence of the LTS on logistic target achievement.

Going one step further, the assumption of due date reliability as a function of lateness not only enables measurement of the impact of the LTS, but also enables estimation of the impact of adjustments on the resulting due date reliability. Hence, the presented qualitative comparison of adjustments in Figure 3.3 of Section 3.1.1 is enhanced by a quantitative calculation.

Table 3.2 depicts an exemplary *initial situation* in which both mean and standard deviation of lateness are two SCDs. With a tolerance period of ± 2 SCD, the actual due date reliability is given with 47% according to Equation 3.24. The reduction in lateness from two to zero SCDs leads in *Option (a)* to an increase in due date reliability of 21%. This instant estimation of a resulting due date reliability applies for the estimated steady state situation of a production process that is assumed in the logistics operating curve theory, excluding the short term fluctuations of the variables that can lead to the LTS. Hence, the maximum possible due date reliability at the given system state is calculated (see also Section 3.1.1). Table 3.2

also shows examples of other possible scenarios of due date reliability improvement (see Figure 3.3 for comparison). The five presented simplified options that could result from measures taken by production planners show the advantages of the introduced theory. Anticipating the expected due date reliability supports production planners in the decision-making process for selecting improvement measures. Moreover, the expected due date reliability improvement can be compared to the required time and effort of implementation for each option. The resulting benefits of this approach for PPC in general, and for production planners in particular is elaborated in Section 6.3 in more detail. It can be concluded that the instant calculation of adjustments enables the quantification of LTS impacts on the logistic target achievement in advance. Thereby, the resulting due date reliability of the five example scenarios reflects the maximum due date reliability that can be achieved in the long-term after the adjustment. The short-term impact of planned lead time adjustments - that was presented in Section 3.1 - will be considered next.

Table 3.2. Examples of measures taken by planners for due date reliability improvement.

	L_m [SCD]	L_{sd} [SCD]	Tolerance period [SCD]	DR [%]	Change of DR [%]
Initial situation	2	2	± 2	47	
Option a: Decrease mean lateness (e.g. adjust WIP or tl_p)	0	2	± 2	68	+21
Option b: Decrease variance of lateness (e.g. avoid rush orders)	2	1	± 2	50	+3
Option c (a&b): Decrease mean and variance of lateness	0	1	± 2	95	+48
Option d: Adjust tolerance period of lateness (in consultation with customers)	2	2	± 3	69	+22
Option e (c&d): Decrease mean and variance & adjust tolerance period	0	1	$\pm 1,5$	87	+40

To depict the impact of a planned lead time adjustment on the resulting due date reliability, Figure 3.6 shows exemplary the resulting due date reliability of the example discussed in Section 3.1.3 where the planned lead time was increased by two periods ($\Delta tl_p=2$) in period five, which leads to an increasing WIP level. As shown in Figure 3.6, the due date reliability initially decreases and recovers only after the actual lead time changes. This example excludes disturbances and assumes a constant actual lead time and an initial lateness of zero. However, this very simplified mathematical example reveals two significant characteristics that lead to the subsequent questions:

Characteristic a) The resulting due date reliability decreases in this example temporarily to a level of 0%.

Question (1) *What leads to a decreasing due date reliability?*

Characteristic b) The performed adjustment in period 5 leads to a decreasing due date reliability for several periods.

Question (2) *What influences the time period until the system (i.e., due date reliability) reaches a steady state again?*

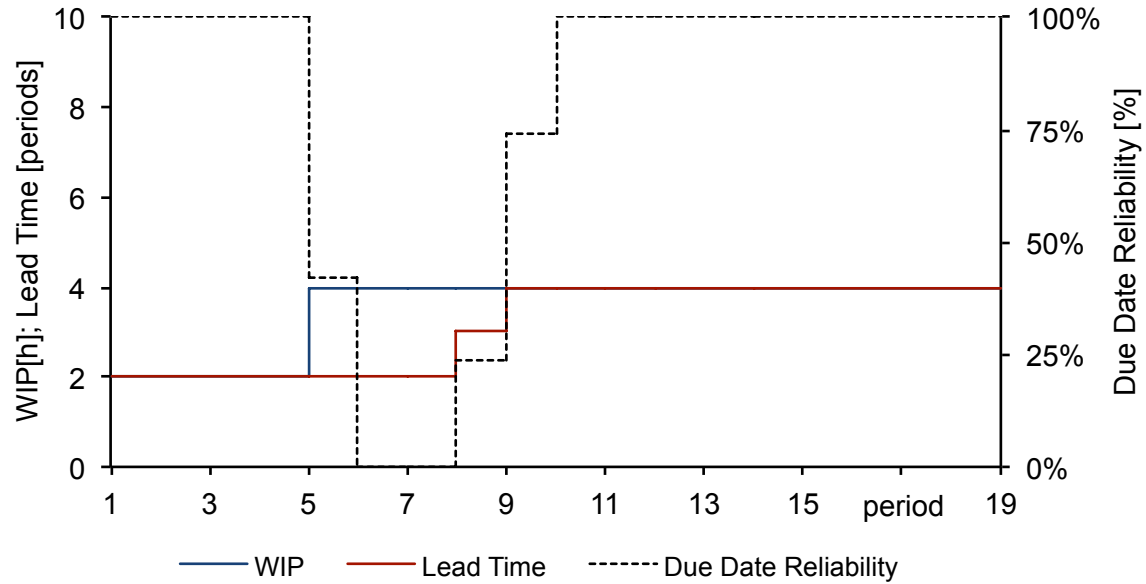


Figure 3.6 Resulting due date reliability at a one-time increase of planned lead times. $\Delta t_l = 2$ SCD; $j=4$; tolerance period: ± 1 SCD; no disturbances; capacity: 1 h/period

A detailed analysis is needed to answer both questions. In scope of the investigation of the LTS both characteristics express the same central question expressed below, which is analyzed in the next section.

Central Question:

What triggers the LTS and what influences the impact of the LTS drawbacks?

3.3 Main Triggers of the Lead Time Syndrome

It was shown that a planned lead time adjustment affects the logistic target values, hence WIP levels, lead times and finally the resulting due date reliability. As the latter one was defined as LTS impact indicator, this section focuses on reasons for a decreasing due date reliability that are able to trigger the LTS. The previous section revealed that the characteristics of the diminishing due date reliability strongly depend (1) on the resulting lead time standard deviation and (2) the time period until the system reaches a steady state again. Hence, reasons for increasing lead time standard deviation are discussed and quantified in Section 3.3.1. Afterwards, the latency period will be introduced in Section 3.3.2, which sums up the underlying delays in the LTS steps. Finally, the frequency of performed adjustments will be examined, which reflects the idea that production planners monitor the actual due date reliability periodically and (according to the LTS) adjust planned lead times without justification if due dates are missed.

3.3.1 Increase in Lead Time Standard Deviation

The LTS line of argumentation was analyzed in Section 3.1 using logistic equations. Obviously, an increasing lead time standard deviation is both a consequence and a trigger of the LTS. Moreover, with its negative impact on the resulting due date reliability (see Observation 1 in Section 3.1.1), the lead time standard deviation is a key value when investigating the LTS. Hence, this section focuses on reasons for and consequences of increasing lead time standard deviation in the scope of the LTS, beginning with a repetition of the mathematical connection and a more detailed investigation of the effects of backward scheduling. Afterwards, other reasons for increasing lead time standard deviation are presented, which are linked with the statistical correlation between mean and standard deviation. Finally, the findings are transferred into the logic of the LTS again.

Extending or reducing the planned lead time when trying to improve due date reliability strongly affects the value of the lead time standard deviation. The resulting lateness standard deviation calculation was shown in Equation 3.23 in Section 3.1.5. Moreover, Equation 3.24 showed that an increasing lateness standard deviation inevitably leads to a decreasing due date reliability.

It was shown in Section 3.1.1 that the lateness standard deviation strongly depends on the planned lead time adjustment. It increases, if the adjustment correlates with the actual lead time values (higher adjustment for longer lead times) or if it is order-specific. If the adjustment is constant for all orders (static adjustment), the lateness standard deviation reaches its initial value again in the long-term (see Equation 3.21). Hence, the more order-specific the planned lead time adjustments are, the higher the resulting standard deviation of both lead time and lateness will become.

In addition to the effect of the adjustment itself, the assumed backward scheduling of orders also affects the resulting short-term lead time standard deviation. In the dynamic environment of production processes, these short-term increases of the lead time standard deviation also lead to further fluctuations within the process chain, such as lead time fluctuations in subsequent processes. Hence, not only is the resulting due date reliability of the adjusted system diminished for a short period, but also subsequent systems are affected in the long-term. Figure 3.7 shows the effect of orders that are released earlier or later than previously planned. The effect itself was already described in Section 3.1.3, which initially only affects the resulting WIP level. However, when these orders are processed, the resulting lead time variables (actual, mean and standard deviation of lead time) react differently, depending on whether they were released earlier or later.

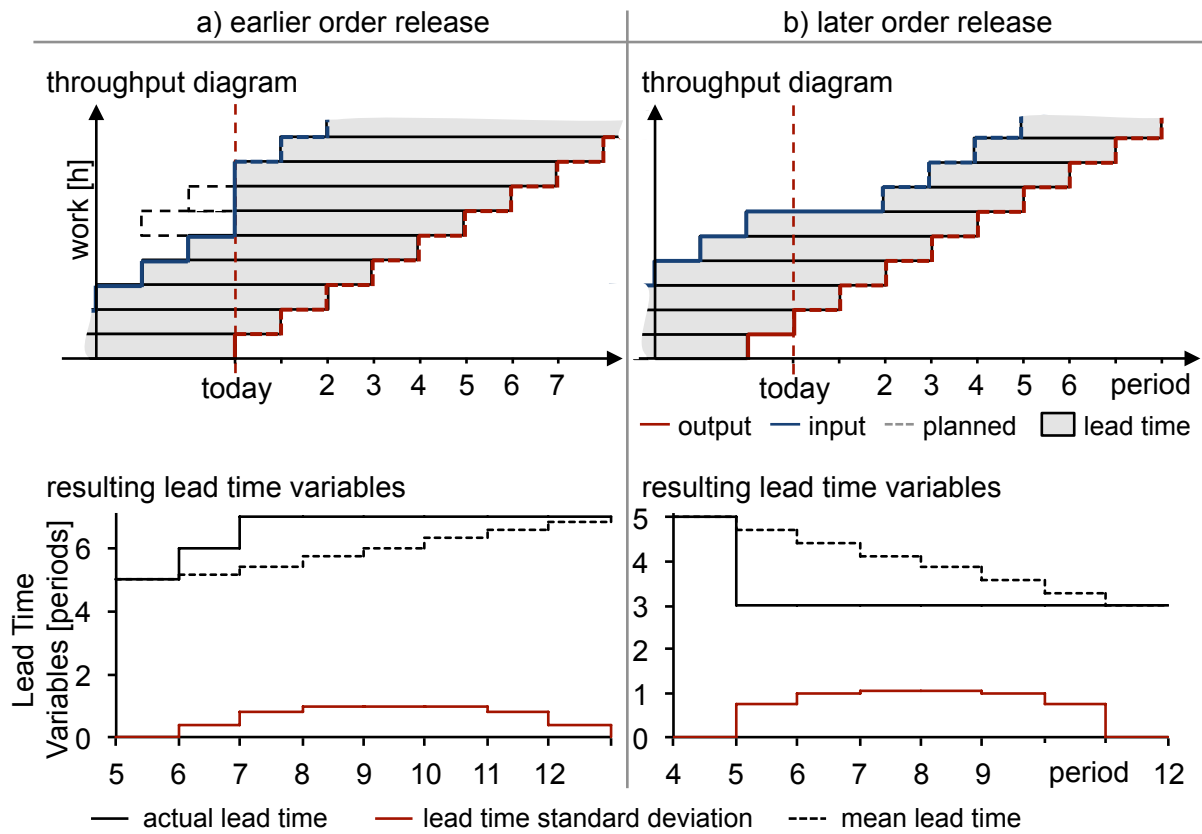


Figure 3.7 Effect of earlier (a) or later (b) order releases on the resulting lead time variables using backward scheduling. Averaging period length $j=7$; a) $\Delta tl_p=2$ SCD; b) $\Delta tl_p=-2$ SCD;

For earlier order releases, the simplified depiction in part (a) of Figure 3.7 shows that the higher the planned lead time increase, the more orders have to be released ‘today’. Hence, the actual lead time does not suddenly jump to the new planned lead time if orders are released earlier. This leads to a longer period in which the lead time standard deviation is increased (in the example case for seven (part a) instead of six periods (part b)). In contrast to this, part (b) of Figure 3.7 shows that a reduction of the planned lead time leads to a later order release, thus to a sudden jump of the actual lead time. In this case, the length of the increasing lead time standard deviation depends only on the averaging period, thus for $j-1$ periods, as the averaging also includes the value in the current period.

Equation 3.23 also includes the actual (LTS independent) lead time standard deviation, which is a consequence of endogenous or exogenous disturbances. Endogenous disturbances arise in the process itself, such as machine breakdowns or sequence deviations. Exogenous disturbances arise outside the process like material shortages. During production, disturbances such as operation disruptions and unstable demand patterns may result in deviations from the original production schedule. According to Wiendahl (1997), it is the responsibility of manufacturing control to mitigate the causes of uncertainty in production and to react to disturbances. Thus, disturbances in production processes inevitably lead to uncertainties in planning processes and thereby to an increasing discrepancy between planned and actual data. On one hand disturbances are by themselves

deviations of planned to actual data and on the other hand incidents that induce these deviations (Patig 1999). Some of the possible disturbances are listed in Table 3.3. These disturbances affect the performance of a production process quantitatively, qualitatively, and regarding its due date performance, while (as a consequence of required rework) qualitative and quantitative deviations also affect the due date performance (Schwartz 2004). More specifically, all disturbances contribute to the measured due date reliability.

Table 3.3. Disturbances and causes of uncertainty in production (based on (Koh 2006; Schwartz 2004; Lindau 1995; Ludwig 1995; Patig 1999)).

Production facilities	<ul style="list-style-type: none"> Machine capacity shortages Processing errors (scrap/rework) Machine breakdown Tool shortages Unexpected maintenance
Human resources	<ul style="list-style-type: none"> Qualification and machine-dedication¹⁴ Absenteeism Processing errors / Fatigue (scrap/rework) Limited flexibility
Material	<ul style="list-style-type: none"> Material shortage Poor supplier delivery performance Material defects High work in process level
Information processing	<ul style="list-style-type: none"> Inaccurate process feedback Wrong planning parameters Data errors Forecasting problems
Order processing	<ul style="list-style-type: none"> Sequence deviation through unexpected rush orders Schedule not followed Fixed batch sizes Priority rules Order cancellations

To mitigate the uncertainties that arise with disturbances and high fluctuations, production planners often execute measures of precaution that themselves can lead to an increasing standard deviation. If, e.g., safety stocks or safety lead times are implemented (Lindau 1995), mean lead times and WIP levels increase, hence triggering the LTS as described in Section 1.1. This correlation between an increasing mean lead time and the resulting increase of the standard deviation is well known in statistics. The mean and standard deviation of a random sample x_1, \dots, x_j are defined as $m(x) = \frac{1}{j} \sum_{i=1}^j x_i$ and $s^2(x) = \frac{1}{j-1} \sum_{i=1}^j (x_i - m(x))^2$ (Hoang Pham 2006). From the LTS point of view, the question is whether or not a higher

¹⁴ The ability to process only specified operations (also a disturbance in terms of the production facility) (Wu 2006).

mean value affects the value of the standard deviation. Thus, multiplying each x_i with a factor $b \in \mathbb{R}$, the following new values of mean and standard deviation result:

$$m(bx) = \frac{1}{j} \sum_{i=1}^j (x_i \cdot b) = m(x) \cdot b \quad \text{Equation 3.27}$$

$$s(bx) = \sqrt{\frac{1}{j-1} \sum_{i=1}^j ([x_i \cdot b] - [m(x) \cdot b])^2} = \sqrt{b^2 \cdot \frac{1}{j-1} \sum_{i=1}^j (x_i - m(x))^2} = s(x) \cdot b \quad \text{Equation 3.28}$$

These equations demonstrate that multiplying the mean with a factor of b leads to an increase of the standard deviation with the same factor. This connection is known in statistics under the term ‘important rules for variance’ for random variables (Kozak 2008). The meaning of this effect is exemplary shown in part (a) of Figure 3.8. Based on a random proportion of mean to standard deviation (blue point in the figure), the slope of the straight line characterizes the mathematical connection between both variables. In the given logarithmic scale, the slope of the straight line does not change with increasing/decreasing ratios or example values of the variables. This logical statistical connection can be compared with the experience of production planners that an increasing lead time automatically leads to a higher lead time standard deviation. Part (b) of Figure 3.8 shows production system feedback data of four different companies. Company A is a global manufacturer in the process industry. Companies B & C are medium-sized machine tool manufacturer with a job-shop production system and company D analyzes steel samples in semi-automated laboratories¹⁵.

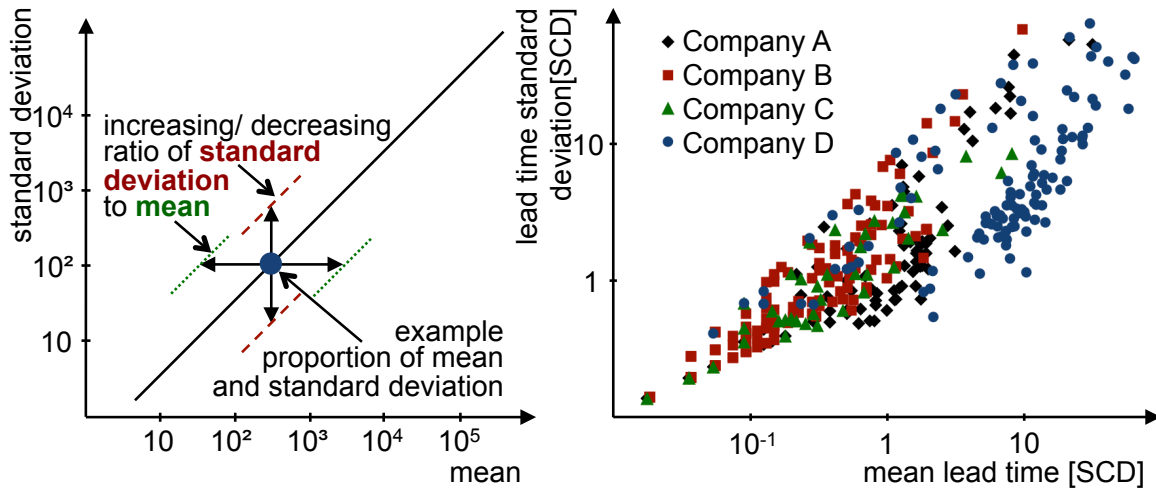


Figure 3.8 a) Statistical correlation between mean and standard deviation; b) Correlation of mean and standard deviation of lead times in real production systems

Part (b) shows the average production system lead times on a logarithmic scale compared with the respective lead time standard deviation. The interpretation of this plot first of all reveals an obvious correlation between both variables. Moreover, the distribution lies in a corridor that is characterized by its lower and upper

¹⁵ The investigation periods of the feedback data differ from three month to one year.

borders. A detailed interpretation of this distribution is out of scope of this thesis. However, it shows that the statistical link between both variables exists in practice. The upper bound describes a straight line from the shape and slope of the statistical correlation of part (a). The lower bound of the distribution can be interpreted as the minimum feasible standard deviation for the given mean lead time. This can be explained, e.g., by the operation time standard deviation (Nyhuis 2009b; Ludwig 1995). One approach to interpret the scattering of the distribution between the upper and lower border can be the attempt of production planners to minimize the lead time standard deviation with respect to the process specific mean lead time.

Transferring this connection into the LTS investigation, an increasing mean lead time through increased planned lead times is directly accompanied by an increase in lead time standard deviation. The statistical correlation between both variables and moreover the correlation in real production systems raises the question, if it is possible to transfer it into a formula that calculates an estimated value of the lead time standard deviation. Depending on the chosen adjustment value, a predictive value of the worst case standard deviation (depicted by the upper bound in part (b) of Figure 3.8) can be derived from Equation 3.28:

$$t_{sd,max}^{new} = t_{sd}^{old} \cdot \left(1 + \frac{\Delta t_l^p}{t_m^{old}} \right)$$

Equation 3.29

The multiplier of the old lead time standard deviation in Equation 3.29 (see term in brackets) is derived by solving the following adjoint equation $tl + \Delta t_l^p = tl \cdot b$ for the fictive multiplier b . Figure 3.9 transfers the described correlation into the context of the LTS. Therefore, by trying to produce late orders in time, lead times are increased to a certain degree. Thus, for example, disturbances get more likely. This leads to an increased lead time standard deviation, which once again demand longer lead times. To absorb the increasing standard deviation, the adjustments increase with each LTS-loop, leading to longer and more erratic lead times with every iteration.

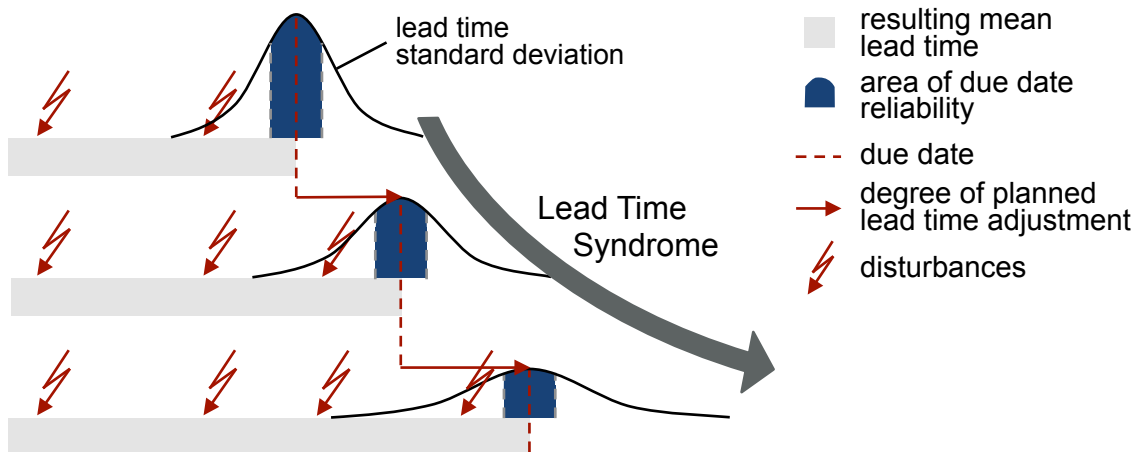


Figure 3.9 Schematic representation of standard deviation caused by lead time adjustments

These explanations suggest that in scope of the LTS, lead time standard deviation is mainly caused by the three factors: backward scheduling, disturbances, and the planned lead time adjustment itself, which is linked to the statistical correlation between mean and standard deviation. Moreover, the level of increase is statistically restricted. An increasing standard deviation as a consequence of increasing lead times confirms the line of argumentation of the LTS. The results presented in this section can be summed up in the following proposition, which has to be validated in the following chapters:

P_1 : Standard deviation: *The longer the lead time and the higher the planned lead time adjustment, the higher the lead time standard deviation, hence the lower the due date reliability.*

3.3.2 Long Latency Period and High Frequency of Adjustments

The due date calculation example presented in Section 3.2 revealed the major influence of the latency period on the resulting due date reliability. The latency period is defined as the time period after a planned lead time adjustment until the calculated due date reliability reaches a steady state again. In practice, various delays sum up to a cumulated latency period in-between checking the actual due date reliability and the situation of a system within a steady state. Therefore, initially the delay components of the latency period are presented in the scope of the LTS. Then, the correlation between the latency period and the observed due date reliability is discussed in different scenarios to finally derive a proposition of the influence of the latency period and the frequency of adjustments (i.e. the time period between successive planned lead time adjustments) on the emergence of the LTS.

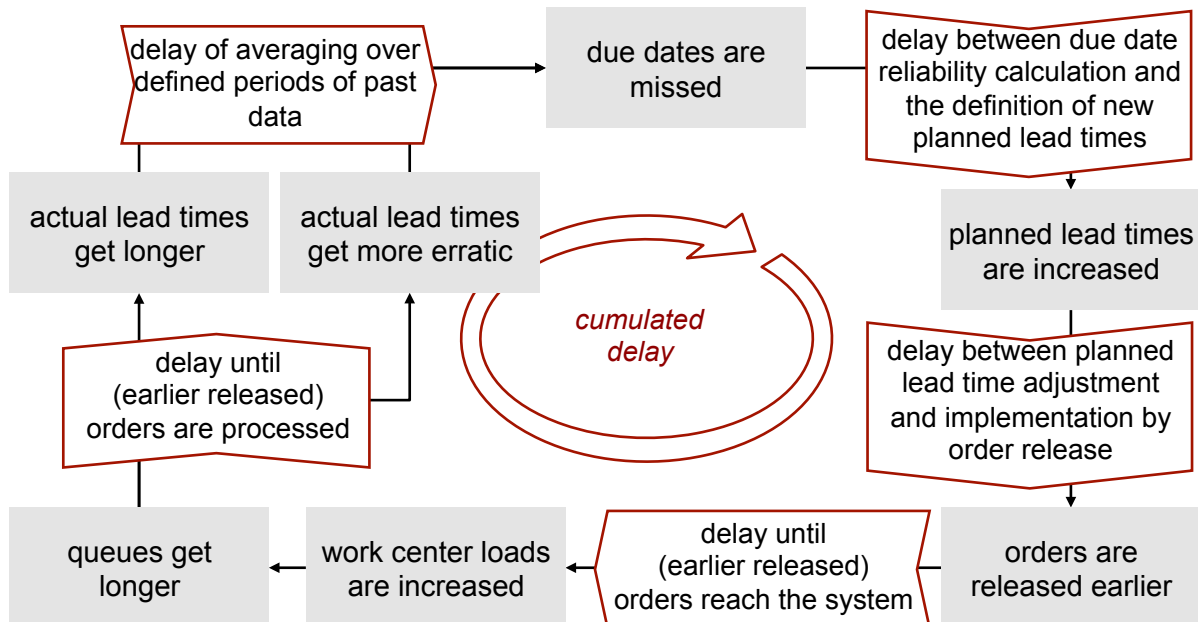


Figure 3.10 Delays between cause and effect in the LTS

Figure 3.10 allocates various delays in the LTS. The first delay arises before planners define new planned lead times. Here, the lead times of recent periods have to be analyzed manually or using an IT-system to monitor the actual due date

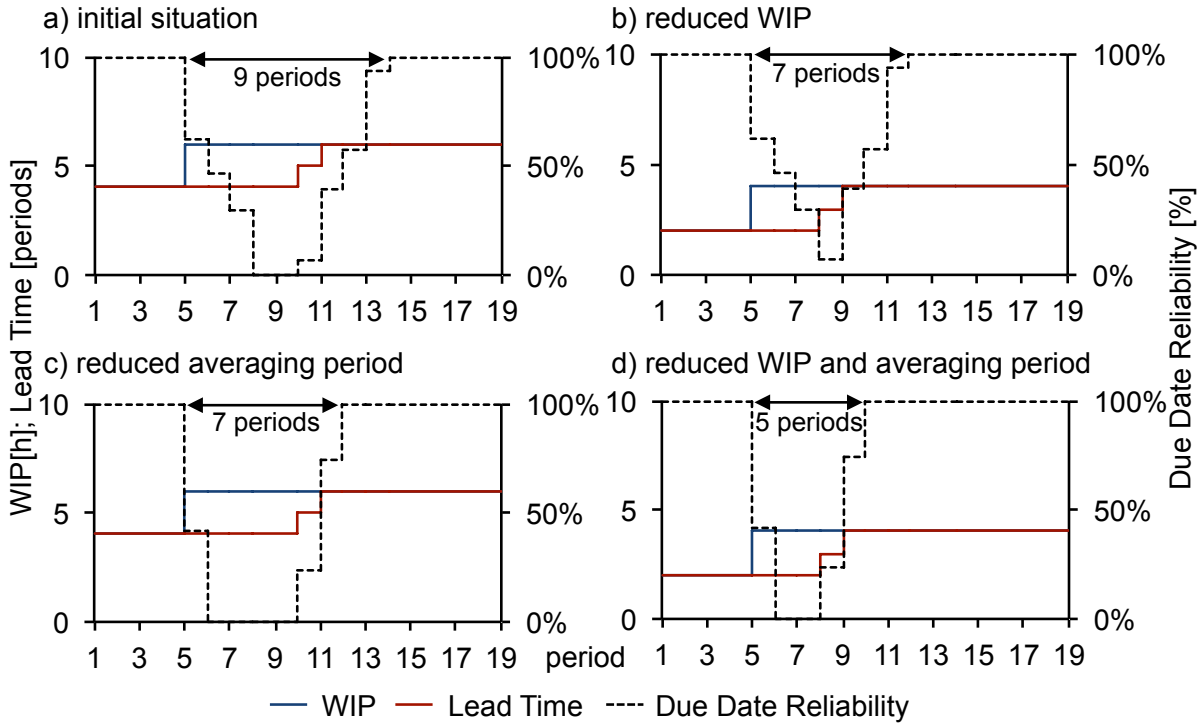


Figure 3.12 Latency period comparison for different responses to a one-time increase of planned lead times by $\Delta tl_p=2$ SCD at period 5; *tolerance period*: ± 1 SCD; *information delay*: 0 SCD; a) initial situation with averaging over $j=4$ periods for an initial WIP level of $WIP=4h$; b) $j=2$; $WIP=4$; c) $j=4$; $WIP=2$; d) $j=2$; $WIP=2$

However, a reduction of the averaging period length leads to an increasing vulnerability to short term fluctuations, as outliers more strongly affect the mean if less values are averaged. With higher sensitivity, short-term fluctuations might decrease due date reliability, thus demand for further planned lead time adjustments. Hence, there is a trade-off between short latency periods and a low sensitivity to short-term fluctuations, as a longer averaging period directly increases the latency period. The definition of the latency period and its influence on the resulting due date is summarized by the following observation:

Observation 3: *The longer the latency period, the longer it takes for a planned lead time adjustment to take effect and the longer the diminished, unstable due date reliability persists.*

The impact of the latency period on the due date reliability does not automatically lead to the LTS. But, as planners continuously monitor the actual due date reliability, short-term reductions of this critical value may lead to renewed planned lead time adjustments, hence into the LTS. The described effect is shown exemplary in Figure 3.13. Planned lead times are adjusted in period two, leading to a short-term reduction of the actual due date reliability. If planners monitor this reduction in period five, a renewed planned lead time adjustment might seem sensible for them again.

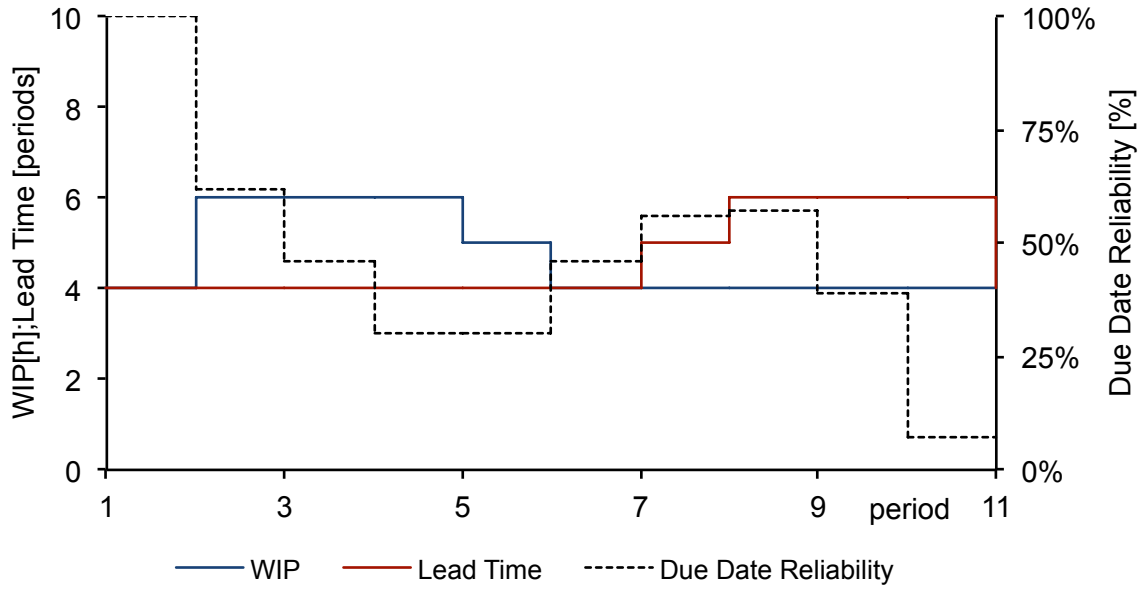


Figure 3.13 Resulting due date reliability after repeated adjustments of planned lead times. $\Delta tl_{p,2}=+2$ SCD; $\Delta tl_{p,5}=-2$ SCD; $j=4$; tolerance period: ± 1 SCD; information delay: 0 SCD;

For this exemplary case, the system is not able to reach a steady state (i.e., at least until period 11). If planned lead times are repeatedly adjusted the latency period will theoretically get infinite, hence the due date reliability does not reach its initial value again. Thereby, the adjustment period length, which is the time period between two consecutive planned lead time adjustments, seems to have a large impact on the likelihood of such a situation, thus characterizing the LTS. If planners monitor due date reliability at a higher frequency (shorter adjustment period length) than the system requires to reach a steady state, the LTS is more likely to be triggered. This simplified example exclusively included the effect of the short-term impact on the lateness standard deviation described in Section 3.1. But, the longer the reaction time of the observed system gets, the more likely endogenous or exogenous disturbances get (see Table 3.3 in Section 3.3.1). These disturbances affect the running processes and affect the measured variance of both lead times and WIP levels. If planners tend to react too soon after the last adjustment, the observed system may not be able to reach a steady state. The correlation between these values leads to the definition of the second proposition, which has to be validated in the following chapters:

P_2 : Frequency of adjustments: *The LTS leads to a reduced logistic performance if the adjustment period length is shorter than the latency period (the sum of processing and information delays) of the adjusted system.*

3.4 Summary of the Lead Time Syndrome Validation and Derived Propositions

The aim of this chapter was mathematical characterization of the underlying LTS effects to validate the LTS line of argumentation and to reveal interactions that trigger the LTS. Following the steps of the LTS, the effect of a planned lead time adjustment on other logistic key figures was quantified in the first section. The mathematically derived influence of planned lead time adjustments on the due date reliability proves that the argumentation of the LTS holds: The adjustment of planned lead times to increase due date reliability leads (in the short-term) to a decreasing due date reliability. If planners overreact and repeatedly adjust planned lead times, the LTS is triggered. The impact of the LTS depends on the resulting lateness (and lead time) standard deviation. Moreover, with the definition of due date reliability as a normal probability density function of lateness, due date reliability and lateness standard deviation correlate negatively. In the second section, due date reliability was defined as an indicator for the obtained system performance. It was shown that, in the scope of the LTS, monitoring due date reliability is sufficient, which makes separated analyzes of the other three target values redundant for the scope of this thesis. Thus, the calculation of due date reliability provides a quantification of the influence of the LTS on logistic target achievement. Moreover, the implicit assumptions of the LTS line of argumentation were noted, among them fixed capacities and backward scheduling as scheduling technique.

The mathematical definition of the LTS and the choice of due date reliability as indicator of the LTS impact provided the fundamental basis for identifying the main triggers of the LTS drawbacks in the third section. Hence, reasons for a decreasing due date reliability in the scope of the LTS were identified. With the negative correlation of due date reliability and lead time standard deviation, the three factors backward scheduling, disturbances, and the planned lead time adjustment were identified as main triggers of lead time standard deviation in the scope of the LTS. Therefore, the increase of standard deviation is both a cause and an effect of the LTS and its level of increase is statistically restricted by the lead time increase. However, while standard deviation induces a diminishing due date reliability, the latency period and the frequency of adjustments lead to the LTS. Thus, the longer the time period after a planned lead time adjustment persists until the calculated due date reliability reaches a steady state again, the more likely it becomes that renewed planned lead time adjustments are performed by planners. More specifically, if adjustments are performed before the system reaches a steady state after the previous adjustment, effects overlap and lead to the LTS (the system is in a non-steady state). Summing up the research results presented in Chapter 3 the following two propositions were derived:

P₁: Standard deviation: *The longer the lead time and the higher the planned lead time adjustment, the higher the lead time standard deviation, hence the lower the due date reliability.*

P₂: Frequency of adjustments: *The LTS leads to a reduced logistic performance if the adjustment period length is shorter than the latency period of the adjusted system.*

Whether the derived conclusions and propositions of this mathematical approach hold true will be analyzed in the control theoretic investigation of the LTS in Chapter 4. Therefore, initially a control theoretic model is developed and validated. Then, based on the first proposition, the impact of a strategy to dampen the LTS by a reduction of the lead time standard deviation is evaluated (reduced magnitude of response). Based on the second proposition, also various ratios of adjustment frequency and delay are investigated to define an ‘appropriate’ adjustment frequency for the given system states.

4 Control Theoretic Derivation of Lead Time Syndrome Interactions and Triggers¹⁶

*“Control theory enables a targeted manipulation
of a partially known system”
(free translation from (Föllinger 2008))*

The mathematical model of the LTS in the previous chapter revealed two triggers of the LTS. First, planned lead time adjustments directly increase the lead time standard deviation. Second, the impact of the LTS effects is higher, if the adjustment period length is shorter than the latency period¹⁷ of adjustment implementations. The aim of this chapter is to validate these propositions and to derive strategies to dampen or, if possible, avoid the LTS.

Section 2.2.3 showed that the LTS phenomenon is closely related to positive feedback known from control theory. Control theory provides tools to simulate and systematically manipulate dynamic systems, with the goal of obtaining desired system behavior (Nagrath 2006). Thus, a control theoretic model of a single work system will be developed to investigate the impact of the LTS on logistic target achievement for varying variable settings¹⁸. In more detail, the approach is structured following the “simulation model development process” of Manuj et al. (2009), which was developed to design, implement, and evaluate logistic simulation models and is modified to meet the needs in this research approach (Manuj 2009):

Step 1: Formulate problem and objectives (Section 4.1.1)

Step 2: Specify independent and dependent variables and develop a conceptual model (Section 4.1.1)

Step 3: Develop and verify control theoretic model (Section 4.1.2)

Step 4: Perform preliminary simulations to validate the control theoretic model and determine model parameters (Section 4.1.3)

Step 5: Analyze and document results (Section 4.2)

Following these steps, the development and validation of the control theoretic model are presented in Section 4.1, thus including Step 1 – Step 4. Under use of this

¹⁶ Parts of this chapter have been published in similar form in (Knollmann 2013a; Knollmann 2014a; Knollmann 2014b; Windt 2014).

¹⁷ The latency period is the sum of information and processing delay (defined in Section 3.3.1). The processing delay is a resulting value and is not controlled in the presented model, while information delay is variable and used to simulate different delay scenarios. See also Section 4.1.1.

¹⁸ The assumption of a single work system is discussed in Section 7.2.

model, the results of the control theoretic investigation of the LTS (Step 5) are presented in Section 4.2 and summarized in Section 4.3.

4.1 Control Theoretic Model Development

To investigate the LTS in a control theoretic simulation, initially the required model has to be developed. Following the above introduced steps of the simulation model development process, a more precise formulation of the control model objectives is presented in Section 4.1.1 (Step 1). This section also aggregates independent and dependent variables in the context of the LTS, which are then transferred into a conceptual model of a single work system with planned lead time control (Step 2). Afterwards, the resulting required model components and assumptions are used to finally develop a control theoretic simulation model in Section 4.1.2 (Step 3). The validation of this model is presented in Section 4.1.3, which also results in a justified determination of underlying model parameters (Step 4).

4.1.1 Development of a Conceptual Model

The development of a simulation model to investigate LTS interactions initially requires a formulation of the problem and model objectives (Step 1). Based on these requirements a modeling methodology has to be chosen. This choice and identification of LTS specific independent and dependent variables (Step 2) enable the derivation of a conceptual model, which builds the foundation for developing a simulation model in the next section.

Step 1: Formulate problem and objectives

Starting with the problem formulation, the mathematical modeling of the LTS in Chapter 3 revealed that it can be triggered by the increase in lead time standard deviation as a direct consequence of planned lead time adjustments and secondarily by the frequency and the information delay of adjustments. However, to derive strategies that enable the damping or avoidance of the LTS a definition of an ‘appropriate’ adjustment frequency of planned lead time adjustments is required. Moreover, the impacts of higher or lower magnitudes of planned lead time adjustments on the resulting system performance have to be comparable. In addition to the derivation of strategies to handle the LTS a validation of the propositions of Chapter 3 is required. Hence, the aim of the simulation model is to gain knowledge about the cause-effect relation between information delay, adjustment frequency, and magnitude of adjustments on the resulting system transient response and performance as measured in due date reliability.

Section 2.2.3 showed that the process of maintaining a high logistic target achievement is basically a classical control problem as manufacturing parameters (control variables) are continuously adjusted according to planned values (reference variables) (Schuh 2006). This correlation was depicted in the closed loop of

production planning and control presented in Figure 2.11 of Section 2.2.3. Furthermore, Section 2.2.3 showed that the LTS problem is closely related to positive feedback, which is a classical problem in control theory. Even small perturbations can lead to unstable system behavior (Nagrath 2006). On one hand the similarity of the LTS to positive feedback enables transferring of strategies from control theory to damp positive feedback into strategies to damp the LTS. On the other hand this correlation suggests the investigation of the LTS in a control theoretic model.

According to DIN 19226, controlling is defined as a process (see Figure 4.1) in which the continuously measured control variable x is compared to a reference variable w , which results in possible reference variable adjustments (DIN19226 1994). Control theory studies the systematic manipulation of dynamic systems to obtain a desired output signal, whereby the principle of feedback enables this continuous controlling and manipulation (Nagrath 2006). Control theoretic models represent the dynamic behavior using differential equations. Moreover, control theory aims to produce a targeted system behavior, which is different from the so-called system dynamics approach that aims to describe characteristics of system behavior (Scholz-Reiter 2008). Hence, control theory can be used to analyze changes over time, while system dynamics especially focuses on long-term behavior. Control theory enables investigation of short-term oscillatory behavior and transient response of a simulated work system. Individual orders are not modeled in a continuous time model, which makes it difficult in control models to directly transfer logistic correlations (Scholz-Reiter 2008). However, research in control theory has made progress in the last decades in modeling discrete-time production systems (see e.g. (Ratering 2003) and Section 2.2.3). Therefore, a control theoretic model of a single work system will be developed to investigate the impact of the LTS on the logistic target achievement.

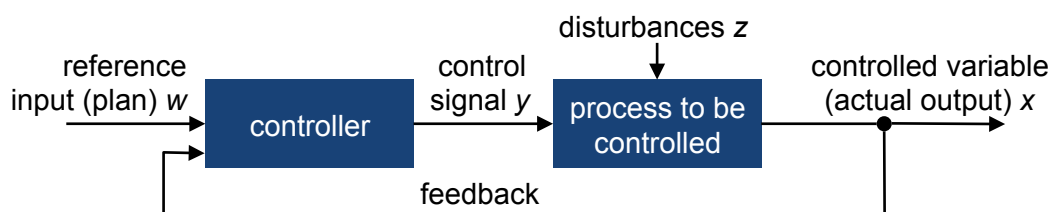


Figure 4.1 Block diagram of a feedback control system (DIN19226 1994; Wendt 2012)

Step 2: Specify independent and dependent variables and develop a conceptual model

To develop a control theoretic simulation model initially the model components and underlying assumptions have to be determined by means of a conceptual model. The necessary variables to develop this conceptual model are according to Manuj et al. (2009) in theory divided into independent and dependent variables. Dependent variables are measured to monitor the performance. Independent variables are adjustable control variables that affect the dependent variables (Manuj 2009). To measure the impact of the LTS on the resulting performance the dependent

variables are defined by the four logistic targets *WIP*, *lead time*, *due date reliability*, and *capacity utilization* as well as the directly related variables (e.g., *lateness* or *actual capacity*). The independent variables are defined on the basis of the mathematical model of the LTS in Chapter 3:

- a variable *input rate variance* to influence the variability in the work system
- the time period between two possible planned lead time adjustments is defined by the *adjustment period length* (adjustment frequency)
- the time required to set new planned lead times and to implement order release adjustments is defined by the *delay* (information delay)
- the level of planned lead time adjustments is adapted by the *magnitude of response*
- the due date tolerance is defined by *lower* and *upper tolerance limits*

Figure 4.2 depicts the resulting conceptual model of a single work system to visualize the key components and connections between the variables. The components of the manufacturing process are similar to the components in the Funnel Model (see Section 2.1.3) and have the same structure as the simple feedback loop presented above (see Figure 4.1).

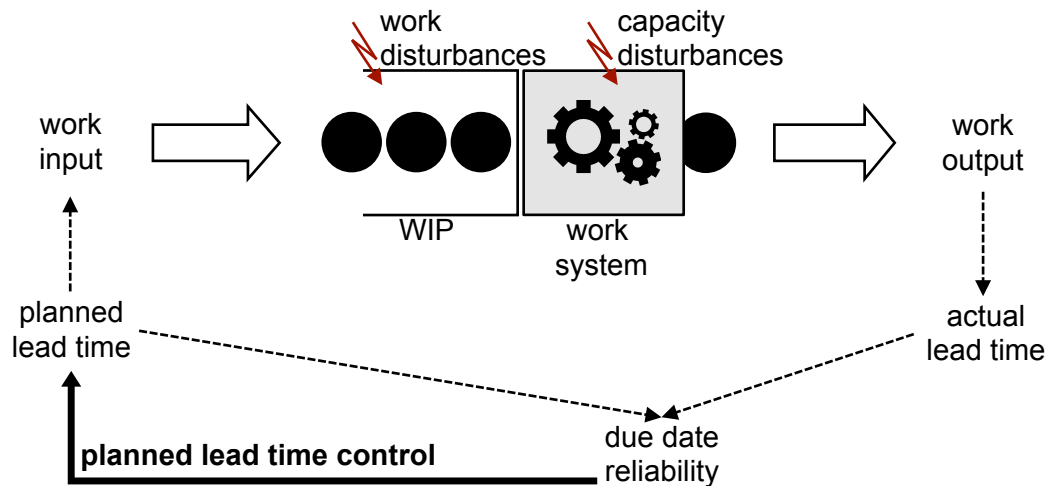


Figure 4.2 Conceptual model of a single work system with planned lead time control

The work system is described by the *WIP* level and *incoming* and *outgoing work*. Also, the planned or maximum output rate is influenced by *capacity disturbances* such as unexpected maintenance, processing errors, shortage of materials or illness. Disturbances also occur in the work inflow and affect the *WIP* such as sequence deviations due to rush orders or fixed batch sizes (see Table 3.3 in Section 3.3.1 for an extended list of possible disturbances). A comparison of *actual lead times* with *planned lead times* results in the *actual lateness*, and hence *actual due date reliability* as a function of the specified tolerance period¹⁹. Following the line of argumentation of the LTS, due date reliability is controlled periodically by production planners at a specific frequency (maximal once each SCD) by adjusting planned lead times, if necessary. This planned lead time control is defined by the parameters *adjustment*

¹⁹ The underlying equations are presented in the next section.

frequency and *magnitude of response* that were identified in the mathematical model of Chapter 3 as the most important starting points for investigating the LTS. The setting of new planned lead times is subject to *information delay* (see Section 3.3.2). If planned lead times are adjusted, order release dates are adjusted accordingly (work adjustment) after a specific implementation delay, thus leading to a temporary adjustment of work inflow and hence an increasing or decreasing WIP level.

Combined with the underlying assumptions of the LTS the following list of requirements can be derived from the conceptual model for the development of the control theoretic simulation model:

- WIP level is not limited, but cannot be negative ($WIP_{actual} \geq 0$)
- machine capacity is constant without disturbances (no capacity disturbances)
- constant work input with defined levels of variability (no work disturbances)
- orders are identical (individual orders are not modeled)
- set up and transportation times are neglected
- orders are released according to their planned lead times (backward scheduling)

The conceptual model provides a framework to develop the required control theoretic simulation model of the LTS, which is presented next.

4.1.2 Description of the Control Theoretic Model of the Lead Time Syndrome

The conceptual model developed in the previous section now has to be transferred into a control theoretic model to simulate system behavior under planned lead time control. Therefore, all model components with their underlying equations and assumptions are described in this section.

Step 3: Develop and verify control theoretic model

To investigate the variable interactions caused by the LTS, first a discrete system model of a single work system has to be designed and verified. The model verification deals with the question whether the model definition is correct (Sargent 2007). This can be ensured by transforming the conceptual model correctly into a control theoretic model (Rabe 2008), which is presented in detail below.

The developed control theoretic model is shown simplified in Figure 4.3. The input and output control structures, which describe the work system, were adapted from a closed-loop production planning and control system proposed by Duffie & Falu (Duffie 2002) and a control theoretic model of manufacturing control proposed by Petermann (Petermann 1996). All control mechanisms that were included in these models (e.g., WIP control and capacity control) were replaced by a feedback loop that models planners' adjusting of planned lead times (see Section 3.1.2) as a function of due date reliability. Besides due date reliability, all logistic targets are considered in the model and highlighted to show the interactions of the independent variables on these dependent variables. The model shown in Figure 4.3 is described

in more detail below. The model was programmed in Simulink (MathWorks MATLAB 2012; model is attached on the enclosed DVD (see appendix)), which is a block diagram environment to design and simulate control systems.

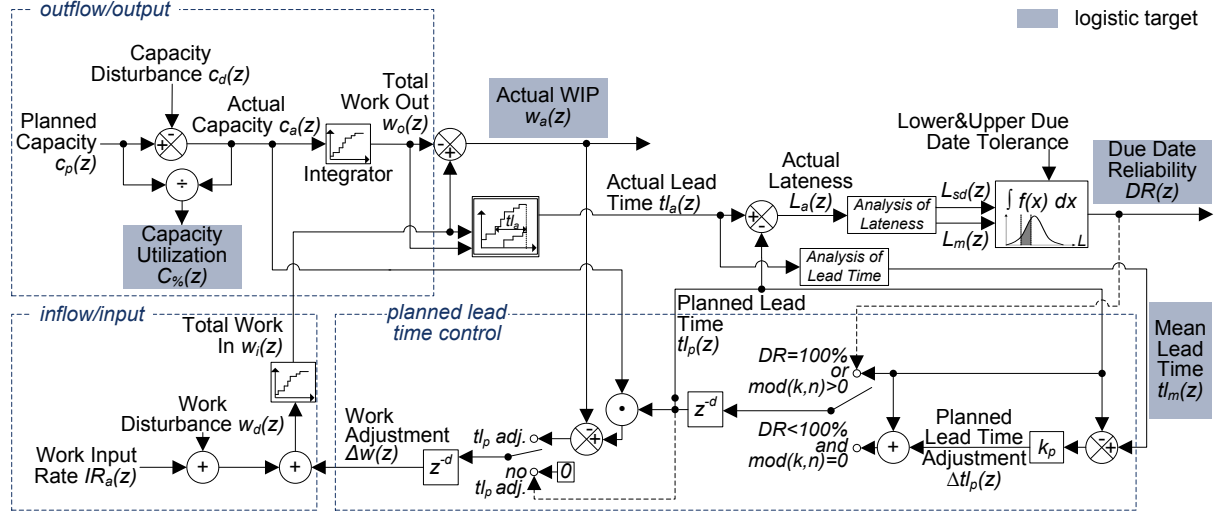


Figure 4.3 Control theoretic simulation model of a manufacturing system with planned lead time control (simulated in Simulink (MathWorks MATLAB 2012))

In the control model the *total work in* $w_i(kT)$ is the sum of the integrated *work input rate* $IR_a(kT)$, any *work disturbances* $w_d(kT)$ such as rush orders or order cancellations, and any work input adjustments $\Delta w(kT)$ that are applied as a result of possible planned lead time adjustments. Thereby, $T=1$ SCD represents the smallest time unit, k is a positive integer, and kT is a discrete instant in time. $w_i(z)$ is the z-transformation that represents the sequence $w_i(kT)$ with $k=0,1,2,\dots$ (Föllinger 2008). The *actual capacity* $c_a(kT)$ is the *planned capacity* minus any *capacity disturbances* $c_d(kT)$ such as equipment failures or worker illness. The *actual capacity* cannot be negative, and is zero if the *actual WIP* level is zero. The *capacity utilization* $c_u(kT)$ is calculated as the ratio of *actual capacity* to *planned capacity*. The integrated *actual capacity* results in the *total work out* $w_o(kT)$. The final step in the work system description is given by the *actual WIP* $w_a(kT)$, which is the difference between *total work in* and *total work out*. Because the focus was on investigating the LTS and for comparability reasons of the different applied control strategies, *capacity disturbance* and *work disturbance* are set to zero in the simulation ($w_d(kT)=0$; $c_d(kT)=0$) (see Section 7.2 for a discussion of this assumption).

The feedback loop starts with the calculation of the *actual lead time*. However, in a continuous flow model of input and output values, no order-specific information is given regarding individual lead times of the current output. With the assumption of no capacity and work disturbances sequence deviations are omitted. Thus, orders are processed in the sequence of First-In-First-Out. This assumption enables the calculation of *actual lead times* $tl_a(kT)$ at the beginning of each period as depicted in Figure 4.4, by finding the value of the actual horizontal distance between the cumulative *work input* and the *work output* curves that satisfies the relationship

$w_i(kT - tl_a(kT)) = w_o(kT)$ (Duffie 2010)²⁰. To obtain more accuracy the calculation is performed each sub-period (i.e., $0,1T$). Then, the average over the last ten sub-periods (as $T=1$ SCD represents the smallest time unit) defines the actual lead time.

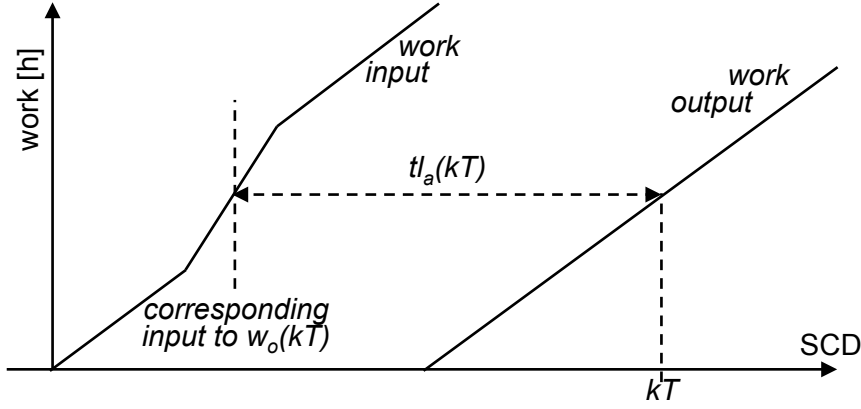


Figure 4.4 Calculation of actual lead times in a continuous model (based on (Duffie 2010))

Comparing *actual* and *planned* lead time results in the *actual lateness* $L_a(kT)$, hence leading to the *mean lateness* $L_m(kT)$ in Equation 4.1 and *lateness standard deviation* $L_{sd}(kT)$ in Equation 4.2. Both equations are based on the mathematical model of the LTS in Section 3.1.1. The values are calculated at the beginning of each period over the last j periods, representing the period of investigation in practice. For reasons of simplification, a fixed length of $j=5$ periods was assumed for all simulations²¹, which represents one working week and is often used in practice (see also Chapter 5).

$$L_m(kT) = \frac{1}{j} \sum_{i=k-(j-1)}^k L_a(iT) = \frac{1}{j} \sum_{i=k-(j-1)}^k [tl_a(iT) - tl_p(iT)]$$

Equation 4.1

$$L_{sd}(kT) = \sqrt{\frac{1}{j-1} \sum_{i=k-(j-1)}^k [L_a(iT) - L_m(kT)]^2}$$

Equation 4.2

tl	lead time [periods]
L	Lateness [periods]
m	mean
sd	standard deviation
a	actual
p	planned
k	current period
j	length of the period of investigation

As discussed in Section 3.1.1 due date reliability is a cumulative distribution function of mean and standard deviation of lateness. Therefore, a specific due date tolerance defines which orders are considered to be produced on time. Thus, system

²⁰ The corresponding MATLAB function is shown in the appendix.

²¹ A fixed value also leads to more comparable results for different variable settings compared to a variable averaging period. Simulations were also run with longer and shorter averaging periods to prove that the derived conclusions hold and are independent of the chosen j .

performance can be measured by the value $DR(kT)$ in Equation 4.3, which represents the due date reliability at time kT . To draw conclusions that are not based on only one input fluctuation example, the input rate $IR(kT)$ of the simulated work system is generated by a random source with a normally distributed input fluctuation. N simulation runs, each with a duration of PT periods, allow a calculation of a mean due date reliability DR_m [%] as defined in Equation 4.4. Hence, DR_m was calculated for each simulation setting to compare the performance of different control strategies.

$$DR(kT) = \frac{100}{L_{sd}(kT)\sqrt{2\pi}} \int_{x=\text{lower due date tolerance}}^{\text{upper due date tolerance}} e^{-\frac{1}{2}\left(\frac{x-L_m(kT)}{L_{sd}(kT)}\right)^2} dx$$

Equation 4.3

$$DR_m = \frac{1}{N} \sum_{j=1}^N \left(\frac{1}{P} \sum_{k=1}^P DR_j(kT) \right)$$

Equation 4.4

DR_m	mean due date reliability [%]
P	simulated periods
N	total number of simulation runs
k	current period

Given the LTS line of argumentation shown in Figure 1.1 (Section 1.1), production planners' reactions to missed due dates are modeled in the control theoretic simulation by the planned lead time control feedback loop (see Figure 4.3). It is assumed that production planners periodically monitor the actual *due date reliability* $DR(kT)$ and, if necessary, adjust the *planned lead time* at the beginning of each time period nT with the consequence of earlier (or later) order releases. Thereby, n is the number of periods between two possible consecutive planned lead time adjustments, where n is a positive integer (adjustment period length nT [SCD]). Based on the current *due date reliability*, two control modes are defined for the calculation of the *planned lead time adjustment* $\Delta tl_p(kT)$ and the resulting *work adjustment* $\Delta w(kT)$: (1) adjustment of planned lead time, and (2) no adjustment.

(1) If $DR(kT) < 100\%$, the reaction of production planners is to adjust *planned lead times* every n^{th} day in order to increase due date reliability. According to Equation 4.3, *due date reliability* can be improved by reducing the mean and standard deviation of lateness (see also Section 3.1.2). Thus, when $DR(kT) < 100\%$ and $\text{mod}(k,n)=0$, the *planned lead time* $tl_p(kT)$ is set to the latest value of the *mean lead time* $tl_m(kT)$ to minimize lateness. A magnitude of response k_r is added to amplify or attenuate the calculated *planned lead time adjustment*, thus accelerating or decelerating the fluctuation response. In practice, the decision-making process of production planners as well as the calculation and implementation of work adjustments takes at least one period T and can take even longer. This is represented by the information delay d (time delay dT [SCD]), where d is a positive integer. For reasons of simplification the delay of planned lead time adjustments and

the delay of order release adjustments have the same length²². The following equations define the planned lead time adjustment logic in the control theoretic model, with the calculation of a new *planned lead time* using Equation 4.5 and, as a consequence, the *work adjustment* by earlier or later order release dates using Equation 4.6. Equation 4.5 is based on Equation 3.8 (Section 3.1.2) with the addition of the magnitude of response parameter and the delay component. The magnitude of response value is introduced to simulate possible behavior of planners to adjust planned lead times. Thus, if they decide to not adjust planned lead times ($k_p=0$ ²³), to calculate the mathematical optimum ($k_p=1$), or to dampen the adjustment ($0 < k_p < 1$)²⁴. The delay component is also added in Equation 4.6, which is based on Equation 3.14 (Section 3.1.3).

$$tl_p(kT) = tl_p((k-d)T) + k_p \left[tl_m((k-d)T) - tl_p((k-d)T) \right]$$

Equation 4.5

$$\Delta w(kT) = c_a((k-d)T)tl_p((k-d)T) - w_a((k-d)T)$$

Equation 4.6

(2) If $DR(kT)=100\%$ due dates are met, hence no reactions or planned lead time adjustments are necessary. Thus, the new planned lead time is the old planned lead time (Equation 4.7) and no work adjustments (Equation 4.8) are needed:

$$tl_p(kT) = tl_p((k-d)T)$$

Equation 4.7

$$\Delta w(kT) = 0$$

Equation 4.8

The control theoretic model of the LTS approximates the production process as simply as possible to demonstrate that even under these simple conditions the negative effects of LTS might occur for specific parameter settings. Thereby, only input rate fluctuations induce variability as work and capacity disturbances are not included. In dependency of the delay, adjustment frequency, and magnitude of response the LTS might lead to an unstable system with a low performance as measured in due date reliability. Before investigating these correlations, a validation of the presented model is required. Moreover, underlying fixed model parameters have to be determined. Therefore, the next section presents a four-stage model validation and – based on preliminary simulation runs – a justified determination of model parameters.

²² See also Section 7.2 for a discussion of this assumption regarding limitations and generalizability

²³ If planned lead times are not adjusted, the work adjustment is zero: $\Delta w(kT)=0$ (see Figure 4.3).

²⁴ $k_p < 0$ would mean that a longer (shorter) planned lead time would be optimal, but planners decide to set a shorter (longer) planned lead time (see Section 5.3.1).

4.1.3 Model Validation and Determination of Model Parameters

Before analyzing simulation results a validation of the model is essential. It proves the model consistency and if it represents the behavior of a real system with sufficient accuracy to investigate the LTS (Sargent 2007; Rabe 2008). Furthermore, a definition of model characteristics such as the warm-up period and a justified determination of underlying model parameters (e.g., planned capacity) are needed. Therefore, this section presents a four-stage process for model validation, which concludes with the determination of model parameters that are used afterwards for the investigation of the LTS interactions.

Step 4: Perform preliminary simulations to validate the control theoretic model and determine model parameters

The validation of a simulation model is needed to check whether it is representing the desired relationships (Law 2006; Manuj 2009). If the model is invalid erroneous conclusions or decisions may arise (Manuj 2009). Thus, the validation of the presented control theoretic model is divided into the four parts (1) face validation, (2) validation of the work system control model, (3) validation of the planned lead time control feedback loop, and (4) sensitivity analysis to also determine the model parameters. Each of the four parts is presented in detail below:

(1) *Face validity*: According to Sargent (2007) a system has ‘face validity’, if the model and the behavior of the model are reasonable. This can be tested by asking knowledgeable individuals and carrying out structured simulation walk-throughs (Sargent 2007; Manuj 2009). Therefore, the model was developed in close contact with experts from control theory, discussed with experts from production logistics, and repeatedly compared to various control theoretic approaches. Finally, structured walk-throughs were carried out with varying parameter settings to validate each component of the model. These walk-throughs were reviewed by integrating so called ‘scope’-blocks after each model component. These blocks display the resulting time series of the corresponding output signals, hence enabling a direct validation of correctness and logic of each component.

(2) *Validation of the work system control model*: In addition to the validation of each model component a validation of the behavior of the control theoretic work system is needed. In Section 2.1.3 the model of the Logistic Operating Curves was presented, which was derived from the Funnel Model by simulating different work system operating states. These operating states are defined by different mean WIP levels that lead to specific mean output rates (mean actual capacity) and mean lead times. The general behavior behind the Logistic Operating Curve theory and related clearing function models has been widely discussed and shown through various simulation experiments and application cases. Thus, a control theoretic model of a work system that yields the same curve shapes of the operating curves as the operating curves presented in Figure 2.6 (Section 2.1.3) can be assumed to be valid. The result of this test is shown in Figure 4.5. Various mean input rates (constant in each of the $N=43$ simulation runs) were simulated to model different WIP levels.

The resulting plot of the corresponding mean lead times and mean capacities has the same shape as the operating curves known from theory. The maximum capacity is given by the planned capacity of five hours per SCD. The minimum lead time is limited by the smallest time unit in the simulation, that is $T=1$ SCD. Also, the mean lead time curve increases proportionally to the mean WIP level above a critical mean WIP of five hours. The simulated system has an ideal minimum WIP level of approximately 5 hours, which corresponds to the calculated value for $IR_{Var}=1$ (see (Nyhuis 2009b)). An additional work system validation is presented in Section 6.1.1 in which capacity control is integrated into the control model.

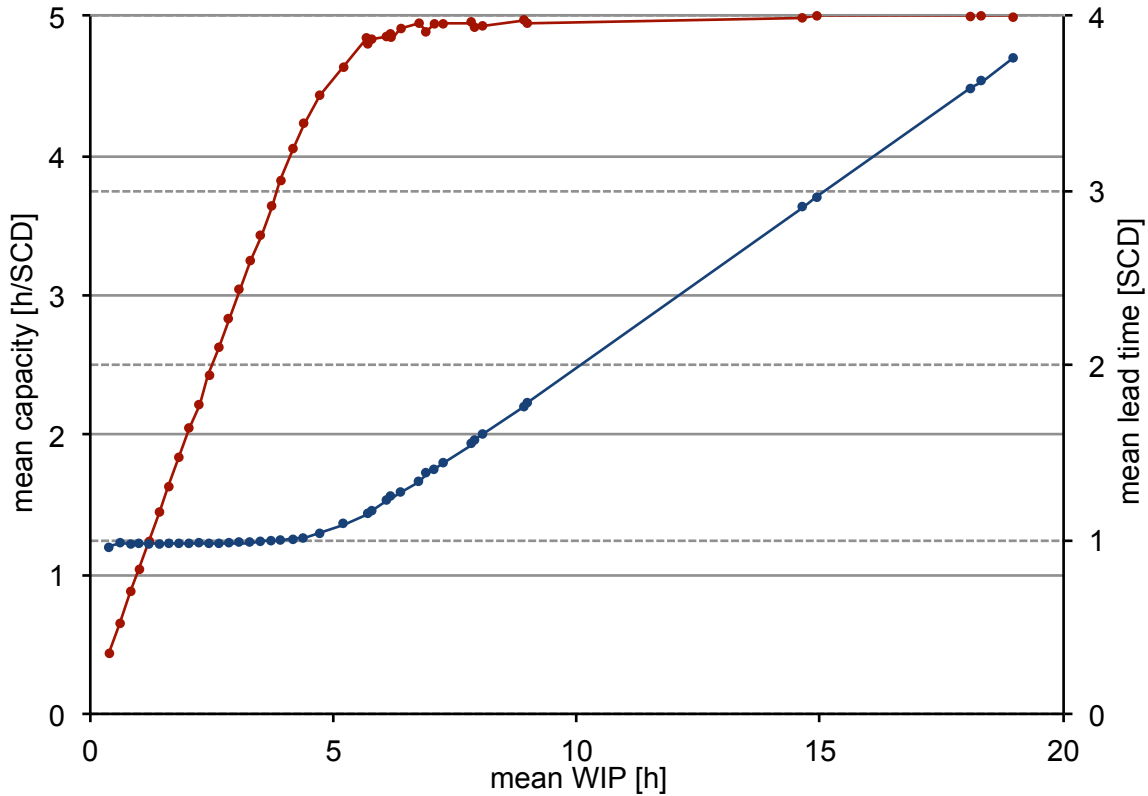


Figure 4.5 Logistic operating curves for the simulated work system for various mean input rates; $C_p=5$ h/SCD; $k_p=0$; $IR_{Var}=1$; $N=43$; $P=500$

(3) *Validation of the planned lead time control feedback loop:* The planned lead time control feedback loop is an extension of the work system control model and requires a separate validation approach. This validation is addressed by visualizing a time series of the WIP, lead time, and due date reliability for a scenario of no input fluctuation except for a one-time impulse. This time series should show on one hand the warm-up phase of the work system, which is given in the beginning until the system reaches a steady-state and on the other hand a planned lead time adjustment in response to the input impulse.

The resulting time series plotted in Figure 4.6 shows that the WIP level increases in the beginning by the level of the constant input rate of $IR_m=5$ h/SCD until the constant capacity of $c_p=5$ h/SCD starts to process orders from period five onwards. Accordingly, the actual lead time increases to a level of $tl_a=3,6$ SCD in period five and to a final level of $tl_a=4$ SCD in period six. The step of the actual lead time is

because of the underlying calculation methodology that was presented in the previous section (see Figure 4.4). It is the average over the last 10 sub-periods, which explains the gap of 0,4 SCD (calculated lead time is zero for one sub-period and four for nine sub-periods). Simultaneously, the resulting due date reliability increases to a level of $DR=100\%$ ($DR(5T)=3.25\%$; $DR(6T)=85\%$; due date tolerance $\pm 0,5$ SCD), as it is a calculated value (analysis of lateness) and strongly influenced by the lead time standard deviation. With these characteristics the control model has a warm-up period of at least six periods.

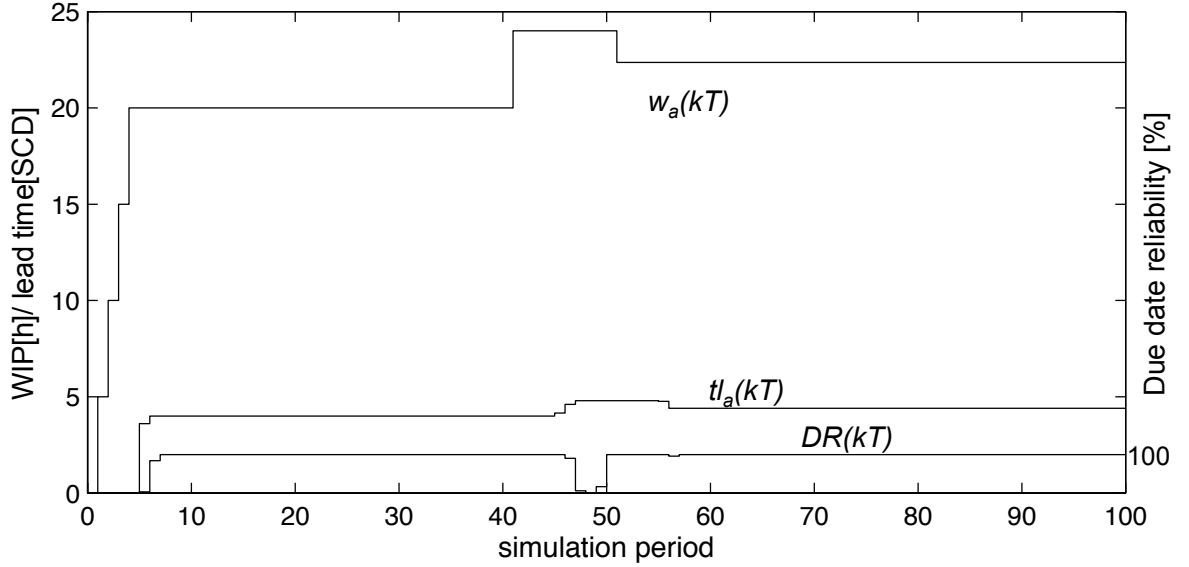


Figure 4.6 Work in process [h], lead time [h], and due date reliability; $k_p=1$; $dT=1$ SCD; $nT=3$ SCD; $IR_{var}=0$; $k_p=1$

To validate the planned lead time control the input rate is increased in period 40 from a level of five to a level of nine hours per SCD and decreased to its original value once again in period 41 (input impulse). The impact on the actual WIP level can be seen in period 41 and on the actual lead time in period 45. This delay is the range of $R = 20\text{h}/5\text{h}/\text{period} = 5$ periods, which is the time until the new incoming orders are processed. The change in lead times leads to a decrease in due date reliability in period 47. This is monitored in period 48 ($nT=3$ SCD) and leads to a planned lead time adjustment in period 49 and a work adjustment in period 50 (both delayed by $dT=1$ SCD). In the simulated case, the planned lead time adjustment led to a due date reliability of $DR=100\%$ that was not reduced once again by the work adjustment, thus leading to no further planned lead time adjustments. Beside the scenario described in detail here, various other variable settings were simulated to validate the feedback loop. In contrast to the presented scenario, all other settings included specific input rate variances, which were not included in this case to highlight and validate the underlying relationships.

(4) sensitivity analysis:

The final step to validate the control model is given by a sensitivity analysis (Manuj 2009). It is commonly used to (a) identify logical or methodological errors

and (b) to identify the input and internal parameters with the greatest impact on the model behavior or the output (Powers 1987; Sargent 2007; Manuj 2009). (a) According to Sargent (2007), the relationships observed in a real system should also occur in the model. The following tests were conducted to validate the directions qualitatively:

- *Increasing or higher mean input rate than planned capacity:* With a constant output rate, but an increasing or higher input rate, the WIP level increases. This leads to an increase in lead times and (with fixed planned lead times) to an increase in mean and variance of lateness. The result is a decrease in due date reliability.
- *Decrease in input variance:* This leads to a decreasing WIP and lead time fluctuation. With fixed planned lead times, this also leads to a decrease in lateness variance, thus to an increasing due date reliability.
- *Higher range of the due date tolerance:* With a constant input rate variance all values except due date reliability, which increases, remain unchanged.

These tests suggest that the model behavior corresponds with the observations in practice. (b) In the second test model parameters have to be identified that affect the model behavior or the output, which is monitored by the resulting due date reliability. As stated above, input rate variance and tolerance period indirectly or directly affect the resulting due date reliability. If the measured due date reliability is 100%, no planned lead time adjustments are required. More specifically, if the range of the tolerance period is too high in proportion to the given input rate variance, planned lead time control would be superfluous and the simulation would lead to unusable results (e.g., a tolerance period of ± 20 SCD would lead to $DR_m = 100\%$ for $IR_{var} = 2$). Thus, the tolerance period controls the sensitivity to the input rate variability and has to be set to a value that guarantees the applicability of planned lead time control. Exemplary, for a tolerance period of ± 1 SCD the model leads to $DR_m > 99,9\%$ for $IR_{var} \leq 0,05$ ($nT = dT = 1\text{SCD}$; $k_p = 1$). For a tolerance period of $\pm 0,5$ SCD the model leads to $DR_m > 99,9\%$ for $IR_{var} \leq 0,003$ ($nT = dT = 1\text{SCD}$; $k_p = 1$). In both examples DR_m decreases with increasing IR_{var} until it reaches a constant (low) level. This level is given for a tolerance period of ± 1 SCD with $DR_m \approx 40\%$ for $IR_{var} > 0,6$ and for a tolerance period of $\pm 0,5$ SCD with $DR_m \approx 20\%$ for $IR_{var} > 0,40$. Thus, to enable the simulation of low input rate variances ($IR_{var} > 0,40$), a tolerance period of $\pm 0,5$ SCD can be assumed to lead to due date reliabilities that are comparable, which means that they are not differently affected by the setting of the tolerance period.

The presented validation results of the control theoretic model suggest that the model is consistent and can be used to investigate the LTS. However, before starting the investigation of various planned lead time control scenarios a justified determination of all fixed or predefined variables and all model specifications is needed. They result from the preliminary simulation runs that were needed for the model validation presented in the four steps above.

- The mean input rate and planned capacity have the same value of $IR_m=c_p=5$ h/SCD. The resulting initial WIP level is on average around 20 hours. Hence, the initial planned lead time is set to $tl_p= c_p/WIP=4$ SCD (according to the Funnel Formula). These values were chosen to create a low overload situation according to the operation curve of the underlying work system that was presented in Figure 4.5, which is defined as the initial situation in which the LTS occurs (Mather 1977).
- Period ten is the first period of possible planned lead time adjustments to avoid planned lead time adjustments during the warm-up period, which is at least six periods long (see step (3) of the model validation above).
- In contrast to the fixed mean input rate, different input rate variances were implemented to simulate fluctuations. In scope of the investigation of the LTS three levels $IR_{var}=\{1;2;3\}$ were chosen to simulate ‘low’, ‘moderate’, and ‘high’ variability in the work system for the given due date tolerance. These levels are classified according to the definition of Hopp (2008), which is based on the resulting coefficients of variation. They lead for a due date tolerance of $\pm 0,5$ SCD (see step (4) of the model validation above) to a mean due date reliability of $DR_{m,Var=1}=15,8\%$, $DR_{m,Var=2}=13\%$, and $DR_{m,Var=3}=12,3\%$ if planned lead time control is inactive ($nT=\infty$; $k=0$). These values determine the reference values of planned lead time control, thus if a simulated parameter setting leads to an increase in performance.
- The averaging periods of the mean lead time and mean due date reliability calculations are set to five periods (equivalent to one working week), which can be assumed as a suitable value in practice (see also Chapter 5 and Section 4.1.2).
- The standard deviation of the resulting due date reliability is 6% for $IR_{var}=2$ ($N=500$; $P=500$). To achieve a confidence level of 95% ($z=1,96$), which is commonly used in statistics, the minimum sample size is $N=35$ to have an accuracy of $\pm 2\%$ with respect to the resulting mean due date reliability in Equation 4.4 (Krejcie 1970; Keller 2014). With $N=100$ runs for each simulation setting, a sufficient accuracy of $\pm 1,2\%$ is given with a confidence level of 95% (accuracy level of $\pm 1,36\%$ for a confidence level of 99%).
- $P=500$ periods were simulated in each simulation run as the maximum simulated adjustment period length is $nT_{max}=12$ SCD (i.e., 41 possible planned lead time adjustments). With a maximum simulated information delay of $dT_{max}=10$ SCD, longer adjustment periods were not necessary in terms of the LTS investigation. Preliminary simulations showed that the mean due date reliability remains almost constant for $nT>dT$. Also, both values are limited to the defined levels to reduce simulation complexity. For the given parameter settings $I=\#n\cdot\#d\cdot\#IR_{var}\cdot\#k_p\cdot N=12\cdot 10\cdot 3\cdot 7\cdot 100=252.000$ simulation runs have to be carried out. With some 15 seconds computation time to finish one simulation run, complexity is a crucial element. The minimal adjustment period length and information delay are given with $nT_{min}=dT_{min}=1$ SCD, as the minimum simulation period length is one SCD. Thereby, the definition of one period as one SCD is only supposed to support the understanding of the variable interactions. Exemplary, if a computer automatically adjusts planned lead times every hour ($nT=1/8$ SCD), all units of

the simulation results presented below have to be replaced only by the unit hours (i.e., $nT=1$ h) to interpret them correctly.

The impacts of the anticipated LTS drawbacks caused by these adjustments on the capacity utilization, WIP level, lead time and finally on the due date reliability were evaluated in the simulation for different settings of adjustment periods, information delay and input fluctuation. If adjustments are implemented too often in proportion to the delay or the magnitude of response to disturbances is too high, system's performance might decrease significantly due to the LTS in which the control's own short term adjustments are amplified before the system reaches a steady state. To investigate for which variable settings the LTS is induced – thus leading to a low due date reliability – the simulation results for different settings of information delay, adjustment period, and magnitudes of response are presented next.

4.2 Control Theoretic Investigation of Lead Time Syndrome Interactions

In the previous sections a control theoretic model was developed and validated that can now be used to investigate LTS interactions (Step 5 of the simulation model development process). The aim of these investigations is to derive strategies that enable damping or avoiding the LTS. Therefore, separate investigations are needed to gain knowledge about the cause-effect relationships between information delay, adjustment frequency, and magnitude of adjustments on the resulting system transient response and performance as measured in due date reliability.

To structure the investigation of the cause-effect relationship between planned lead time adjustments and a decreasing due date reliability initially the transient response of a scenario in which the LTS is triggered is presented in Section 4.2.1. The presented corresponding time series enables a visual comparison with other scenarios in which the parameters adjustment frequency and magnitude of response are adjusted to damp or avoid oscillatory system response²⁵. The identified possible impact of the ratio between adjustment frequency and delay is then analyzed in more detail in Section 4.2.2 and the impact of the magnitude of response in Section 4.2.3.

4.2.1 Initial Visualization of Variable Impacts: Systems Transient Response

Before starting a detailed analysis, research focus areas have to be identified to structure the investigation of the cause-effect relationship between planned lead time adjustments and a decreasing due date reliability. Hence, this section presents the resulting time series of systems' transient response to depict the impact of the dependent variables adjustment frequency and magnitude of response on the

²⁵ The oscillatory response of a control theoretic system corresponds to the definition of the LTS due to the similarities of positive feedback and the LTS as shown in Section 2.2.3.

resulting performance. The presented scenarios that are listed in Table 4.1 were identified in preliminary simulation runs (see Section 4.1.3) to be representative.

Table 4.1. Simulation scenarios of systems transient response.

	dT	nT	k_p	IR_{VAR}
Initial scenario	1	1	1	2
Scenario I	1	2	1	2
Scenario II	1	1	0,25	2

The initial scenario was chosen to depict systems transient response in a situation in which the LTS occurs. Afterwards two scenarios are presented that apparently avoid or dampen the LTS by adjusting either the independent variable adjustment frequency (Scenario I) or magnitude of response (Scenario II). Thereby, the resulting transient responses are compared to the initial scenario to give a first understanding of the system behavior and the respective variable impact.

Figure 4.7 shows the transient response of the initial simulation scenario in which the LTS occurs due to the underlying parameter settings. The magnitude of response is $k_p=1$, thus the planned lead time adjustment corresponds to the difference between actual and planned lead time. It can be seen that the system is unstable, as the actual WIP level begins to oscillate with building amplitude. This means that the system is not reaching a steady state.

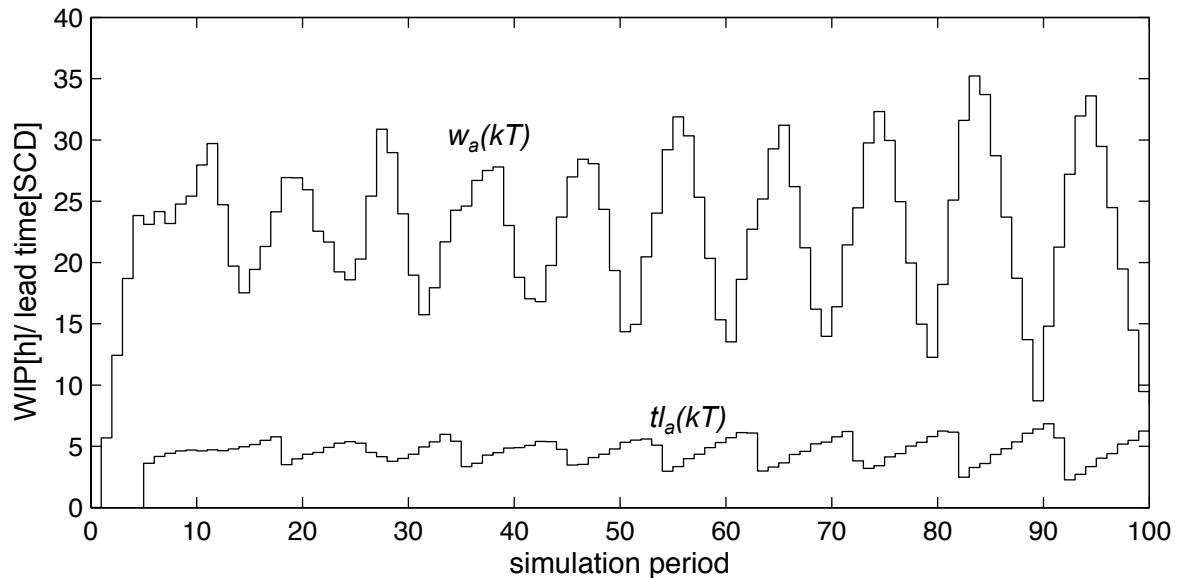


Figure 4.7²⁶ Work in process [h], and lead time [h] in an initial scenario; $k_p=1$; $dT=1$ SCD; $nT=1$ SCD; $IR_{var}=2$; $N=1$; $P=100$; resulting $DR_m=18\%$

Figure 4.7 shows that the resulting actual lead time also oscillates. Both oscillations are time-shifted as the actual lead time directly arises from the WIP

²⁶ This figure, Figure 4.8, and Figure 4.9 are not to be confused with the controller response to set point deviations, which is, e.g., used to depict the transient response of a PID controller.

level in combination with the capacity. Thus, according to the funnel formula the time shift correlates with the actual range (see Section 2.1.3). Thereby, the gradual increase and the sudden decrease (e.g., in period 63 or 72) of the lead time corresponds to the expected behavior of earlier and later order releases as described in Figure 3.7 (Section 3.3.1). The observed lead time oscillation leads to an increase of lead time standard deviation, thus to a low mean due date reliability of 18% (acc. to Equation 4.4 with $N=1$; $P=100$). For comparison, the system already obtained a mean due date reliability of 13% without planned lead time control ($nT=\infty$; $IR_{var}=2$ see Section 4.1.3).

In this initial scenario the LTS is triggered due to an unfavorable variable setting for the given environmental conditions: the adjustment period length is too short in proportion to the delay, or the magnitude of response to fluctuations is too high. In this case, the short-term adjustment of the control feedback loop is amplified before the system reaches its steady state. According to Equation 4.5 (Section 4.1.2), missed due dates in one adjustment period induce a planned lead time adjustment in the next adjustment period ($nT=1$ SCD; $dT=1$ SCD), and then an order release adjustment in the subsequent adjustment period. In this scenario the ongoing monitoring of due date reliability in each period induces new planned lead time adjustments before previous order release adjustments are able to take effect (due to the delay). The result is a low due date performance, which is in line with Proposition P_2 that the adjustment period length should be longer than the latency period (see Section 3.3.2).

Apparently, the ratio of information delay and adjustment frequency is unfavorable in the initial scenario, raising the question of which ratio avoids an oscillatory response or what is an ‘appropriate’ adjustment frequency. According to Proposition P_2 , the impact of the LTS should be reduced if the adjustment period length is longer than the delay. Figure 4.8 shows the transient response of Scenario I for an increased adjustment period of $nT=2$ SCD. The resulting WIP and lead time are significantly more stable without the build-up of the amplitude of oscillation seen in the initial scenario. This leads to a significant increase of the mean due date reliability, which reaches 71% in the depicted scenario. However, the visualization of the resulting WIP and lead time are only able to give an impression of the adjustment frequency impact on the performance, but are neither able to directly quantify it, nor allow a reasonable comparison of scenarios, as the resulting values are based on one random input rate sample. More specifically, the random input rate leads to varying system responses for each simulation run. $N=100$ simulation runs was found in the previous section to be a suitable number of repetitions for each simulation setting. Section 4.2.2 presents results for $N=100$ that enable statistics-based conclusions to be drawn regarding the question of for which adjustment periods and delays the oscillatory response of the LTS occurs.

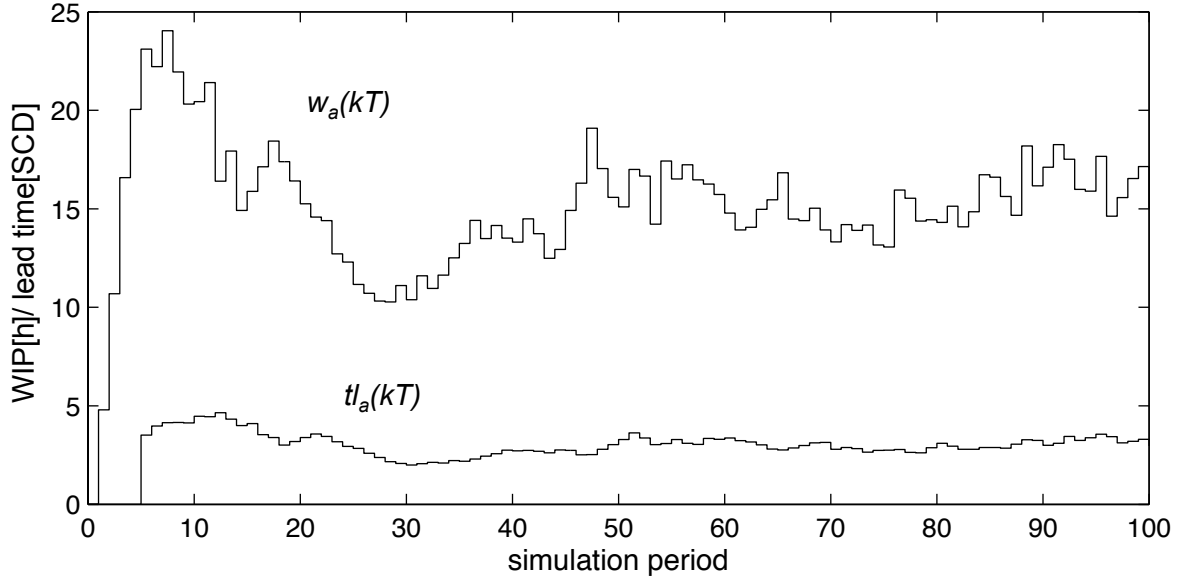


Figure 4.8 Work in process [h], and lead time [h] for an increased adjustment period length (Scenario I); $k_p=1$; $dT=1$ SCD; $nT=2$ SCD; $IR_{var}=2$; $N=1$; $P=100$; resulting $DR_m=71\%$

Another possible strategy to avoid the LTS is to reduce the lead time standard deviation and lateness standard deviation. Changing lead times lead according to Proposition P_l (Standard deviation; see Section 3.3.1) inevitably to an increasing lead time standard deviation, and hence to a decreasing due date reliability. Thus, a reduced level of a planned lead adjustment is expected to lead to a reduced standard deviation. In addition, a reduction of the feedback fraction corresponds to a strategy of avoiding positive feedback (see Section 2.3.2), which has strong similarities to the LTS. Hence, the oscillatory response of the initial scenario shown in Figure 4.7 is damped by the introduced variable magnitude of response k_p in Scenario II. The result is illustrated in Figure 4.9 with $k_p=0,25$.

Comparing both figures, a significant decrease of oscillation can be observed. Consequently, the resulting mean due date reliability increases from a level of 18% in the initial scenario to a level of 51%. Nevertheless, the LTS is not completely avoided, which can be seen in the oscillation of the actual lead time especially at the end of the simulation. Due to the damping influence of k_p , this oscillation is not building-up and stays on a low level. However, the obtained performance measured in due date reliability is lower than in the scenario with the increased adjustment period length. Whether a reduced magnitude of response is still an option to mitigate the LTS is analyzed in detail in Section 4.2.3.

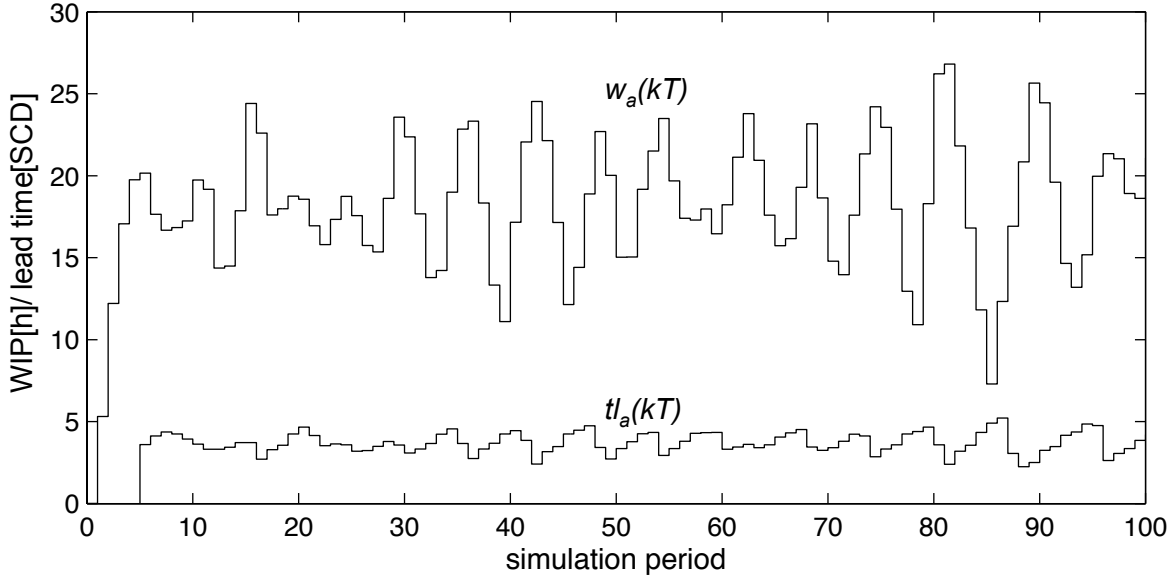


Figure 4.9 Work in process [h], and lead time [h] for a reduced magnitude of response (Scenario II); $k_p=0,25$; $dT=1$ SCD; $nT=1$ SCD; $IR_{var}=2$; $N=1$; $P=100$; resulting $DR_m=51\%$

The presented time series suggest that the LTS is triggered by specific ratios of adjustment frequency and delay and that the LTS can be avoided, e.g., in Scenario I by reducing the adjustment frequency or damped in Scenario II by reducing the magnitude of response. Thereby, the LTS leads to an oscillatory system response in terms of WIP and lead time, which results in a low system performance as measured in due date reliability. However, the visualization of the resulting WIP levels and lead times in the three time series shown above are only able to give a first understanding of the system behavior and the respective variable impact for adjustments, but they are neither able to directly quantify effects, nor allow a reasonable and quantified comparison of scenarios.

By simulating each scenario $N=100$ times, quantified results in the identified areas are presented in the following subsections. Thereby, Section 4.2.2 investigates the correlation between information delay and adjustment frequency as an extension of Scenario I, while Section 4.2.3 analyses the impact of the magnitude of response as an extension of Scenario II.

4.2.2 Correlation of Information Delay and Adjustment Frequency

The preliminary transient response results presented in the previous section showed that the ratio of the adjustment frequency to delay strongly affects the resulting due date performance. A ratio of, e.g., $nT/dT=1$ SCD in the initial scenario led to unstable system behavior with oscillatory WIP level and lead times (see Figure 4.7). Therefore, this section analyzes for which ratios an oscillatory response and consequently a low due date performance occurs to finally derive a strategy to avoid the LTS. As shown in Table 4.2, this section initially analyses Scenario I of Section 4.2.1 for various adjustment periods and a constant delay of $dT=1$ SCD. Afterwards, the resulting due date performance for various delays and

adjustment periods is investigated to gain knowledge about the influence of both variables. Finally, it is tested if the results are sensitive to the level of the input rate variance.

Table 4.2. Simulation settings to investigate the correlation of dT and nT .

	dT	nT	k_p	IR_{VAR}
(A) Influence of adjustment frequency	1	1,...,12	1	2
(B) Correlation of adjustment frequency and delay	1,...,10	1,...,12	1	2
(C) Influence of input rate variance	1; 10	1,...,12	1	1;2;3

(A) To evaluate the influence of the adjustment period and delay on the performance the resulting due date reliability is measured for all simulation setting. As presented in Section 4.1.2, the calculated mean due date reliability is the result of $N=100$ simulation runs (each has $P=500$ simulation periods) with the same parameter setting to draw conclusions that are not based on only one input fluctuation example (as it is the case in the previous section). Figure 4.10 shows the mean due date reliability for all simulated adjustment period lengths $nT=(1 \text{ SCD}, \dots, 12 \text{ SCD})$ with a fixed delay of $dT=1 \text{ SCD}$ (all other parameter settings remain unchanged). The analysis reveals three main attributes:

- 1) adjusting planned lead times each simulation period ($nT=1 \text{ SCD}$) led to the lowest performance;
- 2) adjusting planned lead times every second simulation period ($nT=2 \text{ SCD}$) led to the best performance; and
- 3) the performance decreased to some extent for longer adjustment periods $nT \geq 3 \text{ SCD}$.

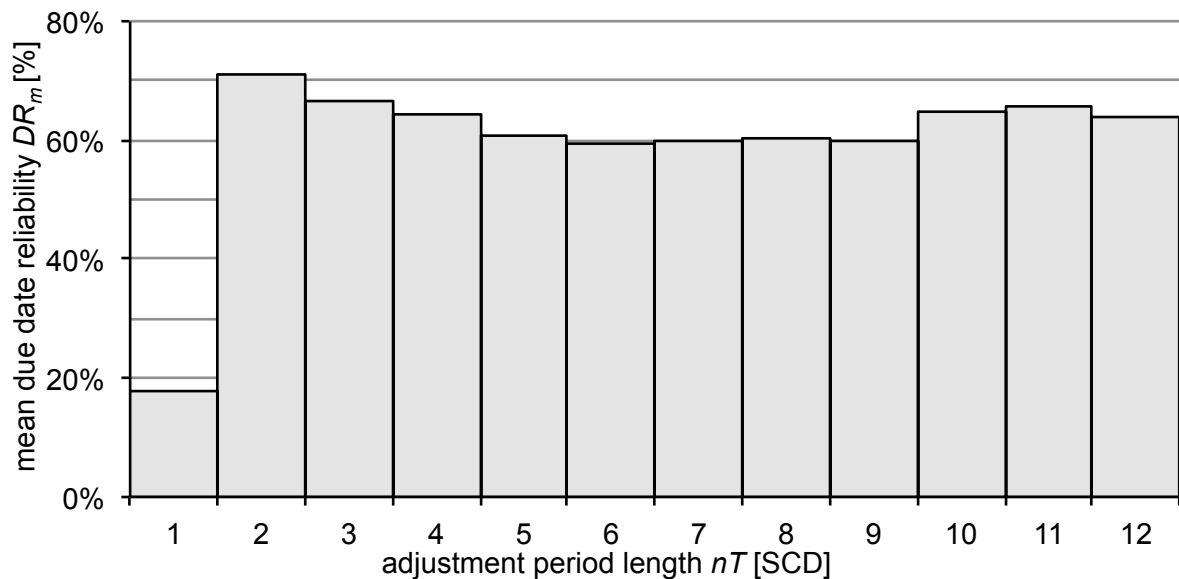


Figure 4.10 Mean due date reliability [%] with various adjustment periods for a delay of $dT=1 \text{ SCD}$; $N=100$; $P=500$; $k_p=1$; $IR_{var}=2$

The system response for the first attribute in the list above was shown in Figure 4.7 of the previous section in which the LTS was induced due to the shortness of the adjustment period compared to the delay. The resulting mean due date reliability is significantly lower in comparison to the other simulated adjustment periods. Systems response for the second attribute was also shown in the previous section in Figure 4.8 ($nT=2$ SCD), representing a significantly less oscillatory response. The resulting mean due date reliability obtained the maximum level in this simulation for $dT=1$ SCD. In combination with the information that the performance decreases to some extent but stays on a high level for longer adjustment periods, it can be concluded in this case that the LTS led to a significant performance decrease for $nT=1$ SCD and that the LTS is avoided for $nT \geq 2$ SCD. However, this simulation only reflected the situation of a constant minimal delay of $dT=1$ SCD. Thus, the investigation of the influence of the period between planned lead time adjustments and various delays is presented next, which also serves to interpret the reason for the third attribute in the list above.

(B) Figure 4.11 shows the mean due date reliability for all simulated delays $dT=(1 \text{ SCD}, \dots, 10 \text{ SCD})$ over all adjustment periods $nT=(1 \text{ SCD}, \dots, 12 \text{ SCD})$. Thus, the black curve for $dT=1$ SCD and the data shown in Figure 4.10 are identical. The plotted trend line of all delay curves represents the average – delay independent – due date reliability for each adjustment period. It shows that the average performance increases approximately asymptotically with an increasing adjustment period length. Firstly, this is due to the stronger influence of LTS for lower nT and, secondly, because planned lead time control combines reactive controlling and a proactive planning. As shown in the control theoretic model (see Section 4.1.2), planned lead time control monitors actual lead times and, as a consequence of possible planned lead time adjustments, it also controls order releases.

Looking at the plot in more detail, each curve more or less remained at an individual maximum mean due date reliability level above a certain adjustment period length and remained on a similar low performance level below. The maximum level strongly correlated with the delay length as it decreased with increasing delay. The ratio of delay and adjustment period for which a significant performance increase can be observed is found in the simulated case to be $nT/dT > 1$. Exemplary, for a delay of $dT=3$ SCD (green curve) due date reliability increases from a level of $DR_m=24\%$ at $nT=3$ SCD to $DR_m=47\%$ at $nT=4$ SCD. Continuing the argumentation in the example of Figure 4.10, the LTS leads to a significant performance decrease for $dT \leq nT$, which can be avoided if $nT > dT$.

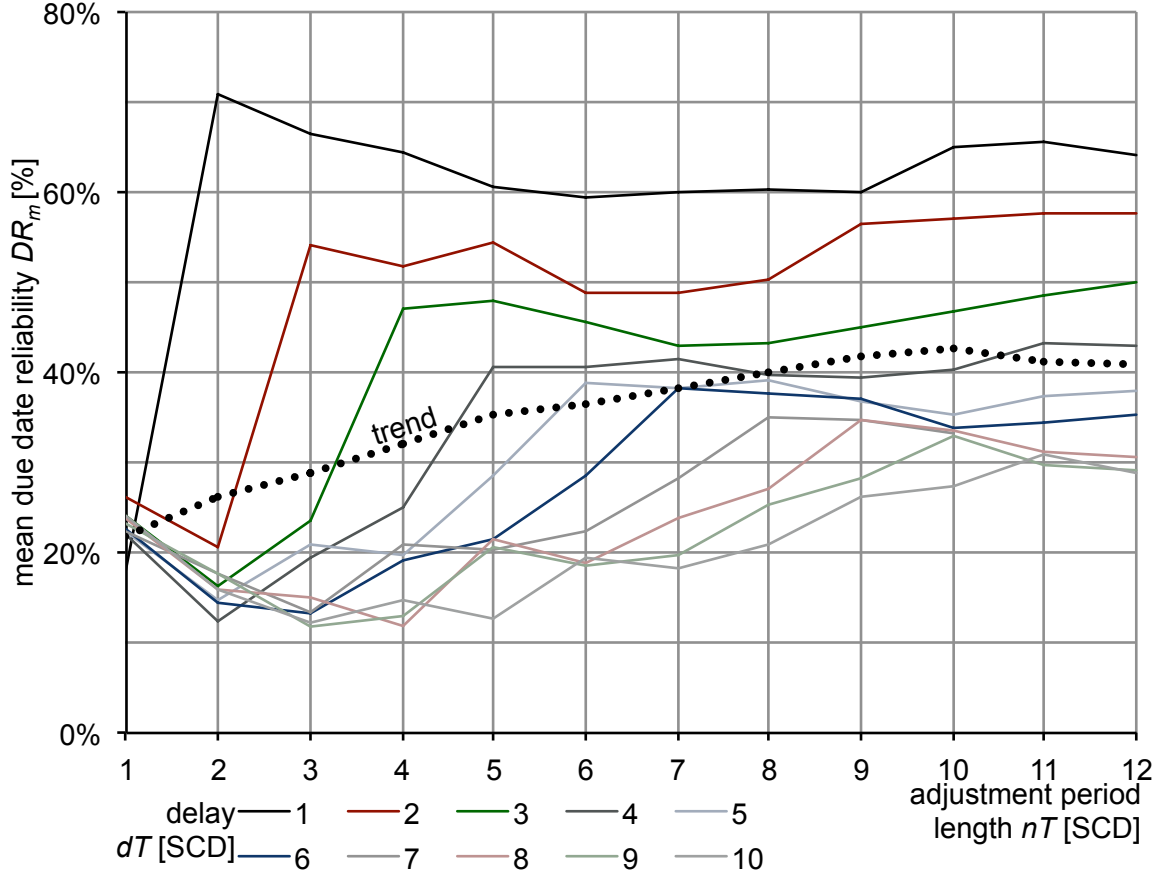


Figure 4.11 Mean due date reliability [%] with various adjustment periods for all simulated delays; $N=100$; $P=500$; $k_p=1$; $IR_{var}=2$

The adjustment period that obtains the highest due date reliability for a given delay is of particular interest. Therefore, to show the correlation between both variables from the delay perspective, Figure 4.12 plots the mean due date reliability for all simulated adjustment periods $nT=(1 \text{ SCD}, \dots, 12 \text{ SCD})$ over all delays $dT=(1 \text{ SCD}, \dots, 10 \text{ SCD})$. The plotted trend line of all adjustment period curves represents in this case the average – adjustment period independent – due date reliability for each delay. It shows that the average performance decreased approximately inversely proportional²⁷ with increasing delay. The individual adjustment period curves also show that the maximum obtainable performance decreased with increasing delay. All curves except $nT=1 \text{ SCD}$ have this characteristic performance curve progression for $nT > dT$. Adjusting planned lead times each period ($nT=1 \text{ SCD}$) leads for all delays to an oscillatory system behavior and, thus, to a low performance. As stated above, for $nT \leq dT$ the modeled system is not able to reach a steady state before planned lead times are adjusted once again. Thus, the results support the conclusion that the adjustment period should be longer than the delay to avoid the negative impact of the LTS.

²⁷ The trend line is almost a straight line in a log-log plot.

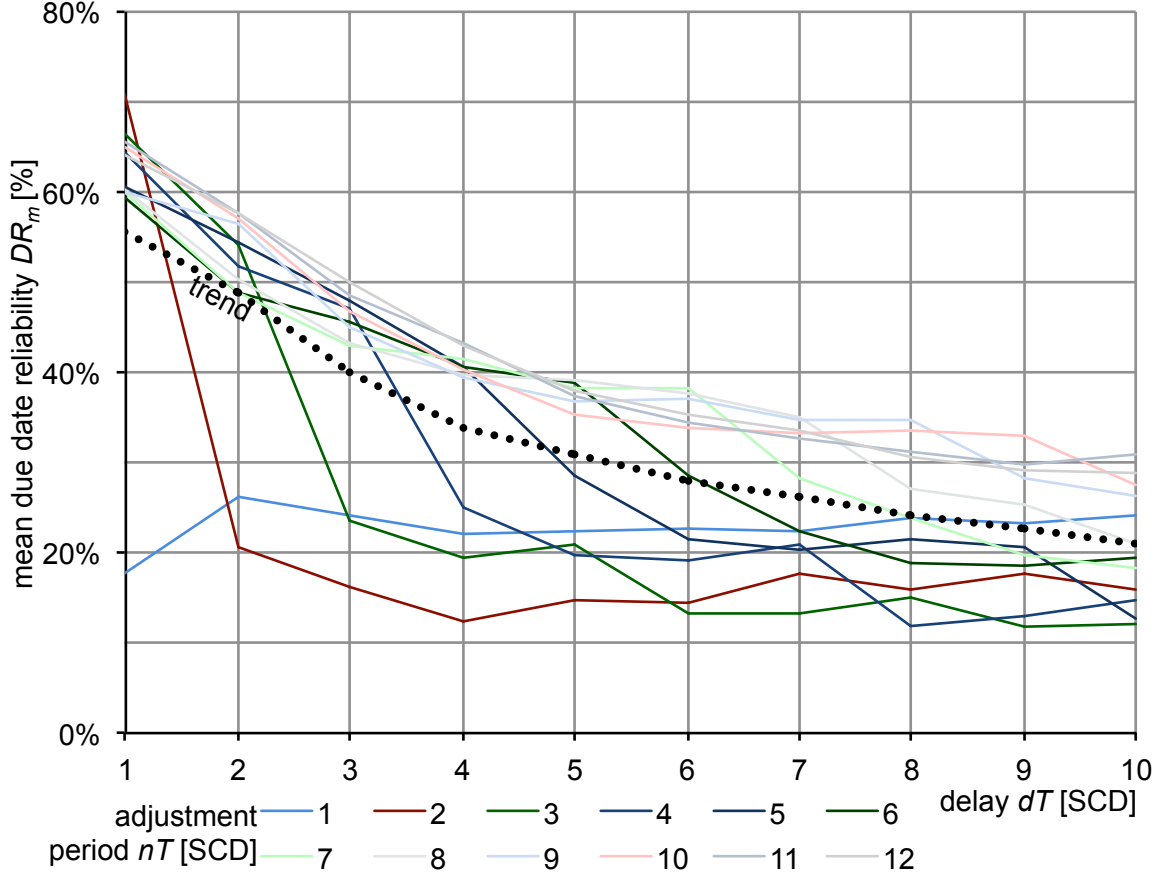


Figure 4.12 Mean due date reliability [%] with various delays for all simulated adjustment period lengths; $N=100$; $P=500$; $k_p=1$; $IR_{Var}=2$

(C) In addition to the presented results also higher ($IR_{Var}=3$) and lower ($IR_{Var}=1$) input variances were simulated to test if the results are sensitive to the level of the input rate variance. Figure 4.13 shows the resulting mean due date reliability for both low ($dT=1$ SCD) and high delay ($dT=10$ SCD) with all simulated input rate variances $IR_{Var}=\{1;2;3\}$. The resulting curves for $IR_{Var}=1$ and $IR_{Var}=3$ have the same significant curve progression like $IR_{Var}=2$. Hence, the results validate the derived correlations of the previously presented plots with $IR_{Var}=2$. However, the maximum achievable due date reliability decreases with an increasing input fluctuation, which reduces the possible impact of the LTS. Exemplary, the maximum obtained mean due date reliability was $DR_m=41\%$ for $IR_{Var}=3$ ($dT=1$; $nT=2$), whereas 84% were obtained for the same parameter setting for the presented variance of $IR_{Var}=1$.

The simulation results indicate that planners should minimize the delay of adjustment implementations to maximize the obtainable performance. Furthermore, if the adjustment period length is not longer than the information delay the LTS can be triggered, which leads to a decrease in performance. Thus, in order to avoid the LTS, long adjustment periods might be inevitable for long and irreducible delays. For such cases, the following section analyses the possibility of reducing the impact of the LTS on performance by setting an appropriate magnitude of response, which reduces the level of the planned lead time adjustment.

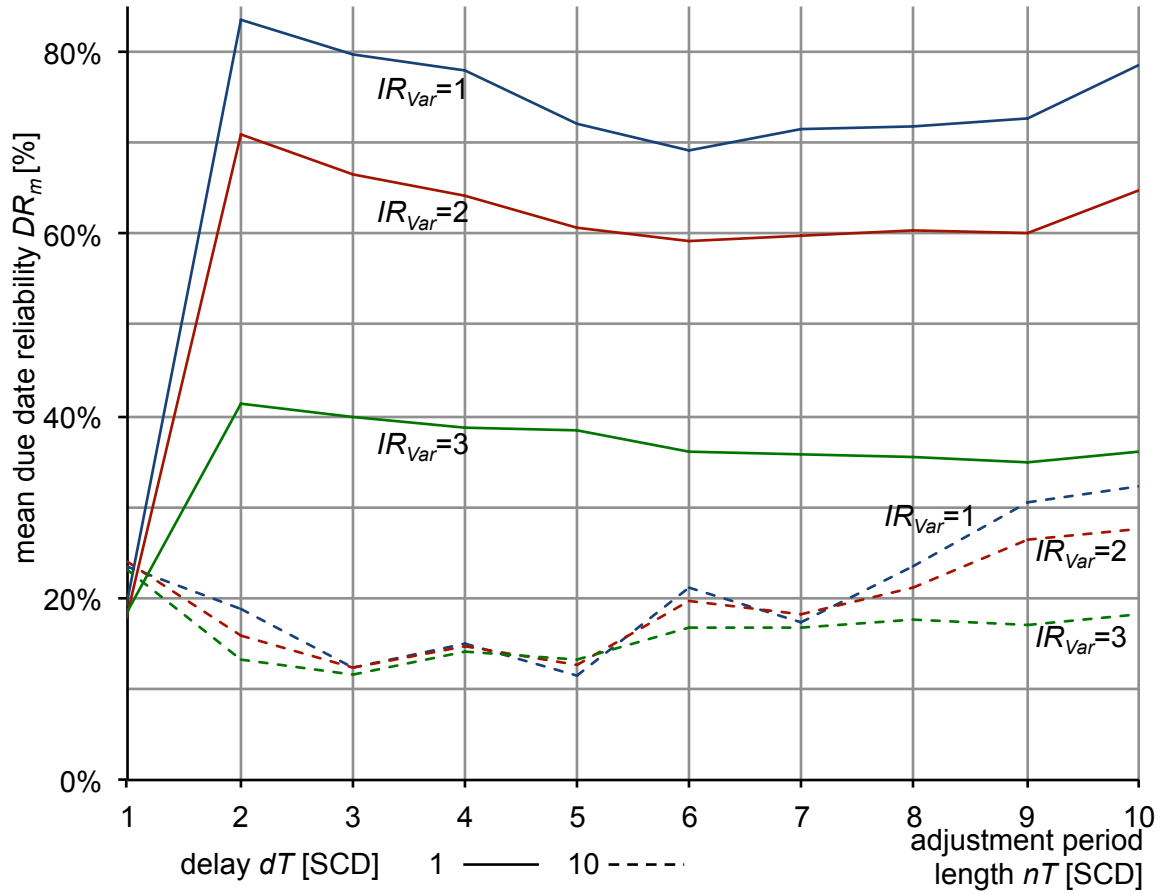


Figure 4.13 Mean due date reliability [%] with various input rate variances for selected delays; $N=100$; $P=500$; $k_p=1$

4.2.3 Impact of the Magnitude of Planned Lead Time Adjustments

The transient response presented in Section 4.2.1 showed that an unfavorable ratio of adjustment frequency to delay could lead to the LTS with a low system performance, with oscillatory WIP levels and lead times (see Figure 4.7). It was also shown that one strategy to dampen the LTS could be a reduction of the lead time standard deviation and lateness standard deviation. The analysis of the transient response for a reduced magnitude of response in Scenario II revealed a significant decrease of oscillation and increase in mean due date reliability, hence a damped LTS impact (see Figure 4.9). However, the previous section showed that the LTS can be avoided by setting the adjustment period longer than the delay ($nT > dT$). Whether a reduced magnitude of response is still an option to mitigate the LTS is analyzed next. As shown in Table 4.3 initially the situation presented in Section 4.2.1 ($dT=nT=1$ SCD) is analyzed for various magnitudes of response (A). Then, the influence of the input variance is analyzed for the same scenario (B). Afterwards, selected ratios of delay and adjustment frequency that lead to the LTS ($nT \leq dT$) are analyzed (C) to gain knowledge about the optimal magnitude of response.

Table 4.3. Simulation settings to investigate the impact of the magnitude of response.

		dT	nT	k_p	IR_{VAR}
(A) Influence of k_p for $dT=nT$		1	1	0,...,1	2
(B) Influence of k_p for varying IR_{VAR} for $dT=nT$		1	1	0,...,1	1;2;3
(C)	Influence of k_p for varying IR_{VAR} for $dT=1,5nT$	3	2	0,...,1	1;2;3
	Influence of k_p for varying IR_{VAR} for $dT=3nT$	9	3	0,...,1	1;2;3
	Influence of k_p for varying IR_{VAR} for $dT=7nT$	7	1	0,...,1	1;2;3

(A) Avoiding the LTS by using an adjustment period that is longer than the delay could lead to long adjustment periods, thus reducing systems' responsiveness. Moreover, the maximum achievable performance decreases with an increasing delay. Therefore, another strategy is needed for damping the impact of the LTS for an unfavorable relationship of $nT \leq dT$. It was shown previously (see Figure 4.9) that decreasing the magnitude of response with $k_p=0,25$ dampens the LTS for $dT=nT=1$ SCD, thus significantly increasing the obtained performance. Of special interest is finding a suitable k_p that is low enough to dampen the LTS, but high enough to maintain system performance. The obtained performance measured in due date reliability for various values of k_p is shown in Figure 4.14 ($dT=nT=1$ SCD).

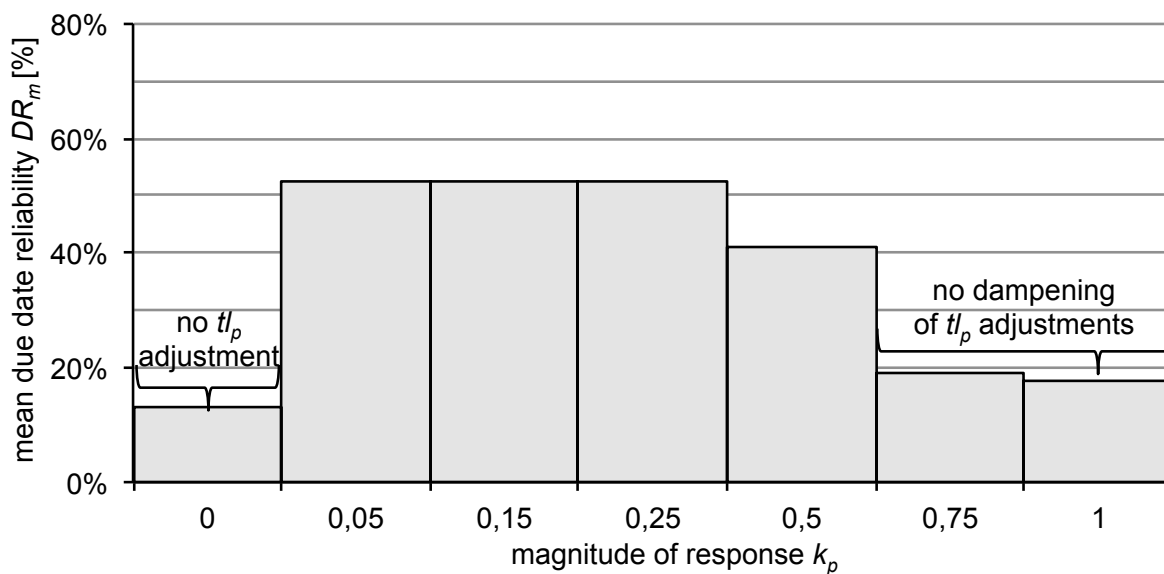


Figure 4.14 Mean due date reliability [%] with various magnitudes of response k_p ; $dT=1\text{SCD}$; $nT=1\text{SCD}$; $P=500$; $N=100$; $IR_{Var}=2$

As already discussed, performance with $k_p=1$ was on a low level, which depicts the initial situation of Figure 4.7. The resulting mean due date reliability (calculated using Equation 4.4) was given with $DR_m=18\%$. An increased damping – a decreasing magnitude of response – led to an increased performance until $k_p=0,25$ and only a marginal increase for even lower magnitudes of response. Coincidentally, the randomly selected magnitude of response of $k_p=0,25$ that led to the transient response shown in Figure 4.9 represents the ideal parameter setting for the given

simulation setting in terms of high responsiveness while maintaining high due date reliability. The increase in performance for an even higher damping suggests that a maximum damping of $k_p=0$ would obtain the highest performance. However, the simulation led to a poor due date reliability of $DR_m=13\%$. Hence, no planned lead time control, which corresponds with $k_p=0$, is not an option to dampen or avoid the LTS in terms of maintaining high due date reliability. In contrast to the relationships of delay and adjustment frequency, which are unaffected by different input fluctuations, the resulting ‘suitable’ magnitude of response differs for varying input fluctuations, which is analyzed next.

(B) Figure 4.15 shows the resulting mean due date reliability for all three simulated input fluctuations for $dT=nT=1$ SCD over all simulated magnitudes of response. Therefore, the red curve ($IR_{Var}=2$) depicts the values that were already shown in Figure 4.14. The results show that a lower input fluctuation enables a higher maximum attainable due date reliability, which is in line with the argumentation of Proposition P_l (Standard deviation; see Section 3.3.1). In addition, the ideal magnitude of response shifts from $k_p=0,5$ for $IR_{Var}=1$ (blue curve) to $k_p=0,25$ for $IR_{Var}=2$ (red curve) and finally to $k_p=0,15$ for $IR_{Var}=3$ (green curve). Thus, the results indicate that a higher damping is required for higher input fluctuations to dampen the impact of the LTS. However, this correlation could not be observed in all simulated scenarios, which are presented next.

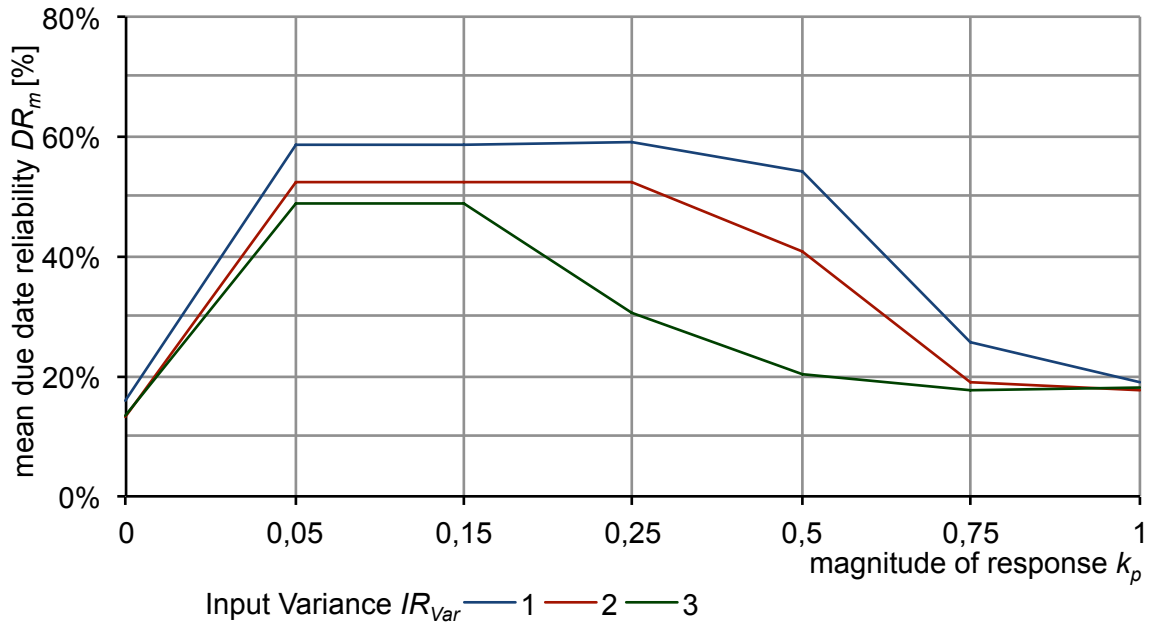


Figure 4.15 Mean due date reliability [%] with various magnitudes of response for all simulated input variances; $dT=1$ SCD; $nT=1$ SCD; $P=500$; $N=100$

(C) The results presented in Figure 4.15 are based on the initial scenario of Section 4.2.1 with $dT=nT=1$ SCD, in which the LTS significantly reduced system performance. Figure 4.16 shows the resulting mean due date reliability for an unfavorable adjustment period length of $nT=2$ SCD for a delay of $dT=3$ SCD ($dT=1,5nT=3$ SCD). Due to the longer delay, the maximum performance is significantly lower than for the situation presented in Figure 4.15. Nevertheless, a reduced

magnitude of response once again led to an increase in performance, with a peak value of $DR_m=41\%$ for the lowest simulated magnitude of response $k_p=0,05$ and the lowest simulated input fluctuation $IR_{Var}=1$. However, the difference between the results obtained for the simulated input fluctuations diminished. The high damping of the planned lead time adjustment needed to increase the resulting performance leads to the question of what happens, if even longer delays occur.

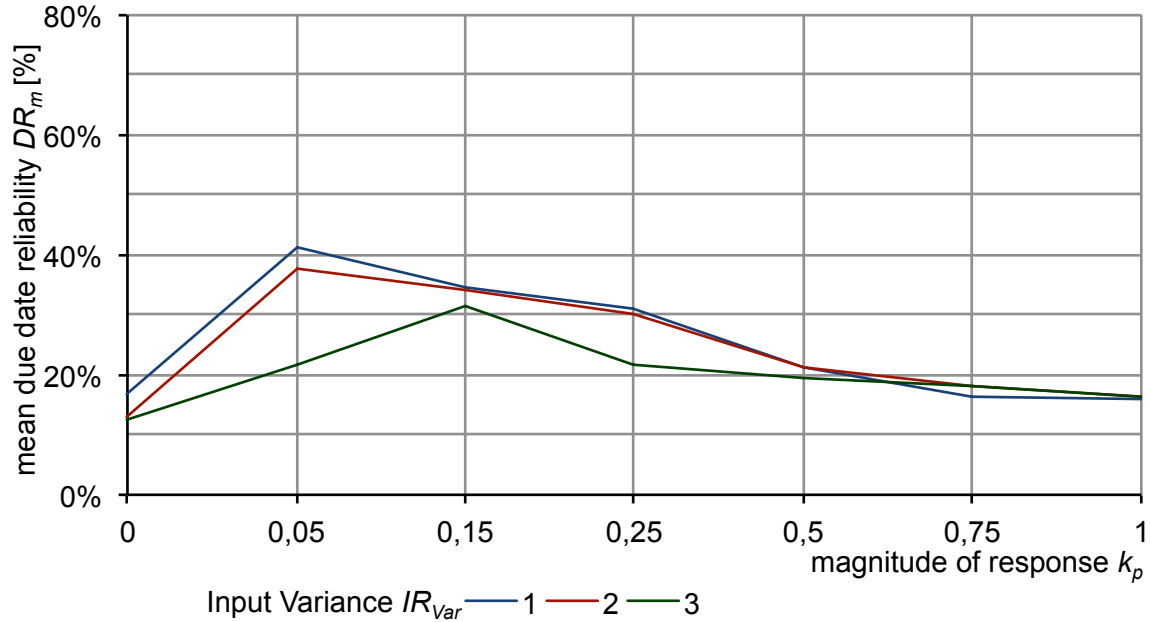


Figure 4.16 Mean due date reliability [%] with various magnitudes of response for all simulated input variances; $dT=3SCD$; $nT=2SCD$; $P=500$; $N=100$

Figure 4.17 shows the resulting mean due date reliability for $dT=3nT=9SCD$ in part (a) and $dT=7nT=7SCD$ in part (b). A ratio of three to one for case (a) led in combination with the high delay of $dT=9SCD$ to an extremely low performance. The resulting mean due date reliability is nearly independent from the magnitude of response. Moreover, the resulting performance for a low input fluctuation was actually higher, if no adjustments were implemented ($k_p=0$). This indicates that the impact of planned lead time control reaches its limits for such unfavorable ratios. This is further substantiated by part (b) in Figure 4.17 for which a ratio of seven to one was simulated. A damping of the planned lead time adjustment in this case had a negative influence on the resulting mean due date reliability. It can be concluded that the implementation of a magnitude of response for such unfavorable ratios of adjustment frequency and delay is inappropriate or even counterproductive. Thus, other control strategies might be more suitable for such situations, which is discussed in Section 6.1.3. Summing up all simulation results, an approximate method for setting a suitable magnitude of response is presented next.

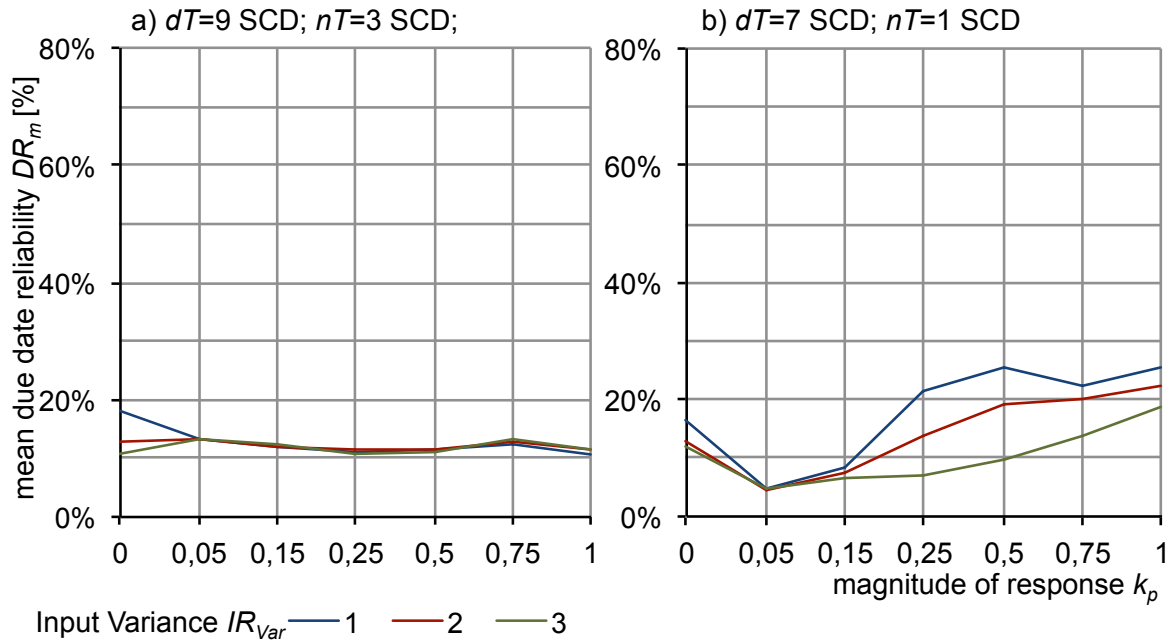


Figure 4.17 Mean due date reliability [%] with various magnitudes of response for all simulated input variances for (a) $dT=9$ SCD, $nT=3$ SCD and (b) $dT=7$ SCD, $nT=1$ SCD; $P=500$; $N=100$

The aim of this section was to evaluate whether a change in magnitude of response is able to increase system performance for situations in which the LTS occurs. In order to find a suitable k_p that is low enough to dampen the LTS, but high enough to maintain system performance, various input fluctuations, magnitudes of response, and ratios of adjustment frequency to delay were simulated. The observed correlations suggest that a suitable magnitude of response can be approximated using Equation 4.9 for ratios of $nT \leq dT$, which is explained below:

$$k_{p,min} < k_p = 0,25 \frac{n}{d} \leq 1 \quad \text{for } n \leq d$$

Equation 4.9

A magnitude of response with $k_p < 1$ for ratios of $nT > dT$ would lead to a damped planned lead time adjustment although the LTS will likely not occur under these parameter settings, hence to an unnecessarily reduced performance. For ratios of $nT \leq dT$, the recommended k_p decreases with an increasing ratio of nT to dT . This is because a system is less and less able to reach a steady state for longer delays at a specific (high) adjustment frequency. The application of planned lead time control should be reconsidered if the resulting k_p is lower than the minimal magnitude of response $k_{p,min}$. The simulation results suggest a minimal magnitude of response of $k_{p,min}=0,05$. However, these approximations exclude the influence of actual lead times, work in process levels, and input fluctuations. A derivation of the underlying differential equations of the presented control model would support the integration of these variables and possibly enable the derivation of more detailed interactions, which is not part of this work. Nevertheless, it can also be concluded that a

reduction of input fluctuation significantly increases system performance and that a suitable magnitude of response dampens the LTS.

4.3 Summary of the Control Theoretic Investigation of the Lead Time Syndrome

The mathematical modeling of the LTS in Chapter 3 revealed that the LTS is first triggered by the increase in lead time standard deviation as a direct consequence of planned lead time adjustments and second by inappropriate ratios of frequency and information delay of adjustment implementations. The aim of the control theoretic derivation of LTS interactions and triggers in this section was to validate these propositions and to derive strategies to damp or, if possible, avoid the LTS.

The presented time series at the beginning of the control theoretic investigation showed that an oscillatory system response can be observed if planned lead time control triggers the LTS. To derive strategies to reduce the impact of the LTS a lower adjustment frequency and a reduced magnitude of response were simulated. These strategies were derived from the Propositions P_1 (Standard deviation; Section 3.3.1) and P_2 (Frequency of adjustments; Section 3.3.2) respectively. Both scenarios led to a significant performance increase by reducing the variability of lead times and WIP levels in the simulated system. Starting with the investigation of the correlation between information delay and adjustment frequency, it was found that planned lead time control triggers the LTS if the adjustment period is not longer than the information delay. However, a satisfactory adjustment period might be too long in practice to obtain high system performance when there are long delays. Thus, it was then analyzed whether a suitable magnitude of response is able to dampen the LTS, while maintaining a high adjustment frequency. It was shown that the implementation of a suitable value to reduce the magnitude of planned lead time adjustments led to a significant performance increase as measured by due date reliability. Moreover, an initial approach to develop a formula to calculate a suitable magnitude of response was presented, which also defines limits of applicability. Other control strategies might be more suitable for short adjustment period lengths (with long delays) or if the calculated magnitude of response is below the minimum limit value, which is discussed and analyzed in Section 6.1. Besides, the reduction of input fluctuation significantly increased system performance by reducing the impact of the LTS. In summary, the presented strategies are able to either avoid or damp the LTS if it is inevitable. In the context of the LTS investigation, the evaluations using the control theoretic model can be summed up as follows:

- *The LTS can lead to an oscillatory system response.*
- *A reduction of disturbances and variation leads to an overall system improvement.*

- *Planned lead time adjustments lead to a short-term reduction in due date reliability.*
- *The LTS is triggered if the planned lead time adjustment period is shorter than or equal to the information delay and can be...
...damped by setting a suitable magnitude of response and
...avoided by choosing an adjustment period length that is longer than the information delay*

The presented research results validate Proposition P_1 that a planned lead time adjustment inevitably leads in the short-term to a decrease in due date reliability, as it increases process variability (e.g. lead time standard deviation). Although information delay is only a part of the latency period, Propositions P_2 was also validated, as the impact of the LTS was significantly reduced for adjustment period lengths that were longer than the information delay. For reasons of simulation complexity, only a single work system was simulated, which leads to a delay of zero until earlier/later released orders reach the investigated system (see Section 7.2 for a discussion of this assumption and limitations of this simulation approach).

In the next chapter, a case study of a manufacturing company is presented to investigate system behavior after planned lead time adjustments, thus to evaluate the LTS effects and confirm the derived propositions. This also includes a detailed evaluation and calculation of the latency period in practice. If, why, and for which scenarios capacity control is an alternative to planned lead time control is analyzed in Section 6.1. In addition, the strategies found for mitigating the LTS are used in Section 6.2 and Section 6.3 to develop suitable planned lead time adjustment strategies.

5 Case Study: Evaluation and Illustration of Lead Time Syndrome Effects²⁸

*“The due date reliability of the work system decreased once again.
I would like to adjust planned lead times”
(production planner of a manufacturing company)*

The mathematical and control theoretic investigation of the LTS in Chapter 3 and Chapter 4 identified underlying interactions and triggers of the syndrome. However, both investigations are subject to assumptions and limitations. Hence, another investigation is needed to confirm and evaluate the derived propositions. The choice of a suitable research method for this task strongly depends on the open research questions, which are:

- *How do planners adjust planned lead times without additional information about the LTS and is there a difference between the situation with no and full transparency of actual system states?*
- *How does the adjustment of planned lead times affect systems' due date performance?*
- *How long are adjustment periods in practice?*

According to Yin (2009) the case study research method can be used to answer 'how' and 'why' questions which seek to explain a phenomenon that can be observed in real-life. The research results of a case study can thereby confirm, challenge, or extend the tested theory. For this purpose, a descriptive case study is comprised of five important components (Yin 2009):

1. Study questions
2. Propositions of expected outcomes
3. Unit of analysis
4. Analytic techniques to answer the study's questions
5. Criteria for interpreting the findings

The following case study is in line with these steps for answering the above mentioned study's questions. Section 5.1 presents the unit of analysis, which is a manufacturing process in a division of a steel manufacturer. In this context the sources of evidence, the approach of data validation, and limitations of the research are presented. Section 5.2 and Section 5.3 present separate analytic techniques for answering the study's questions. Based on the previous investigations and propositions, both sections initially present expected outcomes, which are then compared to the observed situation in the case company. Section 5.2 focuses on the

²⁸ Parts of this chapter have been published in similar form in (Knollmann 2013c; Knollmann 2014b; Knollmann 2014c).

description of a situation before implementing a computer-aided PPC system, thus with limited transparency about actual system states. In Section 5.3 a PPC IT-system gave the planners better transparency. Here, the actual implementation and effects of planned lead time adjustments are described. The criteria for interpreting the observations are derived from expectations that are based on the above presented research results on the LTS. Finally, Section 5.4 summarizes the observations made in the case study and whether or not the initial propositions were confirmed.

5.1 Case Description, Data Preparation and Validation

Before starting to evaluate the LTS effects, a unit of analysis initially has to be selected and described in detail, which also includes the sources of evidence, the approach of data validation, and limitations of the research. Thus, Section 5.1.1 presents the unit of analysis, the reason of choice for the case company, and the quality criteria to generate valid results by means of a single-case study. Then, Section 5.1.2 explains the process of data gathering and describes in detail the datasets that were analyzed. Finally, Section 5.1.3 presents the approach taken for validating feedback data and analysis results, and discusses the limitations of a single-case study.

5.1.1 Manufacturing Process Description and Reason for Selection

The case company is a division of a globally operating steel manufacturer. In this job-oriented production environment individual customer orders are processed separately on a given set of machines. The work plans differ between orders because not only one ‘product’ is produced, but rather incoming materials are characterized. These characteristics are, e.g., surface defects, corrosion behavior or material properties. As part of a research project of the Production & Logistics Networks Workgroup at Jacobs University Bremen, a custom-made PPC IT-system was developed, which replaced manual order planning to improve due date reliability. It was developed in close cooperation with production planners, shop floor workers, and employees of the IT-department from September 2011 to June 2014.

Each incoming order is scheduled backwards with defined planned lead times for each processing step. The processing sequence of orders is defined by the due dates of the orders at the current processing step. Besides the automated planning and scheduling of orders, the IT-system also calculates logistic KPIs such as lead times, lateness or WIP levels and visualizes the logistic performance in operating curves, histograms, time series, throughput diagrams, etc.

The selection of the unit of analysis depends on the study questions, thus if the case is suitable to gain knowledge about the LTS (Eisenhardt 2007). The initial situation of the company describes a worst case steady state of the LTS, as no transparency of actual system states was given. In the course of the research project

transparency was given by the implementation of the IT-system. However, planned lead time adjustments were discussed over the entire period to control the system. This planned lead time control enables the evaluation of impacts on the due date performance and the calculation of adjustment periods. Besides, the system characteristics of the current situation in the company match the underlying assumptions of the LTS:

- Due date reliability chosen as main performance indicator
- High fluctuation of processing times
- Computer-aided production planning and control system with backward scheduling
- Short-term restricted maximum capacity of workers and long term restricted capacities of bottleneck systems with almost 100% capacity utilization
- Low due date performance as initial situation with the intention of planners to increase it by planned lead time adjustments

To establish the quality of a single-case Yin (2009) suggests to test (and guarantee) the (1) construct validity, (2) external validity, and (3) reliability throughout the study (see also (Voss 2002; Riege 2003)):

(1) The construct validity tests if the applied methods are suitable for the investigation to gain knowledge about the study questions. Following the suggestions of Yin (2009), the construct validity of the presented single-case was increased by the investigation of multiple subunits (i.e., planned lead time adjustments in multiple systems at different SCDs), establishing chains of evidence, and constant reviews of preliminary results by workers in the company.

(2) If the results are generalizable and transferable beyond the presented case is tested by the external validity. In single-case studies it can be supported by trying to generalize the findings to “theory”, thus to the research outcomes on the LTS presented in the previous sections (Yin 2009).

(3) Finally, the reliability of a case study design tests if it is possible to repeat the analyses and to come up with the same results (Riege 2003). This criterion was supported by the detailed description of the observations and analyses and by providing all revised datasets (including the original feedback data) on the attached DVD (see Appendix)

The underlying dataset will be used in the following subsections to further investigate the LTS, and thus to evaluate and confirm the propositions of the mathematical and control theoretic investigations. The following section initially describes how and which data were collected.

5.1.2 Data Gathering and Data Description

According to Yin (2009) the main sources of evidence in a case study research are documents, physical artifacts, interviews, and observations. Although no physical artifacts are given, documents, expert interviews, and observations lead to a sufficient data basis:

Expert interviews: During the period of investigation (09/2011-06/2014, 34 months) appointments took place almost every second week. Shop floor workers, production planners, and software developers attended these meetings. In these meetings specifications, problems and solution alternatives were discussed. As the scope of the research project was to improve due date reliability and not the investigation of the LTS, individual persons of these groups were interviewed primarily to validate and discuss KPIs and diagrams.

Observations: The knowledge required to interpret and understand the data was obtained in intensive, continuous observations during the whole period of investigation. The research project started in 09/2011 and had a duration of 34 months. The last of the biweekly meetings took place in 06/2014.

Documents: The implemented IT-system continuously collects all relevant information. It is necessary to distinguish between the master data and the feedback data. The master dataset includes planning values (e.g., interoperation times; set up times; operation times) and dates of implemented updates for each work system. The feedback dataset includes the actual and planned input, output and due dates of each order for each work system. Moreover, the work content and the name of the predecessor are available. For further data analysis, the feedback data has to be prepared according to the following steps. These steps are based on the approach for gaining knowledge from databases (Fayyad 1996), which is shown in Figure 5.1.

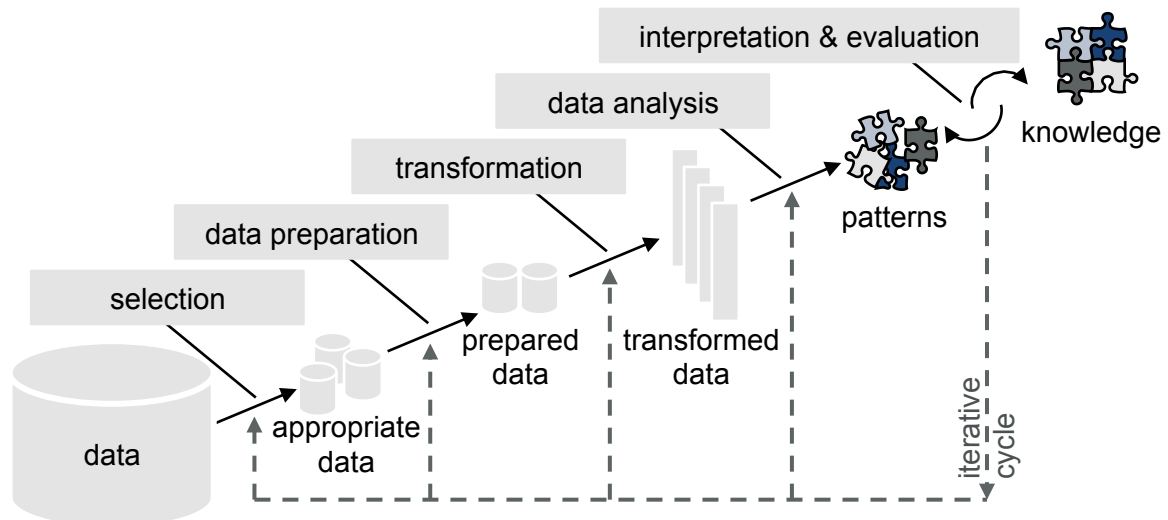


Figure 5.1 Generalized process of knowledge discovery in databases (KDD) (based on (Fayyad 1996))

1. Data gathering: As described above, Excel sheets are available that include feedback data and a master dataset (see appendix).
2. Selection of relevant data: During the whole research project order data were recorded to calculate lateness and lead times of orders. This *total period of investigation* covers 34 months (from 09/2011-06/2014). The focus of the subsequently planned investigations lies on effects that occur during or after planned lead time adjustments. Hence, a more detailed dataset includes the data of work systems that implemented planned lead time adjustments. The

final period of investigation corresponding to this dataset is limited by the launching month of the IT-system and covers a period of 8 months (from 11/2013-06/2014).

3. Data preparation: The resulting datasets are based on user entries. Thus, input errors have to be deleted. This data revision includes wrong terms, missing data fields, and obviously wrong dates, i.e., dates that would lead to negative lead times.
4. Transformation: Depending on the selected data analysis method the prepared data have to be transformed into a compatible formatting. Exemplary, all dates were transformed from the Gregorian calendar into shop calendar days (SCD).
5. Data analysis: The transformed dataset allows all subsequently presented analyzing methods.

The presented sources of evidence will be used in the following sections to describe and analyze the influence of the LTS on a running manufacturing system with human planners and controllers making decisions.

5.1.3 Data Validation and Limitations of Research

The performed analyses that are based on the collected data are subject to limitations and have to be validated. This section focuses on identifying these limitations and presenting the process of validating the analysis results (See also Section 7.2 for limitations and generalizability of a single-case).

The underlying dataset has some weaknesses that have to be considered in analysis and evaluation. One weakness is that order feedback data include exact date and time information. However, these data are not collected automatically, but rather entered by the workers on a daily basis. Thus, only the shop calendar day of the feedback data is used for calculations to avoid conclusions based on spurious data accuracy. Another weakness is the short final period of investigation in which the PPC IT-system started to plan orders automatically. Therefore, only a few work systems are suitable candidates for further analyses. Moreover, planned lead time adjustments were implemented only after discussions with planners to avoid the LTS. Hence, the observation of impacts of too frequent or unnecessary adjustments, which possibly reinforce the impact of the LTS, is impossible with the given dataset.

The results presented in the subsequent sections only depict the condensed outcome of a wide range of investigations performed during the research project. Process experts evaluated and confirmed the presented outcomes and discussed reasons for observed characteristics. These discussions are also directly considered in the interpretation and evaluation sections. This qualitative data validation is supported by a quantitative validation by the implemented IT-system of the company. The case study results are based directly on the feedback data evaluations. To validate the results similar analyses were performed with the IT-system in the company that creates KPIs on a higher level of aggregation. The comparison of both discrete analysis approaches provided sufficient validation.

5.2 Initial Situation before PPC implementation: Worst Case Steady State of the Lead Time Syndrome

The second question of this case study was how planned lead times adjustments affect systems' due date reliability. However, as there is no planning system in the initial period of investigation of the case company, transparency regarding system states and logistic target achievements was rarely possible. Time-consuming manual calculation were necessary to determine the actual due date reliability. Due to the low transparency, planners' decisions to release orders earlier are mostly based on gut feelings, which can lead to the situation described below. Before this description, a more precise characterization of the initial system state is given. Then, the expected situation according to the LTS line of argumentation will be defined. Finally, the outcomes of the logistic analysis are presented and compared to the expected situation of the worst case.

At the beginning of the research project, due dates of incoming orders were defined manually by planners. If orders had no predefined due dates, they were scheduled based on gut feelings. Therefore, due dates were set to a date in one, two or three weeks from current date on. These due dates defined the planned completion date of the whole order without considering further due dates of required intermediate processing steps. This 'planning' resulted in 80% of orders with a planned lead time of three weeks, thus 15 SCDs (five-day working week). Incoming orders were released immediately. More specifically, planned orders were directly given to the first processing step. Without further information about order priorities, workers processed orders in no predefined sequence. It was often observed that either orders were processed that seemed to be urgent or aroused the interest of the worker. This means that orders were processed depending on personal interests of the workers, as they preferred analyzing the surfaces of special cases rather than 'normal' orders. Thus, just like rush orders, some orders were finished within a few days regardless their due date priority. Accordingly, other orders were finished too late as they remained in queues too long. If these orders became urgent, they were declared as rush orders, thus leading to even more disruptions.

The described situation seems to be similar to the worst case steady state of the LTS, which is shown in Figure 5.2 and can be derived from the line of argumentation of Mather and Plossl (1977): If planned lead times are repeatedly increased to meet due dates, the cycle of the LTS repeats until lead times reach a high level (Wiendahl 1997a; Mather 1977). Figure 5.2 describes the expected steady state of the analyzed process. Planned lead times remain unused for planning and scheduling. Orders lead times are planned without calculation of expected lead times, and order sequencing in front of the work systems is largely arbitrary. An immediate order release thereby leads to high WIP levels and long lead times. Long lead times and the lack of sequencing once again lead to a high lead time standard deviation. Finally, the observed due date reliability is on a low level. Without transparency and no planning system, orders are not scheduled and not finished

according to the underlying due dates. Thus, the lateness distribution is not normally distributed (as assumed in Section 3.1.1), hence inducing a poor due date reliability.

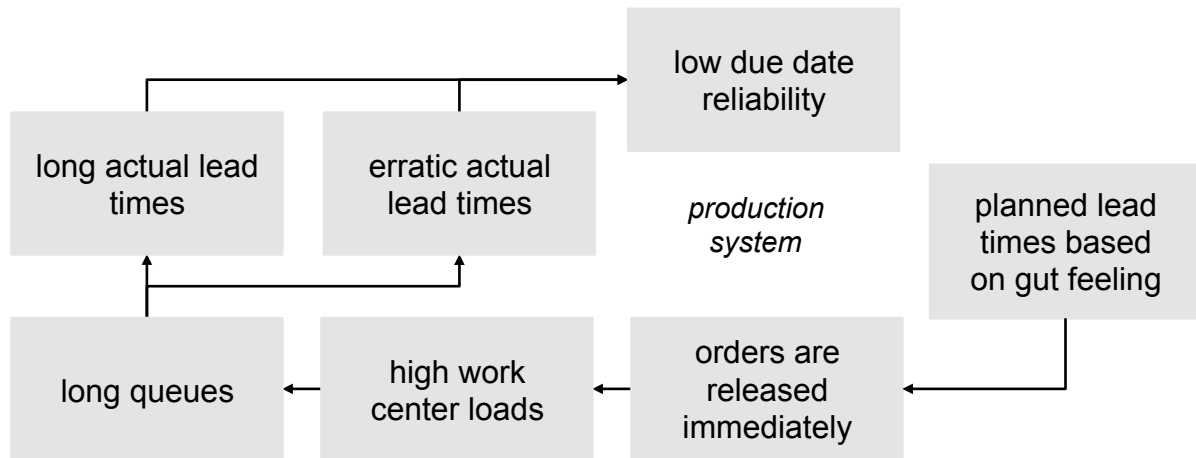


Figure 5.2 Worst case steady state of the Lead Time Syndrome

Initially the WIP level is evaluated to test whether a worst case scenario as described above can be assumed for the initial state of the case study. Figure 5.3 shows the throughput diagram of one exemplary work system in the process chain, which is situated at the beginning of the process chain. At this system a worker takes macroscopic pictures (manually) of the surface of an object. The end of the shown *initial period of investigation* is defined by the starting date of the research project (SCD 180). It can be seen that at each day a high WIP level was measured. In detail, 840 hours of work were waiting on average in front of the work system. Thus, with an average output rate of some 30 h/SCD, a range of 28 SCD was given. In summary, the system is operating in the overload area (according to the Logistic Operation Curve theory presented in Section 2.1.3).

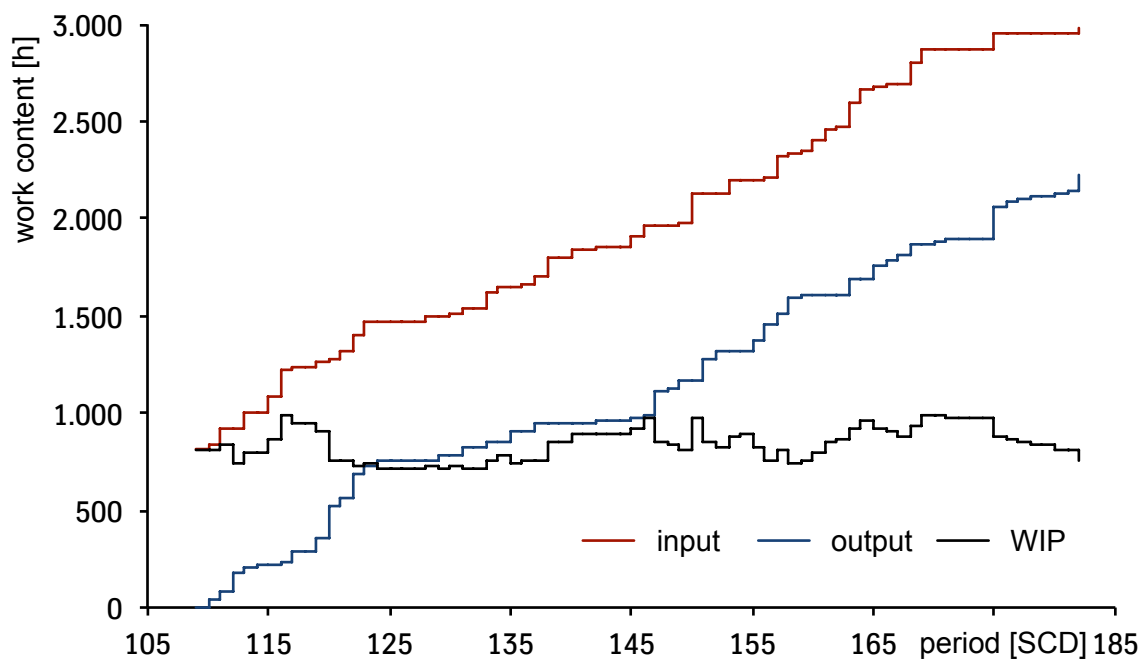


Figure 5.3 Throughput diagram of an exemplary work system before PPC implementation

Figure 5.3 reflects only one processing step. Over all processing steps, the mean lead time of orders reached a level of 35 SCD, with a standard deviation of 55 SCD. This standard deviation is extremely high, as the coefficient of variation (CV) is 1,57 ($=55 \text{ SCD}/35 \text{ SCD}$), which is according to Hopp (2008) a value of high variation. For comparison, at the end of the research project mean lead times reached a level below 11 SCD, with a standard deviation below 8 SCD ($CV=8 \text{ SCD}/11 \text{ SCD}=0,72 \triangleq \text{'low' variance}$). Thus, the high WIP level and the long lead times correspond to the worst case steady state of the LTS. The high variation of lead times in the beginning is reflected in the resulting lateness distribution shown in Figure 5.4, which is – as expected – not normally distributed. It shows that almost 30% of the finished orders are either produced directly or according to their due date. About 60% of all orders that were processed were finished ahead of the agreed due date, thus potentially blocking capacities for tardy orders.

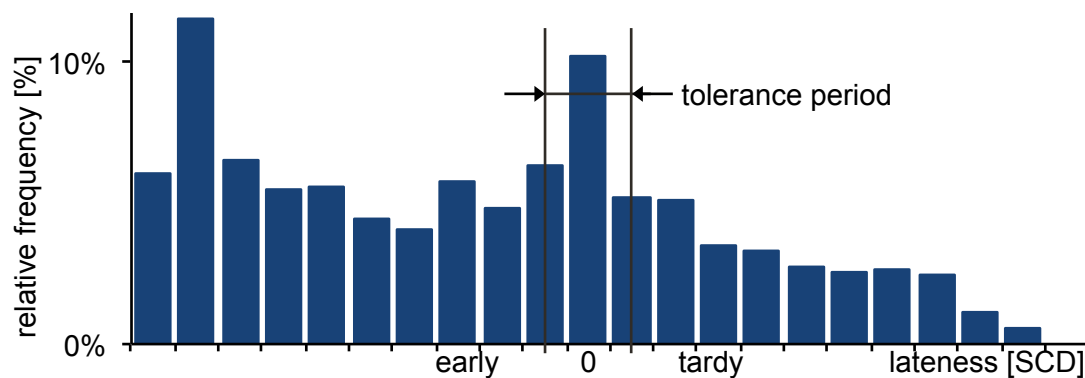


Figure 5.4 Process lateness distribution before implementing PPC. $DR=18\%$; $L_m=-5\text{SCD}$; $L_{sd}=10\text{SCD}$; *tolerance period: $\pm 2 \text{ SCD}$*

The implemented PPC system significantly reduced WIP levels and lead times along with an increased due date reliability. However, according to the LTS assumptions, planned lead time adjustments affect the resulting due date reliability. The impact of such adjustments will be investigated next.

5.3 Exemplary Examination of Planned Lead Time Adjustments in a Manufacturing System

During the research project a custom-made PPC IT-system was implemented to increase due date reliability. This system increased the level of transparency of the logistic situation, e.g., by providing throughput diagrams, lateness distributions, and due date reliability over time. These analyses are available for responsible decision makers at any time and include the possibility of individual settings such as the period of investigation, selected work systems, selected order types, etc. The result was a significant increase of due date reliability as shown in Figure 5.5. The distribution shows the lateness of processed orders at the end of the final period of investigation.

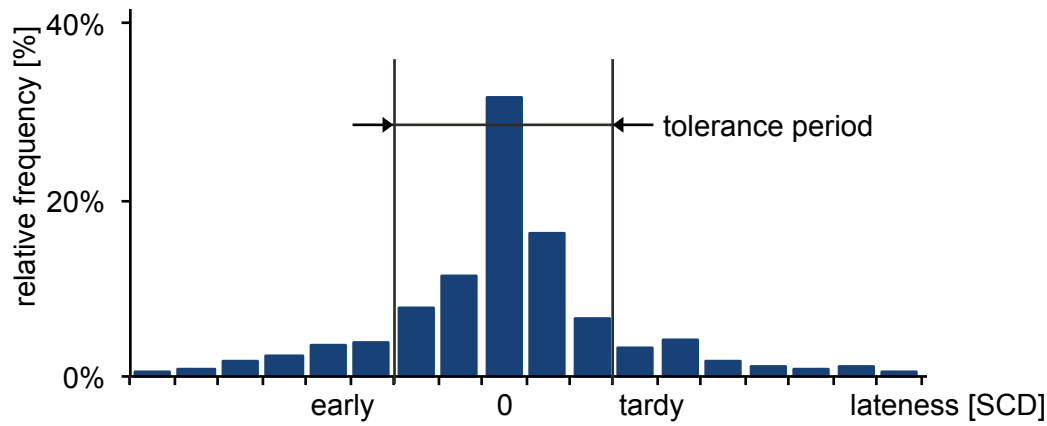


Figure 5.5 Process lateness distribution after PPC implementation. $DR=74\%$; $L_m=0,1SCD$; $L_{sd}=2.7SCD$; tolerance period: $\pm 2SCD$

The implementation of the IT-system also provided planners with a tool to adjust planned lead times very quickly and in an uncomplicated way (by adjusting one value in the master data). Therefore, demand fluctuations occasionally lead to adjustments in lead times and, consequently, to a temporary decrease of due date reliabilities. Even with full transparency, it was observed that planners would tend to adjust planned lead times instead of working against increasing lead times and WIP levels by short-term capacity adjustments²⁹ (e.g., by extra shifts). This situation led to the pro-active decision to test the correctness of planned lead times only quarterly to avoid the LTS. Hence, the observation of too frequent adjustments that possibly reinforce the impact of the LTS is impossible with the given dataset. Nevertheless, the implementation and the impact of planned lead time adjustments will be discussed in this section. Initially, suitable work systems have to be selected for further investigations. Thus, the unit of analysis shifts from the production process as a whole in the previous section to a more detailed investigation of individual work systems in the production process. The selection of suitable work systems that are listed in Table 5.1 was based on the following requirements:

- The work system is part of the production process in the investigated division³⁰.
- A planned lead time adjustment had to take place during the final period of investigation, in which full data transparency was given by the implemented PPC IT-system (from 01.11.2013-20.06.2014; SCD 1342-1497).
- A suitable number of operations has to be given to enable a characterization of system's behavior.

The chosen work systems are subsequently analyzed regarding their magnitude of response of planned lead time adjustments (Section 0), and the resulting latency period and due date performance after adjustments (Section 5.3.2).

²⁹ See also the quotation of a production planner in the introduction of Chapter 5.

³⁰ The dataset also includes feedback data of work systems of other divisions.

Table 5.1. List of work systems with planned lead time adjustments in the final period of investigation (SCD 1342-1497).

	SCD of Adjustment	Number of operations	Old tl_p	New tl_p
System A	1394	781	1.8	1.5
System B	1482	126	2.5	3
System C	1475	193	3	2
System D	1394	343	1.5	1
System E	1474	40	2	6

5.3.1 Magnitude of Response of Planned Lead Time Adjustments

The mathematical approach presented in Chapter 3 implied the ideal situation of maintaining the maximum due date reliability by setting the new planned lead time to the latest mean value of actual lead time. In practice, this is not necessarily possible. However, the magnitude of response was introduced in the control theoretic investigation of Chapter 4 to set the magnitude of planned lead time adjustments. Thus, the variable magnitude of response enables an ex-post analysis of implemented planned lead time adjustments in the chosen work systems examples of the case study. The aim of this section is to evaluate and discuss these adjustments.

The variable magnitude of response k_p was introduced into the control theoretic model to dampen the magnitude of planned lead time adjustments. Hence, values between zero (no planned lead time adjustment) and one (adjustment corresponds with the mathematical optimum) were set. The mathematical optimum is not an optimum in the narrow sense, but rather the calculated value that would maximize the resulting due date reliability. The ex-post analysis of adjustments brings a new meaning to the variable, which is the relationship between the implemented adjustment in practice and the mathematical optimum. The calculation of this ratio is shown in Equation 5.1, which is based on Equation 4.5. The resulting value directly classifies the implemented adjustments into five different classes. These classes indicate the logic of adjustments from a mathematical point of view. Besides the already mentioned classes (between 0 and 1) also magnitudes higher than one or lower than zero are mathematically possible. For the case of negative values planners increased/decreased planned lead times instead of decreasing/increasing them.

$$k_p = \frac{\Delta tl_p^{\text{implemented}}}{\Delta tl_p^{\text{mathematical optimum}}} = \frac{tl_p^{\text{new}} - tl_p^{\text{old}}}{tl_m - tl_p^{\text{old}}} = \begin{cases} > 1 & , \text{amplified} \\ 1 & , \text{mathematical optimum} \\]0;1[& , \text{damped} \\ 0 & , \text{no adjustment} \\ < 0 & , \text{error / misconception} \end{cases}$$

Equation 5.1

During the final period of investigation five planned lead time adjustments were implemented (see Table 5.1). Table 5.2 lists up the relevant KPIs at the moment of decision-making. In order to improve the current due date reliability planned lead times were increased or decreased. Exemplary, Figure 5.6 shows two lateness distributions at the moment of decision-making that help explain the decisions taken.

Table 5.2. Ex post calculation of the magnitude of response at the moment of planned lead time adjustments during the period of investigation.

	DR	tl_m	Old tl_p	New tl_p	k_p
System A	88%	1.7	1.8	1.5	3
System B	78%	3.8	2.5	3	0,4
System C	80%	1.4	3	2	0,6
System D	90%	0,5	1.5	1	0,5
System E	13%	11.2	2	6	0,4

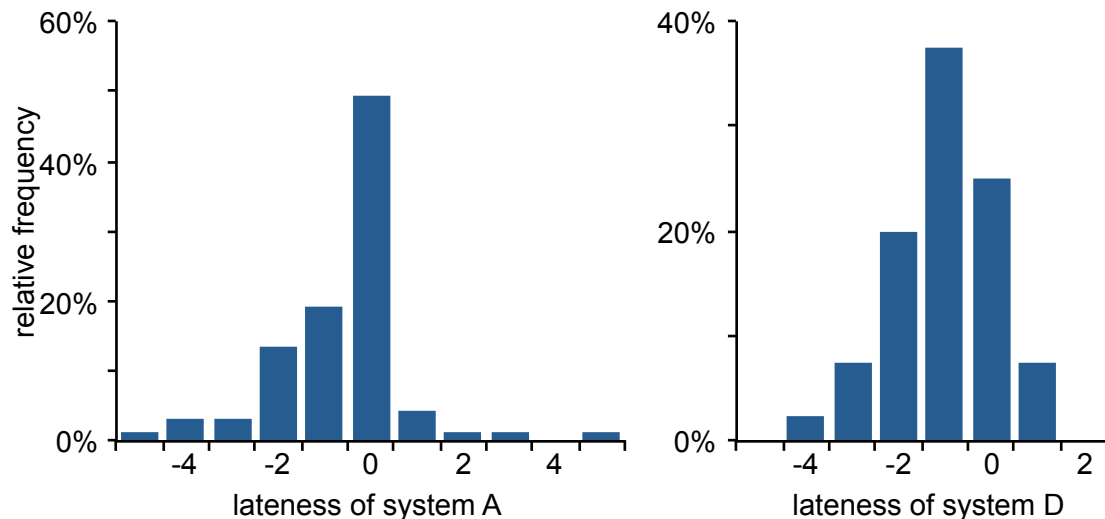


Figure 5.6 Lateness distributions of the exemplary work systems A and D at the moment of decision-making (period of investigation for both systems SCD 1374-1394)

Both distributions show a shift towards earliness with a very low number of tardy orders. This means that orders are more often finished too early (regarding the planned due date) and that less than 4,5% of all orders are delayed in system A (no delayed orders in system D). The due date tolerance was set to ± 2 SCD in the case company, which explains the high values of due date reliability for each system listed in Table 5.2. Planned lead times were decreased due to the shift toward earliness in both distributions, which means that actual lead times are on average shorter than planned lead times. The resulting magnitude of response has a value of three for system A. Thus, the implemented adjustment for system A is three times higher than the calculated difference between the actual mean lead time and the old planned lead time (which is the calculated mathematical optimum). The relatively high number of orders with a lateness lower than -2 SCDs (8% in system A) was the reason for the amplification of the calculated mathematical optimal adjustment. For

System A it was assumed by planners that unplanned sequence deviations led to both too early and tardy order processing. Thus, planners anticipated that not only planned lead times are slightly different, but that the system is able to perform better. A different approach can be seen for system D. The shape of the distribution is already very similar to the shape of a normal distribution. This indicates that the system processes orders according to the planned sequence. As the planned lead time is very short already (in comparison to other work systems in the investigated company) it was decreased only half as much ($k_p=0,5$) as calculated. In Table 5.2 it can be seen that planned lead times were adjusted at four out of five systems with a magnitude of response between zero and one. Thus, planners damped the calculated 'optimal' adjustment in these cases.

The increased logistic transparency with throughput diagrams, lateness distributions and other KPIs enables more precise adjustments rather than adjustments based on gut feelings. The effect of these adjustments was an increase in due date reliability, which will be shown in the next section. To avoid the LTS, planners decided to meet quarterly to check planned lead times³¹. Therefore, one-time adjustments that set a final planned lead time are not necessarily required and allow (if needed) reoccurring damped adjustments to approach the optimal parameter setting of this changing environment. As discussed in the control theoretic investigation in Chapter 4, a damped magnitude of response decreases fluctuations and the impact of the LTS for long latency periods. Hence, it can be concluded that the LTS was avoided during the final period of investigation, as the implemented planned lead time adjustments were found appropriate in terms of magnitude and frequency. However, if and how latency periods can be observed in the investigated case will be evaluated in the following section.

5.3.2 Evaluation and Calculation of the Latency Period and Due Date Performance after Adjustments

The mathematical investigation of the LTS presented in Section 3.1.4 suggested that the implementation of a planned lead time adjustment not results in an immediate due date reliability increase to the desired level, but instead results in a gradual change over time (see also Observation 3, Section 3.3.2). In terms of the investigation of the LTS, this leads to the question, if this phenomenon can be observed in practice as well. Thus, this section presents the investigation of the change process after a planned lead time adjustment and an evaluation of the resulting latency periods in a real manufacturing system. This enables to compare the expected system behavior, which is based on the investigations presented in the previous sections, with the actual system behavior in practice. Therefore, initially the expected latency periods will be calculated. Then, due date reliability of exemplary work systems is plotted over time to compare the calculated latency periods with the observations in the case study.

³¹ This time period was calculated according to the definition presented in Section 6.2.

The latency period of a system was defined in Section 3.3.2 as the time period required for a system to reach a steady state again after planned lead time adjustments (see Observation 3; Section 3.3.2). It was further defined as the sum of information and processing delays. On one hand the information delay determines the time period between monitoring the actual lead time and the implementation of new values into the planning and controlling system. On the other hand the processing delay is defined as the sum of the averaging period of the due date reliability calculation and the sum of ranges of the adjusted system and its predecessors. Table 5.3 shows the resulting delays after the planned lead time adjustments of the exemplary case study work systems (see Table 5.2). The resulting information and processing delays are calculated separately.

Table 5.3. Calculation of delays during planned lead time adjustments in the case company. *WIP* [orders]; *ROUT* [h/SCD]

	SCD of adjustment determination	SCD of adjustment implementation	$d_{information}$ [SCD]	System range (WIP/ROUT) [SCD]	Implemented averaging period [SCD]	$d_{processing}$ [SCD]
System A	1394	1394	<1	$29 / 10 = 2.9$	20	23
System B	1473	1482	9	$15 / 4 = 3.8$	20	24
System C	1473	1475	2	$12 / 4.3 = 2.8$	20	23
System D	1394	1394	<1	$4 / 4.6 = 0.9$	20	21
System E	1473	1474	1	$2 / 0.7 = 2.8$	20	23

The underlying dataset includes a data field called ‘valid from’ that defines the SCD of the adjustment implementation. New planned lead times were discussed and determined in two separate meetings on SCD 1394 (for system A & D) and almost four month later on SCD 1473 (for system B; C; E). The difference between the determination day and the implementation day results in the length of the information delay $d_{information}$. Therefore, the implementation of the new planned lead times lasted up to 9 SCD for system B, while other adjustments were implemented even on the same day (i.e., systems A and D).

The due date reliability results from the actual lateness of orders, which in turn results from the actual lead times. However, newly planned orders have to await their processing in the work system queues to finally affect lead times, which are once again calculated after order processing. The variable ‘range’ represents this time period and is dependent on the WIP level and the output rate *ROUT* (see Funnel Formula in Section 2.1.2). Both values were measured at the moment of the adjustment, resulting in the range value for each system. The averaging period defines the mathematical delay until a jump from one to another value is covered completely. In the case company due date reliability is calculated over the last 20 SCDs, representing one month. The processing delay $d_{processing}$ is the sum of the range and the averaging period. Hence, for the analyzed work systems, gradually

increasing due date reliabilities for 21 up to 24 SCDs are expected after implementation of the planned lead time adjustments.

To evaluate whether the resulting due date reliability increases gradually or not, the resulting due date reliability has to be plotted over time. Figure 5.7 and Figure 5.8 show the resulting due date reliability of system A and system D. These work systems were chosen because their planned lead times were adjusted in the middle of the final period of investigation. This characteristic guarantees that the investigated system is able to reach – if possible – a steady state during the final period of investigation. Unfortunately, the adjustment at the end of the period of investigation of the other three work systems prevents a detailed evaluation. Moreover, system A and D are first processing steps without predecessors. Thus, processing delays of predecessors, which would further conceal effects, are not given. Compared with this optimal situation the other work systems have predecessors, which lead to very long processing delays. However, the resulting due date reliability of system A and D are strongly affected by work input fluctuations that are due to the process characteristics beyond planners' control. For this reason, quantifiable statements that are universally valid are only possible to a limited extent. Nevertheless, causal relationships can be observed for both systems.

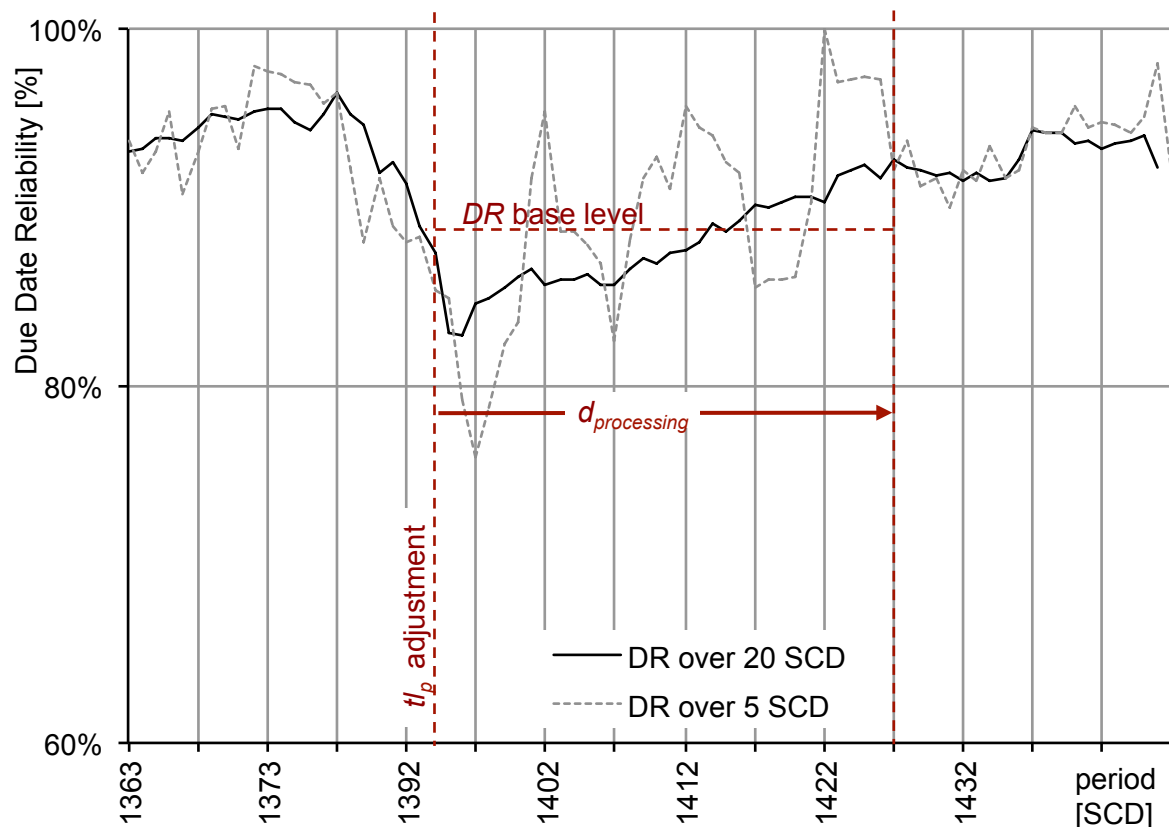


Figure 5.7 Moving average of due date reliability of system A over time

Figure 5.7 shows the due date reliability of system A. The planned lead time adjustment was implemented at SCD 1394. It can be seen that the due date reliability initially decreases from the base level of 89% at SCD 1393 to 83% at SCD 1396. Afterwards, a gradual increase can be observed at least until SCD 1427 with

92% due date reliability. Thus, the observed processing delay is at least 33 periods ($1427 - 1394 = 33$ SCD).

This means that the observed processing delay is longer than the calculated value of 23 periods (see Table 5.3). One possible explanation for this long and almost linear increase of due date reliability can be seen in the lateness distribution at the moment of the planned lead time adjustment (see system A in Figure 5.6). As already discussed, it was assumed by planners that system A would perform better if, e.g., unplanned sequence deviations are avoided. Thus, the effects of the planned lead time adjustment and the increasing schedule adherence overlap.

For a more precise analysis of system A and to decrease the overlapping, a week based (over 5 SCD) due date reliability curve was calculated in addition to the calculation over the last month. Once again due date reliability decreases from a base level of 88% at SCD 1393 to 76% at SCD 1397. In contrast to the situation with the long averaging period, a rapid increase of due date reliability to a level of 95% at SCD 1402 can be observed afterwards. Thus, the processing delay is given with 8 periods, which meets the calculated delay ($d_{range} + d_{averaging} = 3 \text{ SCD} + 5 \text{ SCD} = 8 \text{ SCD}$). Due to the high oscillation of the resulting due date reliability and the possibly overlapping impact of an increased schedule adherence, another work system was evaluated in the same manner.

Figure 5.8 shows the resulting due date reliability of system D. The planned lead time adjustment was also implemented at SCD 1394, leading to a decrease in due date reliability from the base level of 92% at SCD 1393 to 90% at SCD 1394. Afterwards, once again a gradual increase can be observed until SCD 1411 with 98% due date reliability. For this case the observed processing delay is 17 periods ($1411 - 1394 = 17$ SCD).

The observed processing delay is shorter than the calculated delay of 21 periods. A separate investigation of the work system and the discussion with an expert revealed that a sudden input decrease occurred from SCD 1417 on. It dropped from 1.3 h/SCD to only 0,3 h/SCD. Hence, the WIP level decreased, leading to shorter lead times and therefore deviations with respect to the new planned lead times. This effect explains the lower due date reliability in the end of the observation period.

Again, the same evaluation was performed for a shorter observation period of 5 instead of 20 SCDs. Here, due date reliability drops from a base level of 95% at SCD 1393 to 90% at SCD 1394. Afterwards, once again a more rapid increase of due date reliability to the maximum level of 100% at SCD 1400 can be observed. Thus, the processing delay is given with 6 periods, which meets the newly calculated delay of 6 periods ($range + averaging = 1 \text{ SCD} + 5 \text{ SCD} = 6 \text{ SCD}$).

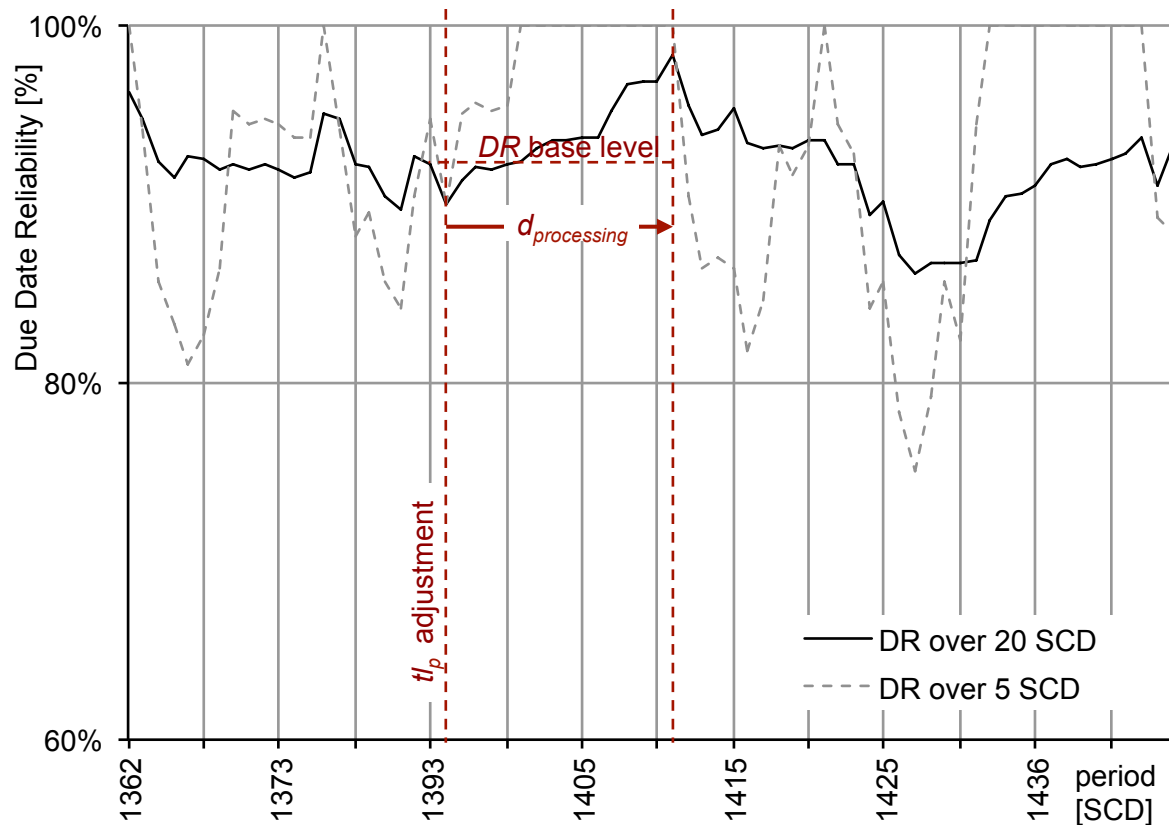


Figure 5.8 Moving average of due date reliability of system D over time

The investigation of the latency period in Section 3.3.2 suggests a sudden decrease of due date reliability after the implementation of new planned lead times (see Figure 3.12), because the resulting latency period depended on the underlying WIP level and averaging period. Both investigated systems show a sudden decrease of due date reliability for both long and short averaging periods. A gradual increase can be observed afterwards which corresponds with the expected development. Moreover, the calculated latency periods approximately correspond with the observed latency periods. However, in the scope of the LTS investigation the delay until due date reliability reaches the base level again is even more interesting. If planners would check actual lead times before this event, they would detect a due date reliability reduction and once again adjust planned lead times. Hence, in practice the adjustment period length has to be longer than this delay. For system A it is 20 periods for an averaging period of one month and seven periods for an averaging period of one week. In system D the delays are four periods and one period, respectively. These significant differences would demand individual choices of adjustment period lengths to avoid triggering the LTS. The investigated systems moreover represent optimal cases, as they have no predecessors leading to even longer latency periods. For a system at the end of the production process very long latency periods may arise. Exemplary, system C is a final processing step. With an average lead time (corresponds on average with the mean range (Nyhuis 2009b)) of 11 SCDs for incoming orders and an averaging period of 20 SCDs, the expected processing delay is 31 SCDs. Including the average measured information delay of 3 SCDs, the resulting latency period of System C is expected to last for at least 34

SCDs, which is approximately seven weeks. The next section summarizes the observations of the case study and evaluates the propositions of the previous investigations with these observations.

5.4 Summary of the Evaluation and Confirmation of the Derived Propositions

This section presented a case study of a steel manufacturing company. The aim was the evaluation and confirmation of previously derived propositions. The investigation of the LTS by means of a mathematical and a control theoretic model revealed underlying relationships that led to the formulation of three research questions to be answered by the case study. Summing up the presented results, the questions can be answered as follows:

How do planners adjust planned lead times without additional information about the LTS and is there a difference between the situation with no and full transparency of actual system states?

A distinction must be made between the situation with full transparency (e.g., given by an implemented PPC IT-System) and no transparency of actual system states. The latter case can easily lead into the worst case steady-state of the LTS. This situation is characterized in the case study by immediate order release and order planning that is based on gut feelings of planners³². The steady-state manifests itself in high WIP levels, long and erratic lead times and a low due date reliability. Moreover, the lateness distribution is not normally distributed. The implementation of a PPC IT-System significantly increased transparency and the overall logistic performance. The investigation of the implemented planned lead time adjustments showed that the resulting magnitudes of adjustments were damped in comparison to the mathematical optimum in four out of the five observed adjustments, and amplified in one. Hence, according to the control theoretic investigation in Section 4.2.3, the impact of the LTS was mitigated in most of the cases. This was possible due to the increased logistic transparency, including throughput diagrams, lateness distributions and other KPIs. These tools enable reasonable adjustments rather than adjustments based on gut feelings. The transparency revealed other effects that were held responsible for the decrease in due date performance. Thus, planners decided to damp the magnitude of the mathematical ‘optimal’ adjustment to avoid shortcomings of the LTS.

How does the adjustment of planned lead times affect systems’ due date performance?

The preceding investigations of the LTS led to the assumption that a planned lead time adjustment results in a sudden decrease of due date reliability with a

³² The observed situation corresponds to the worst case steady-state of the LTS, but it is not clear from the data if this situation was initially triggered by the LTS or by other effects.

gradual increase to the initially desired level afterwards. The time period until due date reliability once again reaches a steady state was defined by the latency period, which consists of information and processing delays. The calculation of the expected latency period in the investigated work systems revealed that the due date reliability averaging period of one month is the longest delay contribution. The WIP levels added an average of only three shop calendar days to the resulting processing delay. The information delay was two and a half days on average. Afterwards, the expected and calculated behavior of two work systems was evaluated in separate time series plots of the moving average of the resulting due date reliability. Both systems showed a sudden decrease of due date reliability, followed by a gradual increase for both long and short averaging periods. The observed time periods almost match the calculated values of the latency periods and the progressions correspond with the expected ones.

How long are adjustment periods in the evaluated case company?

The presented case study does not include a situation during the final period of investigation (with full transparency) in which planners were able to adjust planned lead times without restrictions. Adjustments were discussed and determined in consultation with the project team. The knowledge of the existence of the LTS prevented the implementation of careless adjustments. However, in discussing system states and diminishing target achievements for some systems, planners eagerly discussed the necessity of planned lead time adjustments, instead of, e.g., reducing WIP levels by adjusting capacities. Being aware of the LTS, a quarterly meeting was set to discuss the correctness of master data, which include planned lead times. Therefore, this research question cannot be answered in a direct way. However, the time series investigation showed that the adjustment period length should exceed the time period required for due date reliability to reach its base level again. More specifically, to avoid the LTS the results of the case study suggest that the adjustment period length should be longer than the time period required for the due date reliability to reach its base level again. In contrast, the investigation of the LTS in the control theoretic model in Chapter 4 showed that an adjustment period length that is longer than the information delay is sufficient to avoid the LTS. Nevertheless, the argumentation is in line with Proposition P_2 , that the adjustment period length should be longer than the latency period to guarantee avoidance of the LTS. With a calculated latency period of 7 weeks for system C (representing the maximum latency period as one last processing step), the chosen adjustment period of 13 weeks (quarterly meeting) was sufficiently long.

The summing-up of observations made in the case study shows that the underlying assumptions of the mathematical and the control theoretic investigation led to a reasonable anticipation of system states after planned lead time adjustments. Moreover, it was possible to confirm both Propositions P_1 and P_2 and to illustrate the effects of the LTS, which can be summed up as follows:

- *Adjusting planned lead times leads to a short-term reduction in due date reliability.*
- *Planners tend to adjust planned lead times too often even if they are aware of the LTS*
- *The longer the latency period, the longer diminished due date reliability persists.*
- *The LTS is triggered if the adjustment period length is shorter than the latency period*

These research results confirm and illustrate the LTS line of argumentation of Mather and Plossl (1977). The negative impacts of the LTS and in particular of planned lead time adjustments were shown in the mathematical model, the control theoretic model and finally in the case study. Thus, the results presented in this chapter complete the first focus area of this thesis. Moreover, the derived interactions now enable the derivation of strategies for avoiding the LTS in practice, hence the development of a roadmap to face the LTS. This also includes the investigation of the question of how planners should react in terms of the planned lead time adjustment, which is presented in the next chapter.

6 Development of a Roadmap of Strategies to Avoid the Lead Time Syndrome in Practice³³

*“How often, when and how
should we adjust planned lead times?”
(Production planner in a strategy meeting)*

The presented case study showed that the intention of planners to increase due date reliability is likely to lead to a situation of low performance in terms of a low due date reliability, long lead times and high WIP levels. The research on the LTS described up to this point was mainly focused on the investigation of the impact of planned lead time adjustments on the resulting due date reliability, which is only one of the research focus areas. How planners should react in terms of the planned lead time adjustment to avoid the LTS in practice is still an open question. This was implicit in the question of a production planner of the case company (see quotation above), who was uncertain about how to maintain a high system performance while avoiding the LTS. This problem can be transferred into the following three sub-research questions that will be answered in this chapter:

1. *When,*
2. *how often, and*
3. *on which value should planned lead times be adjusted?*

(1) Question one extends the investigation of the LTS by the question of whether planned lead time adjustments are the method of choice or if other control strategies are preferable in terms of system performance. Hence, Section 6.1 addresses whether capacity control provides an alternative control strategy for planned lead time control, in other words, does it result in higher due date reliability. Capacity control was chosen as suitable control strategy as it is both recommended in theory to avoid the LTS and directly affects the actual lead time and WIP level³⁴ (planned lead time control affects them indirectly) (Lödding 2013; Wiendahl 2005; Plossl 1988).

(2) The second question aims at determining how often planned lead times should be adjusted according to the given environmental situation. Section 6.2 presents a methodology that transfers the research results of the previous chapters into a definition of a suitable adjustment period length in practice, which also proposes a strategy for situations in which planned lead times have to be adjusted more frequently.

³³ Parts of this section have been published in similar form in (Knollmann 2013a; Knollmann 2014a).

³⁴ See also Section 2.2.2, which presents the manufacturing control model of Lödding (2013) that depicts the influence of both control strategies on the lead time.

(3) The third question covers the problem of adjusting planned lead times. Thus, on which value to adjust planned lead times to maintain high system performance in practice. Section 6.3 presents a methodology for calculating new planned lead times and determines boundary conditions of suitable adjustments.

The answers to each of these questions are finally merged into a roadmap in Section 6.4. This roadmap presents comprehensive instructions for mitigating the LTS in practice, as the questions cover both focus areas and transfer theoretic research results into practice.

6.1 When Should Planned Lead Times be Adjusted? Testing Capacity Control as Alternative for Planned Lead Time Adjustments

The control theoretic investigation of the LTS in Chapter 4 showed that the occurrence of the LTS strongly depends on the magnitude of response, the adjustment frequency of planned lead time adjustments as well as the delay until changes take effect in a production system. It was concluded that the LTS is triggered if the planned lead time adjustment period is not longer than the information delay. However, the strategy developed to damp the LTS by setting an optimal magnitude of response was not able to improve performance significantly for all simulation settings. Thus, it was suggested that the choice of other control strategies might be more suitable for situations in which the information delay is longer than the adjustment period length.

According to the manufacturing control model of Lödding, lead time and WIP can be influenced indirectly by planned lead time control or directly by capacity control (Lödding 2013). Furthermore, capacity control was independently recommended by Wiendahl et al. (2005) and Plossl (1988) as the preferable manufacturing control method to avoid the drawbacks of the LTS (Wiendahl 2005; Plossl 1988). Thus, the aim of this section is to compare planned lead time control to the control of lead time using adjustments in capacity. This will enable the identification of preferable strategies for certain environmental conditions, by considering the benefits or drawbacks that are linked to each strategy. Moreover, a central issue is to clarify whether planned lead time control is a good choice when the drawbacks of the LTS are considered.

To compare both control strategies, a control theoretic model of a work system with capacity control initially is developed in Section 6.1.1. Then, the control theoretic model is used to evaluate the effects of different input variances, adjustment periods and information delays on the resulting performance of the capacity control strategy. Finally, Section 6.1.3 compares the control strategies, and conclusions are presented regarding which strategy obtains the best performance under which circumstances and restrictions.

6.1.1 Control Theoretic Model Development to Simulate Capacity Control

To develop a control theoretic simulation model of a work system with capacity control the five steps of the ‘simulation model development process’ that were already presented in Chapter 4 have to be followed again (Manuj 2009):

Step 1: Formulate problem and objectives

The control theoretic investigation of the LTS in Chapter 4 showed that planned lead time control on one hand triggers the LTS for specified ratios of adjustment frequency to information delay and, on the other hand, that a damping of the LTS by a suitable magnitude of response value is not appropriate for all scenarios. Thus, it was concluded that other control strategies might be more suitable in such cases. The aim of this section is to compare the obtained performance of capacity control with the performance of planned lead time control that was presented in Chapter 4. Therefore, the capacity control strategy has to be modeled and simulated for various adjustment frequencies, information delays, and input variances to gain knowledge about the obtained performance as measured in due date reliability.

Step 2: Specify independent and dependent variables and develop a conceptual model

Following the approach presented in Section 4.1.1 the conceptual model of planned lead time control has to be adapted for capacity control. Therefore, the necessary adaptations of underlying independent and dependent variables have to be specified in a first step. Afterwards, the conceptual model of a work system with capacity control can be developed.

To develop a control theoretic model initially the model components and underlying assumptions have to be determined. The independent variables have to be identical with the variables defined for planned lead time control to enable a comparison of both control strategies. Thus, to measure the obtained performance of capacity control the dependent variables are defined by the four logistic targets *WIP*, *lead time*, *due date reliability*, and *capacity utilization* including the directly linked variables (e.g., *lateness* or *actual capacity*). Also the independent variables are similar, as the performance of capacity control is going to be evaluated for the same scenarios of parameter settings:

- A variable *input rate variance* to simulate more or less variability in the work system.
- The length between two possible capacity adjustments is defined by the *adjustment period length* (adjustment frequency).
- The time period to set new actual capacities is defined by the *information delay*.
- The level of capacity adjustments is given by the *magnitude of response*.
- The due date tolerance is defined by *lower und upper tolerance limits*.

Figure 6.1 depicts the resulting conceptual model of a single work system and shows the key components and connections between the variables. The control

strategy in Figure 4.2 (Section 4.1.1) has been replaced by capacity control to enable a comparison of performance of both control strategies. The work system model therefore remained unchanged, along with the corresponding assumptions. One fundamental principle of capacity control is that it should control the *planned work output*, which is defined by the *planned capacity* (Lödding 2013). Thus, production planners periodically compare the actual *work input* and *work output* to determine capacity adjustments, if necessary. The presented conceptual model provides the framework for the development of a control theoretic simulation model with work output control, which is presented next.

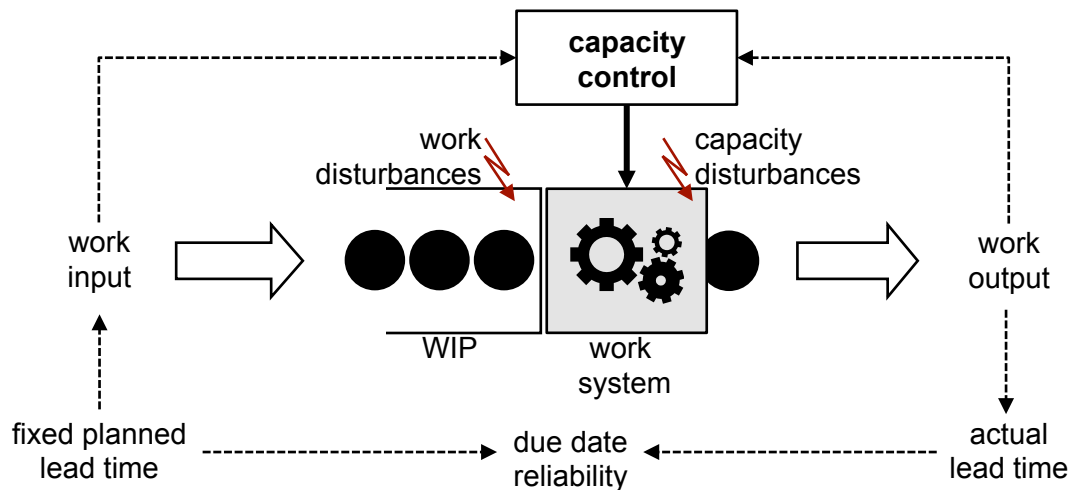


Figure 6.1 Conceptual model of a single work system with capacity control

Step 3: Develop and verify control theoretic model

To evaluate the system performance of work output control, the control theoretic simulation model presented in Section 4.1.2 has to be enhanced by adding a work output control strategy. Duffie et al. (2010) investigated the two control theoretic methods ‘lead time control’ and ‘work output control’ to regulate lead times by adjusting the actual capacity. Both of these capacity control strategies are influenced by the length of time between capacity adjustments and the delay until these adjustments take effect. They showed that the performance of lead time control and work output control are similar to each other for low work input and capacity fluctuations. For higher fluctuations, work output control is preferred to lead time control, because it produces more consistent and stable behavior (Duffie 2010). Therefore, only work output control is considered in the present work and compared with planned lead time control. Figure 6.2 shows the simplified block diagram of work output control, which is based on the control model of Duffie et al. (2010). This capacity control strategy replaces the planned lead time control strategy and enhances the model of the work system presented in Figure 4.3 of Section 4.1.2³⁵.

³⁵ Also, the main components of the work system control structure are presented in Section 4.1.2.

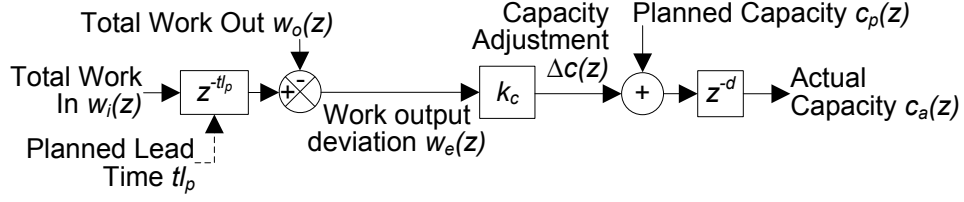


Figure 6.2 Block diagram of work output control (simulated in Simulink (MathWorks MATLAB 2012)³⁶; based on (Duffie 2010))

The lead time control strategy described by Duffie et al. (2010) considers a work system that periodically calculates and adjusts the *actual capacity* c_a with the goal of minimizing the *work output deviation* w_e . As shown in Equation 6.1 they define the work output deviation as the difference between the *desired work out* $w_i(kT - tl_p(kT))$ and *actual work out* $w_o(kT)$, using the accumulated values of actual work in and actual work out (see Figure 4.4; Section 4.1.2).

$$w_e(kT) = w_i(kT - tl_p) - w_o(kT)$$

Equation 6.1

w_e	work output deviation [h]
w_i	work input [h]
w_o	work output [h]
tl_p	planned lead time [SCD]
k	current period

The calculation of the *actual capacity* in Equation 6.2 is performed at instants in time separated by the time period nT , where n is a positive integer. Adjustments are delayed by d (time delay dT [SCD]). The magnitude of response k_c amplifies or attenuates the calculated capacity value, thus accelerating or decelerating the response to fluctuations. Equation 6.3 calculates a simulation setting dependent k_c to avoid both slow and oscillatory response (Duffie 2009).

$$c_a(kT) = c_p((k-d)T) + k_c \left[\sum_{x=0}^{(k-d)T-tl_p} w_i(x) - \sum_{x=0}^{(k-d)T} w_o(x) \right]$$

Equation 6.2

$$k_c = \frac{d^d}{n(d+1)^{d+1}}$$

Equation 6.3

k_c	magnitude of response
c_p	planned capacity [h/SCD]
d	delay of actual capacity adjustments [SCD]
n	adjustment period length [SCD]

Step 4: Perform preliminary simulations to validate the control theoretic model and determine model parameters

In addition to the validation of the control theoretic model in Section 4.1.3 a separate validation of the new control strategy is required. As the control model of

³⁶ The corresponding simulation model is on the enclosed DVD (see appendix).

the underlying work system remains unchanged for the simulation of capacity control, this validation builds on the validation step (2) presented in Section 4.1.3. To validate the capacity control strategy the resulting WIP, actual capacity, and lead time of the above presented control model are compared to the resulting values presented in the paper of Duffie et al. (2010). It can be assumed that the control strategy implementation is valid if both diagrams are identical for the same parameter settings. Figure 6.3 shows the work input rate $IR(kT)$ that was used in the simulations of Duffie et al. (2010). These data are from a supplier to the automotive industry and were used in their discrete-time simulation to predict the work-system response for capacity control. The mean input rate is $IR_m \approx 5$ h/SCD with a standard deviation of $IR_{sd} \approx 2$ h/SCD. Work disturbance and capacity disturbance are set to zero. The planned capacity is $c_p = 5$ h/SCD with a planned lead time of $tl_p = 3$ SCD. Capacities are controlled each period $nT = 1$ SCD with a delay of $dT = 1$ SCD. According to Equation 6.3, the magnitude of response is set to $k_c = 0,25$ for the given delay and adjustment period.

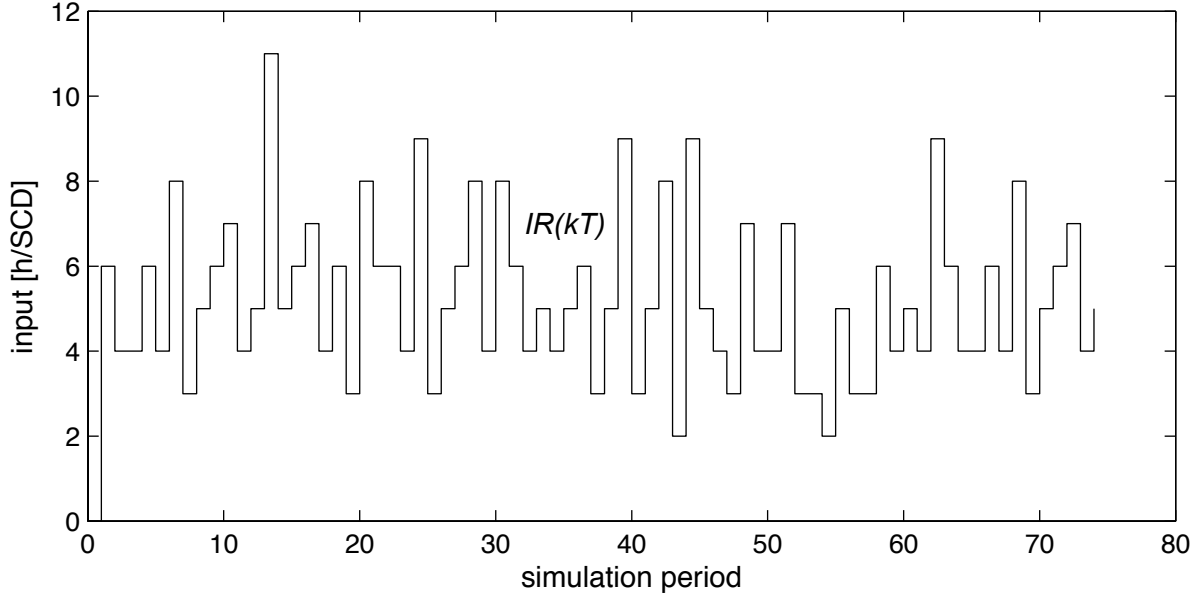


Figure 6.3 Example work input rate to validate the control model (from (Duffie 2010))

The resulting WIP, actual capacity, and lead time are shown in Figure 6.4. The plotted curves of WIP and actual capacity are identical to the curves presented in Figure 5 of the paper of Duffie (2010). The plot of the actual lead time is shifted by one period and the calculated lead time is more precise (more exact). This is due to the implemented calculation methodology, which calculates the actual lead time as the average over the last ten sub-periods and plots them the end of each period kT (see also Section 4.1.2). The equality of the simulation results to the plot presented in the literature validates the modeled work system and capacity control strategy. It suggests that the model is consistent and can be used for the evaluation of the capacity control strategy.

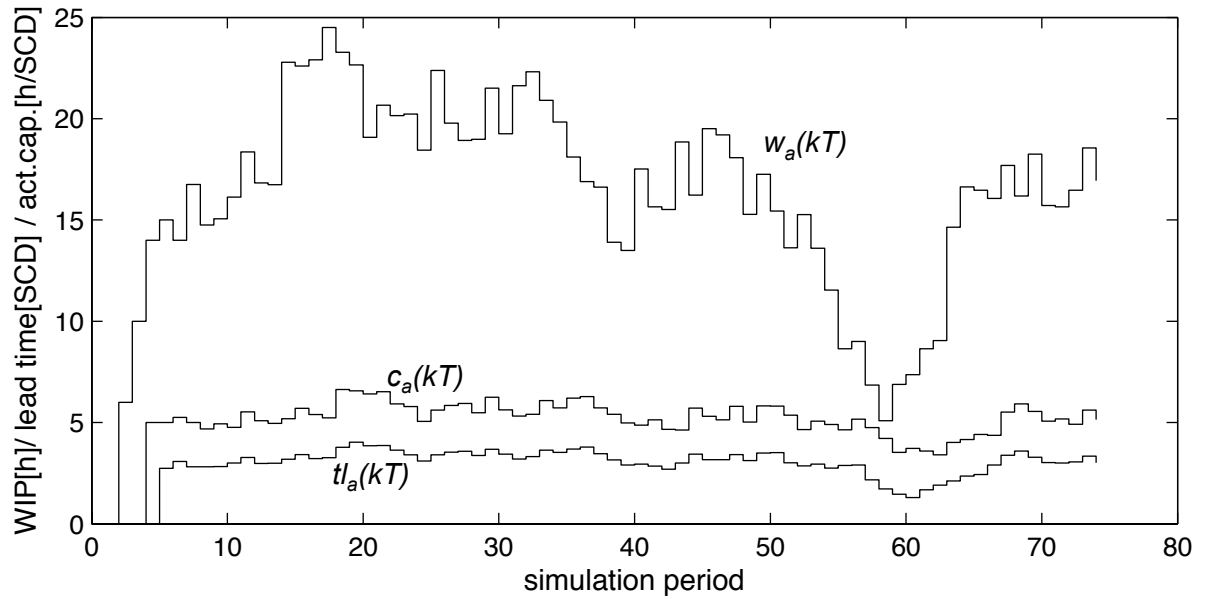


Figure 6.4 WIP [h], lead time [SCD], and actual capacity [h/SCD] under capacity control; $c_p=5$ h/SCD; $tl_p=3$ SCD; $nT=1$ SCD; $dT=1$ SCD; $k_c=0,25$

Before starting the simulation, a determination of all fixed or predefined variables and all model specifications is needed. The following list repeats and extends the list of specifications presented in Section 4.1.3 that result from the preliminary simulation runs for the model validation:

- Input rate and planned capacity have the same value $IR_m=c_p=5$ h/SCD.
- Simulated input rate variances $IR_{var}=\{1;2;3\}$.
- Due date tolerance of $\pm 0,5$ SCD.
- Work and capacity disturbances are zero.
- Planned lead time of $tl_p=4$ SCD, which is not adjusted (fixed planned lead time).

Step 5: Analyze and document results

The system performance of capacity control as measured using due date reliability was simulated for different settings of adjustment period, information delay, and input fluctuation. The results are presented in the next section and compared to the obtained performance of planned lead time control in Section 6.1.3 to enable development of a recommended control strategy selection for various parameter settings.

6.1.2 Influence of Information Delay and Adjustment Frequency on the Performance of Capacity Control

To investigate the correlation of delay and adjustment frequency under capacity control, this section follows the approach of the investigation of planned lead time control presented in Section 4.2.2. Afterwards, this enables the comparison of both control strategies. Thus, simulations were run with various adjustment frequencies, delays, and input fluctuations, as listed in Table 6.1, to enable a comparison of the

resulting system performance for capacity control as measured using due date reliability.

Table 6.1. Simulation settings to investigate the obtained performance of capacity control.

	dT	nT	IR_{VAR}
(A) <i>Correlation of adjustment frequency and delay</i>	1,...,10	1,...,12	2
(B) <i>Influence of input rate variance</i>	1,...,10	1;12	1;2;3

(A) Figure 6.5 shows the resulting mean due date reliability of the first scenario for simulated adjustment periods $nT=(1 \text{ SCD}, \dots, 12 \text{ SCD})$ and delays $dT=(1 \text{ SCD}, \dots, 10 \text{ SCD})$ for an input variance of $IR_{VAR}=2$. According to Equation 6.3, for each setting of dT and nT a specific k_c is defined to obtain the best results for work output control. As expected by the research results of Duffie (2010), the best performance is achieved when actual capacities are updated more rapidly and there is less delay. With increasing delay, the performance of work output control decreases approximately inversely proportional, and the influence of the adjustment frequency decreases.

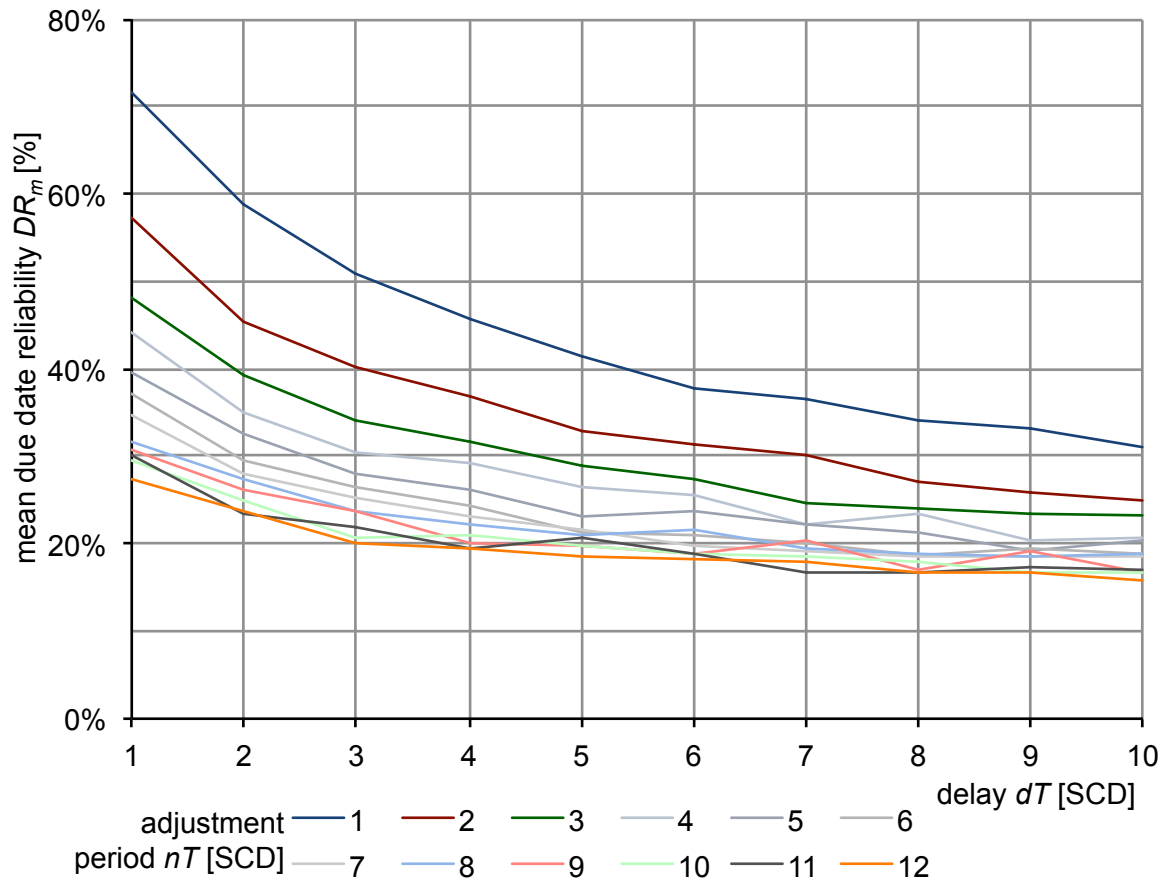


Figure 6.5 Mean due date reliability [%] under capacity control with various delays for all simulated adjustment period lengths; $N=100$; $P=500$; $IR_{VAR}=2$

This means that the differences between the obtained due date reliabilities decrease with increasing delay. In addition, for longer adjustment periods the

influence of delay decreases (for $nT=1$: $DR_{m,dT=1}=72\%$ decreases to $DR_{m,dT=10}=31\%$ [difference of 41%]; for $nT=12$: $DR_{m,dT=1}=27\%$ decreases to $DR_{m,dT=10}=16\%$ [difference of only 11%]). Thus, if planners are able to maintain a high adjustment frequency and decrease information delay in adjustment implementation, performance as measured by due date reliability can be expected to significantly improve under work output control. To investigate system behavior of capacity control for different fluctuations, all three input variances are analyzed next.

(B) Figure 6.6 shows the resulting mean due date reliability of the second scenario for all simulated input fluctuations $IR_{Var}=\{1,2,3\}$ for the exemplary simulated maximum and minimum adjustment frequencies $nT=1$ SCD and $nT=12$ SCD and delays $dT=(1 \text{ SCD}, \dots, 10 \text{ SCD})$. Thus, the red curve ($IR_{Var}=2$) depicts the values that were already analyzed in Figure 6.5 for $nT=1$ SCD and $nT=12$ SCD. The adjustment periods $nT=(2 \text{ SCD}, \dots, 11 \text{ SCD})$ are not shown, but lie in ascending order between the minimum and maximum adjustment period curves. The resulting curves for higher and lower input fluctuation have the same shape as the medium input fluctuation of $IR_{Var}=2$. However, the maximum achievable due date reliability decreases with increasing input fluctuation. Thus, if planners are able to decrease input fluctuation, a significant performance increase can be expected.

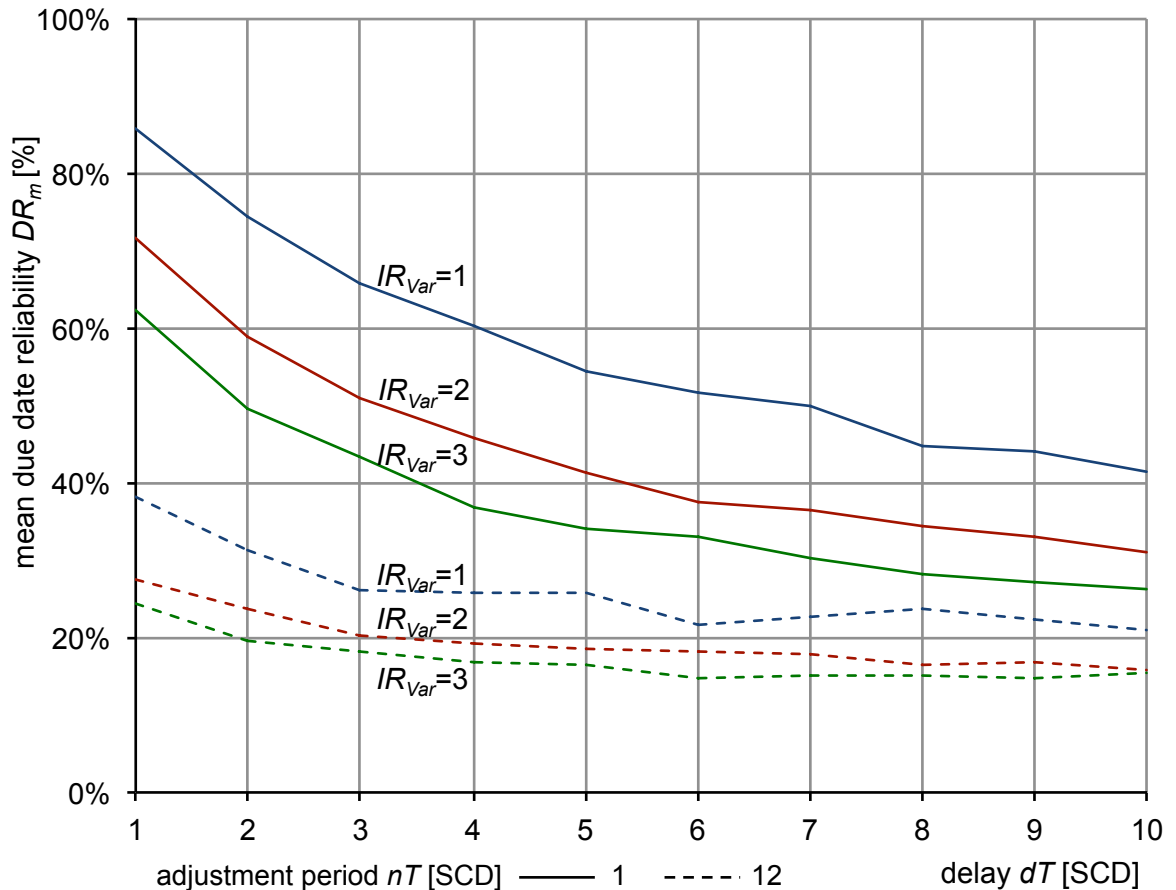


Figure 6.6 Mean due date reliability [%] under work output control with three different input variances and a low and high adjustment period length; $N=100$; $P=500$

The presented simulation results of capacity control have to be compared to the results of planned lead time control to evaluate if capacity control should be preferred to planned lead time control for specific parameter settings. Thus, the next section presents a comparison of the obtained performances of both control strategies.

6.1.3 Performance Comparison of Capacity Control and Planned Lead Time Control

The investigation of the performance of capacity control in the previous section showed that capacity control obtains an increasing due date reliability for higher adjustment frequencies and lower delays. For planned lead time control Section 4.2.2 showed that the resulting mean due date reliability does not deteriorate with longer adjustment periods as is the case under capacity control. However, if planned lead times are adjusted too often in proportion to the given delay, due date reliability significantly decreases due to the LTS. In order to dampen the drawback of the LTS for too frequent planned lead time adjustments, the control variable magnitude of response k_p was added to planned lead time control (see Section 4.2.3). Then, it was observed that a suitable magnitude of response is able to significantly increase due date reliability for unfavorable ratios of adjustment frequency and delay. The aim of this section is to compare the resulting performance of capacity control and planned lead time control (with a suitable k_p) and to develop recommendations for which strategy should be preferred in which scenario. Therefore, initially the obtained performances of both control strategies are compared at an input variance of $IR_{Var}=2$. Then, the observed characteristics are validated in scenarios of lower ($IR_{Var}=1$) and higher ($IR_{Var}=3$) input variance.

Part (a) in Figure 6.7 shows the resulting mean due date reliability of planned lead time control with a damped LTS. The magnitude of response value was set individually according to Equation 4.9 that was derived in Section 4.2.3 for each simulation setting in which $nT \leq dT$. Part (b) in Figure 6.7 shows the resulting performance of capacity control that was already presented in Figure 6.5. The comparison of both parts shows that even if the influence of LTS is taken into account, the performance of capacity control is significantly better for short adjustment periods for both high and low delays. In contrast to this, the performance of planned lead time control is significantly better for increasing adjustment periods. The differences in strategy performance are primarily explained by the different approaches: The simulated capacity control strategy of work output control monitors the work deviation, which is a past-oriented value (Duffie 2010). In contrast to this planned lead time control monitors the actual lead time, but as a consequence of a possible planned lead time adjustments it also controls the order release. Therefore, this strategy combines the reactive aspect of lead time control and the proactive aspect of planning. More specifically, planned lead time control outperforms capacity control for adjustment periods longer than four periods ($nT > 4$ SCD) for the given simulation settings. One possible explanation for this value could

be the underlying planned lead time of $tl_p=4$ SCD, as it defines the critical value between reactive and proactive controlling. Further research is needed to challenge and confirm this conclusion (see Section 7.4). However, for both control strategies the performance decreases approximately inversely proportional with increasing delay. Whether these characteristics can also be observed for situations of lower or higher input variance will be investigated next.

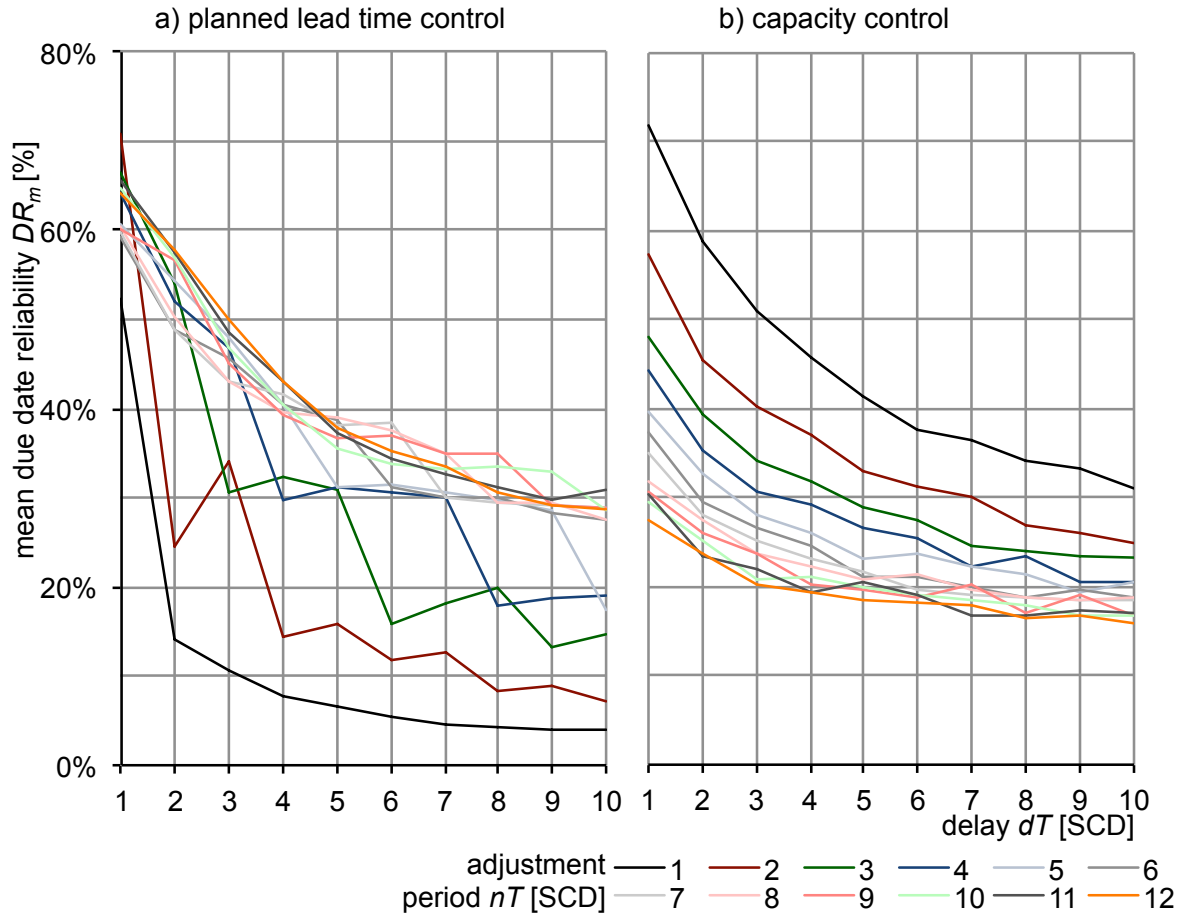


Figure 6.7 Mean due date reliability [%] under (a) planned lead time control; (b) capacity control with various delays for all simulated adjustment period lengths; $N=100$; $P=500$; $IR_{var}=2$; k_p acc. to Equation 4.9; k_c acc. to Equation 6.6

Figure 6.8 shows a comparison of the resulting mean due date reliability of short ($nT=1$ SCD) and long adjustment periods ($nT=10$ SCD) for both control strategies for low (part (a)) and high (part (b)) input variances. As discussed before, the overall performance of both control strategies decreases with increasing input variance. However, the curve shapes remain constant and suggest that planned lead time control should be preferred for long and capacity control for short adjustment period lengths, regardless of the magnitude of input variances.

In addition to the comparison of the obtained due date reliabilities also the related costs of implementation should be considered before choosing a control strategy. The adjustment of planned lead times does not require direct investments. However, capacity adjustments require both flexible workers and flexible machines (Lödding 2013) (see also (Breithaupt 2000a; Wiendahl 2001)). The flexibility of

workers is given for example by the flexibility in working times, working speed, recruitment and dismissal of employees, and the existence of multiple qualifications. The machine flexibility is defined for example by the possibility to change the number of machines, adjust tact times, outsource work, or postpone maintenance (Lödding 2013).

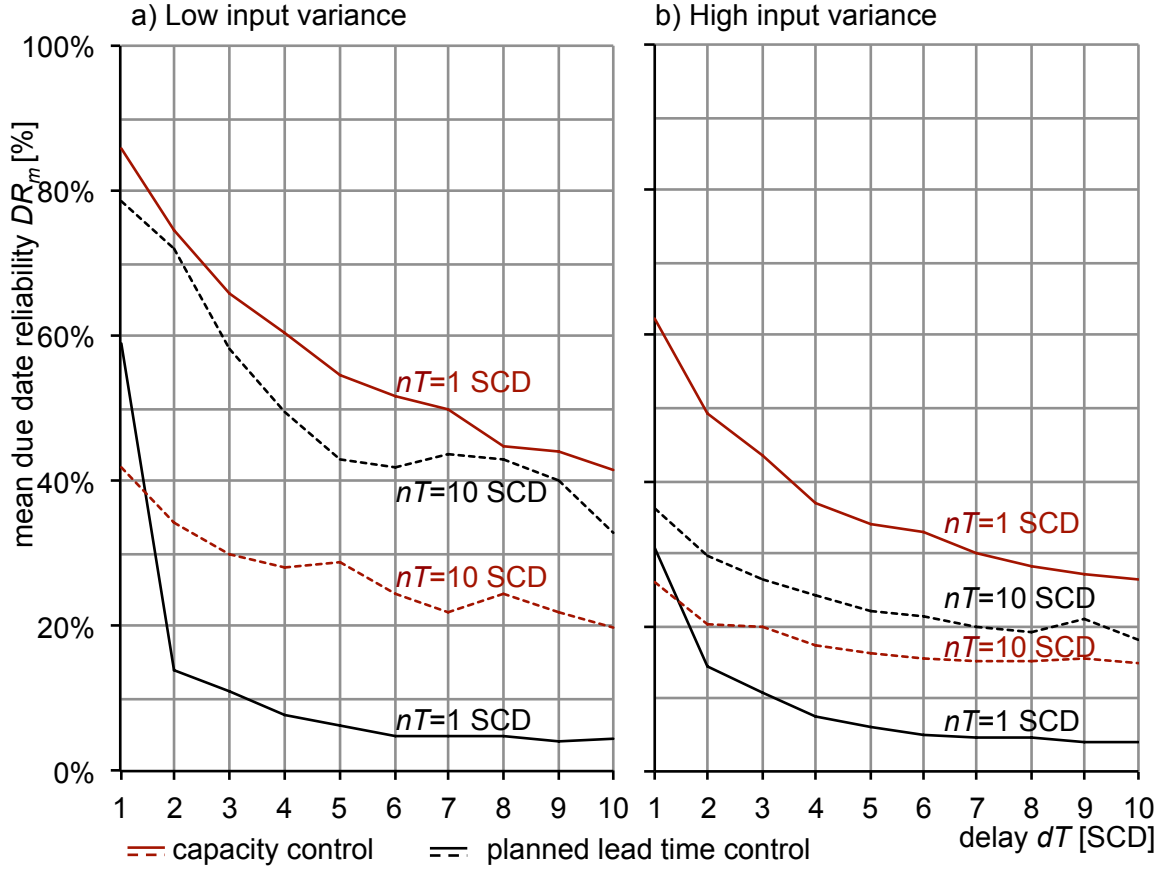


Figure 6.8 Comparison of capacity control and planned lead time control with (a) low input variance $IR_{var}=1$ and (b) high input variance $IR_{var}=3$; $N=100$; $P=500$; k_p acc. to Equation 4.9; k_c acc. to Equation 6.6

Based on these simulation results recommendations can be derived regarding which control strategy is preferable for which parameter setting. When adjustment periods get longer the results support the conclusion that planned lead time control is able to perform better than capacity control for either short and long delays. Even if the LTS is considered (by implementing a suitable magnitude of response) capacity control produced better results for short adjustment periods. Thus, depending on system characteristics such as capacity flexibility, frequency of adjustments, and information delay the most suitable control strategy can be selected. These results are included in Section 6.4 in the merged roadmap. To answer the second question presented in the introduction of Chapter 6, a methodology for adjusting planned lead times in practice (if planned lead time control is implemented) is presented next.

6.2 How Often Should Planned Lead Times be Adjusted? Determination of a Suitable Adjustment Frequency

Planned lead times are used in scheduling to calculate planned start times (Hopp 2008). Using backwards scheduling (e.g. in MRP), the start time is the due date demanded by the customer minus the planned lead time. As noted by Nyhuis and Wiendahl (2010), planned lead times are often of poor quality in practice, even if more sophisticated scheduling procedures were given. They further argue that PPC-systems often lack the support to define and maintain planned values. However, transferring these research results to a practical methodology specifying how planned lead times should be controlled is still an open question. The aim of this section and of Section 6.3 is to define a methodology that determines how planned lead times should be adjusted in practice in the scope of the LTS. This includes the questions *how often* and *on which value* to adjust planned lead times. The first question is answered in this section. Therefore, a methodology is presented that answers the questions of how to determine a suitable adjustment period length and how to proceed if planned lead times have to be adjusted more frequently.

The presented research results suggest that production planners should be aware of the LTS effects if trying to improve the performance by planned lead time adjustments. Thus, planners should minimize information delay, set appropriate adjustment period lengths according to the given delay, and, if necessary, reduce the magnitude of the adjustment. The investigation of the LTS revealed that the ratio of the frequency of adjustments and the information delay specifies whether the LTS is triggered or not, thus the resulting due date performance of a manufacturing system. However, the transfer of the theoretic investigations into a practical choice of a ‘suitable’ adjustment period length (how often planned lead times should be controlled) is still an open question. In the case study example presented in Chapter 5, a quarterly meeting was set to discuss and (if necessary) adjust planned lead times. As mentioned above, the aim of this section is the definition of a methodology for determining such adjustment frequencies. The research results suggests two main strategies: The *first strategy* is a strategy that avoids the drawbacks of the LTS, while the *second strategy* dampens the impact of the LTS, if it is inevitable.

Strategy 1: According to Proposition P_2 (see Section 3.3.2) the impact of the LTS effect is higher, if the adjustment period length is shorter than the latency period of the adjusted system. Hence, to avoid the LTS, a suitable adjustment period length can be defined according to Equation 6.4:

$$nT_{\text{suitable}} > dT_{\text{latency period}}$$

Equation 6.4

n_{suitable} suitable adjustment period length [SCD]

$d_{\text{latency period}}$ latency period after planned lead time adjustments [SCD]

The adjustment period length is defined as the time period between two consecutive planned lead time monitorings. The latency period is defined as the sum

of information and processing delay with the following components (see also Section 3.3.2 for a more detailed definition):

$d_{information}$	<i>information delay</i>
➤ $d_{monitoring}$	<i>delay between due date reliability calculation and the definition of new planned lead times</i>
➤ $d_{implementation}$	<i>delay between planned lead time adjustment and implementation by order release</i>
$d_{processing}$	<i>processing delay</i>
➤ $d_{predecessors}$	<i>delay until (earlier released) orders reach the system</i> (Sum of range values of predecessors (see Equation 2.4))
➤ d_{range}	<i>delay until (earlier released) orders are processed</i>
➤ $d_{averaging}$	<i>delay of averaging over defined periods of past data</i>

The control theoretic investigation (see Section 4.2.2) and the case study (see Section 5.3.2) revealed that a reduction of the delay components significantly increases system performance as measured in due date reliability. Thus, a reduction of the latency period is essential to enable more frequent planned lead time adjustments in practice. To minimize information delay planned lead time adjustments should be implemented using a planning or scheduling system on the same day that due date reliability is measured. A reduction of WIP levels along the process chain reduces the processing delay by the decrease in the resulting range values. Furthermore, to reduce the averaging period, a separated long- and short-term averaging period of due date reliability or other performance indicators could be implemented into a controlling tool to allow earlier detection of impacts of planned lead time adjustments (e.g., a combination of a one week and one month view, as presented in the case study in Figure 5.8 in Section 5.3.2).

Strategy 2: Regardless of the calculated suitable adjustment period length, short-term planned lead time adjustment might be reasonable if process characteristics change. Such changes can be unplanned performance decreases due to premature cancellations of highly qualified workers, the loss of a major customer, and other influences that lead to a sudden change. As stated above, such situations are likely to induce the LTS, as the system might not have reached a steady state after the previous planned lead time adjustment. To damp the impact of the LTS in such scenarios Proposition P_l (Standard deviation; see Section 3.3.1) and the control theoretic investigation presented in Section 4.2.3 suggested the multiplication of the calculated planned lead time adjustment (which is presented in the subsequent section), with a magnitude of response k_p as defined in Equation 6.5.

$$0,05 < k_p = 0,25 \frac{n_{actual}}{d_{information}} \leq 1 \quad \text{for } n_{suitable} \leq d_{latency\ period}$$

Equation 6.5

k_p	magnitude of response [%]
n_{actual}	actual adjustment period length [SCD]

The actual adjustment period n_{actual} is the difference between the SCD of the planned adjustment and the SCD of last implemented adjustment. If the resulting magnitude of response is below 5%, capacity control instead of planned lead time control should be implemented. However, further research on the LTS is needed to select the optimal magnitude of response, as the underlying assumptions of the control theoretic model so far exclude the influence of actual lead times, work in process levels, input fluctuations, and predecessors (see also Section 4.2.3). Also, the case study indicates that a minimal adjustment period can be calculated, which is defined as the time required for due date reliability to reach its base level again (see also Section 5.3.2). The more precise definition of a suitable adjustment period length and the simulation of other parameter settings would enable a more precise definition of an optimal adjustment period length, but are not part of this work.

The research results presented in the previous chapter support the conclusion that the determination of a suitable adjustment period length using Equation 6.4 ensures the avoidance of LTS drawbacks. Therefore, in combination with the implementation of a magnitude of response, the LTS can be avoided or damped for all ratios of latency period and adjustment frequency. The definition of the value on which planned lead times should be set is discussed next.

6.3 On Which Value Should Planned Lead Times be Adjusted? Calculation Methodology of Planned Lead Time Adjustments and Estimation of Impacts on the Resulting Due Date Reliability

The previous section presented a methodology for setting a suitable adjustment period length, which determines how often planned lead times should be adjusted. However, PPC-systems often lack the support to define and maintain these planned values (Nyhuis 2010). Therefore, firstly this section presents a methodology for calculating new planned lead times and defines boundary conditions of suitable adjustments. Secondly, a methodology is presented that quantifies the anticipated due date reliability after planned lead time adjustments. This supports planners in their decision-making process, as it allows a direct consideration of costs and benefits in terms of the resulting due date reliability of proposed improvement measures.

Planned lead times are used to schedule orders (e.g., in backward scheduling) but are also used to measure the logistic performance of a manufacturing system (Schuh 2006). The due date reliability depends on the correlation between planned and actual lead times (i.e. the lateness (see Section 2.1.2)), and this correlation was defined by the due date reliability function (Section 3.1.1; Equation 3.7). Thus, according to *Observation 2*, due date reliability is maximized, if planned and actual lead times match, which minimizes mean and variance of lateness (see Section 3.1.1). Based on this correlation, the level of adjustment Δtl_p was defined in the

mathematical approach in Chapter 3 as the difference between the moving average of the actual lead time and the previously planned lead time. Equation 6.6 defines the resulting new planned lead time calculation. It includes the magnitude of response variable to dampen (if necessary) the LTS, which was defined in the previous section in Equation 6.5.

$$tl_p^{new} = tl_p^{old} + k_p \cdot \Delta tl_p = tl_p^{old} + k_p \cdot (tl_m - tl_p^{old})$$

Equation 6.6

tl	lead time [SCD]
p	planned
m	mean
k_p	magnitude of planned lead time adjustment

This equation defines a new target operating point on the Logistic Operating Curves. As described in Section 2.1.3 (see Logistic Positioning), it also defines a new WIP level and output rate for the work system. The resulting consistent target system therefore includes a feasible planned lead time that can be used for scheduling (Nyhuis 2010).

However, this direct determination of planned lead times is valid only if operation times are constant or only a fraction of the lead times³⁷ (Nyhuis 2007). In practice, operation times often vary or comprise larger parts of the lead times in particular for system states in the underload area with low WIP levels. In such cases a more detailed definition of planned lead times is required in terms of a separate determination of the controllable planned interoperation time – operation times are assumed to be given, thus not controllable (Nyhuis 2007; Ludwig 1992).

The relationship between the values lead time and operation time is thereby given by the flow rate³⁸ (FR) in Equation 6.7 (Ludwig 1995; Wiendahl 1997a). It is used to evaluate the length of the lead time. A high flow rate indicates long interoperation times with high WIP levels. The minimal flow rate of $FR=1$ would indicate interoperation times of zero SCD, thus a work system that has no idle times between consecutive orders (operating point in the underload area). In addition to the evaluation of operating points it can also be used to determine due dates (Fowler 2006; Driessel 2007). Thereby, the lead time for scheduling is determined by the product of the operation time and the flow factor. A combination of both approaches is given by so called *Flow Rate Oriented Scheduling* that was developed to set and monitor planned lead times (Ludwig 1992; Ludwig 1995).

$$FR_m = \frac{tl_m}{top_m} = \frac{tio_m + top_m}{top_m}$$

Equation 6.7

FR	flow rate [-]
tio	interoperation time [SCD]
top	operation time [SCD]

³⁷ See also ideal operating curves and ideal minimum WIP level in (Nyhuis 2010).

³⁸ Also called flow factor (Fowler 2006).

In the Flow Rate Oriented Scheduling approach planned interoperation and operation times are defined separately (Ludwig 1992; Ludwig 1995). Figure 6.9 shows the proposed principle. The target operating point defines the planned interoperation time for each work system, following once again the approach of Logistic Positioning. The routing and the underlying master data (e.g. maximum output rate) give the planned operation time (see Section 2.1.1). The sum of the work independent planned interoperation time and the order-specific planned operation time results in planned lead times for each operation.

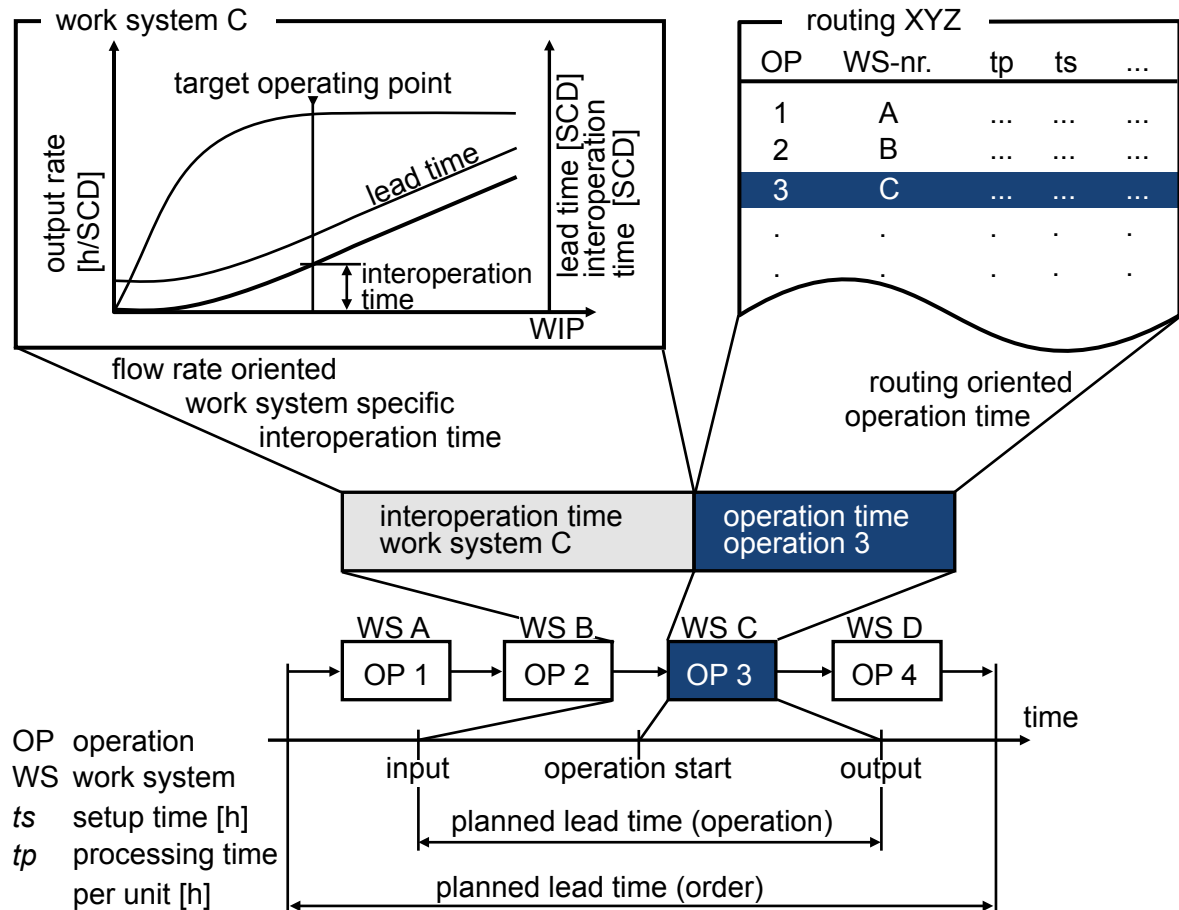


Figure 6.9 Determination of planned lead times based on the principle of Flow Rate Oriented Scheduling (Ludwig 1995; Nyhuis 2010; Lödging 2013)

The Flow Rate Oriented Scheduling approach significantly increases planning accuracy, thus leading to increased due date reliability (Ludwig 1992; Ludwig 1995). However, the determination of the above mentioned target operating point can be supported by the research results on the LTS, as the optimal planned interoperation time should be known when decisions are made about adjustments. Thus, the research on the LTS is used in the following to define an optimal planned interoperation time and to define adjustment limitations in terms of upper/lower limits of adequate lead times.

The planned interoperation time that reflects the actual system state and that maximizes the due date reliability is calculated in Equation 6.8 by adapting the initially presented Equation 6.6. The resulting flow rate of this new planned

interoperation time has a lower limit of $FR=2$ and an upper limit of $FR=5$, which were defined by Lödding (2013) as suitable boundaries for an optimal flow rate. Thus, the maximum planned interoperation time is defined in Equation 6.9 by four times the mean operation time, the minimum planned interoperation time by the length of the mean operation time (based on Equation 6.7). If these flow rates determine optimal adjustment limits has to be validated in further research. However, the suggested limits of Lödding are supported by the experiences made during the research project presented in Chapter 5. Moreover, Nyhuis defines the transition area limits in the Logistic Operating Curves by two and three times of the ideal minimum WIP level (i.e., $FR_{min}=2$; $FR_{max}=3$) and Rose suggests an optimal flow factor of 2,5 in the semiconductor fab (Rose 2002; Nyhuis 2010). If the flow rate exceeds the maximum level the capacity should be adjusted or work should be outsourced to reduce WIP levels and decrease actual lead times (Nyhuis 2010).

$$tio_p^{new} = tio_p^{old} + k_p \cdot \Delta tio_p = tio_p^{old} + k_p \cdot (tio_m - tio_p^{old})$$

Equation 6.8

with

$$top_m \leq tio_p^{new} \leq 4 \cdot top_m$$

Equation 6.9

The presented methodology defines a planned lead time that maximizes the resulting due date reliability if the system is operated in the transition area of the Operating Curves (see Section 2.1.2). Thereby, planned lead times should not be adjusted too frequently as described in Section 6.2. However, the case study in Chapter 5 showed that planners tend to adjust planned lead times too often even if they are aware of the LTS. The following approach introduces a calculation methodology that quantifies the anticipated due date reliability after planned lead time adjustments. This supports planners in their decision-making process, as it allows a direct consideration of costs and benefits in terms of the resulting due date reliability. It is based on the investigation of the impact of the LTS on due date reliability presented in Section 3.1.1.

Figure 3.3 in Section 3.1.1 showed a qualitative visualization of the influence of four exemplary adjustments on the resulting due date reliability, thereby presenting options that lead to an increase in due date reliability. It is obvious that it is impossible for a production planner to anticipate an exact value of the resulting due date reliability with reasonable efforts. However, a prerequisite for a solid definition of business strategies is a quantitative comparison of different strategies to enable a cost-benefit calculation.

Also, Equation 6.10 was derived in Section 3.1.1 assuming due date reliability as a normal probability density function of lateness. Besides calculating the actual due date reliability, it enables a quantitative estimation of the impact of planned lead time changes or changing tolerance periods on the resulting due date reliability. Exemplary, a reduction of the lead time standard deviation by 10% leads to an

increase of DR by 6%. The estimation of a resulting due date reliability applies for the steady state situation of a production process that is assumed in the Logistics Operating Curve theory. Therefore, Equation 6.10 calculates the maximum possible due date reliability at the given system state.

$$DR = \frac{1}{L_{sd} \cdot \sqrt{2\pi}} \int_{x=\text{lower due date tolerance}}^{\text{upper due date tolerance}} e^{-\frac{1}{2} \left(\frac{x-L_m}{L_{sd}} \right)^2} dx$$

Equation 6.10

DR	Due Date Reliability [%]
L	lateness [SCD]
m	mean
sd	standard deviation

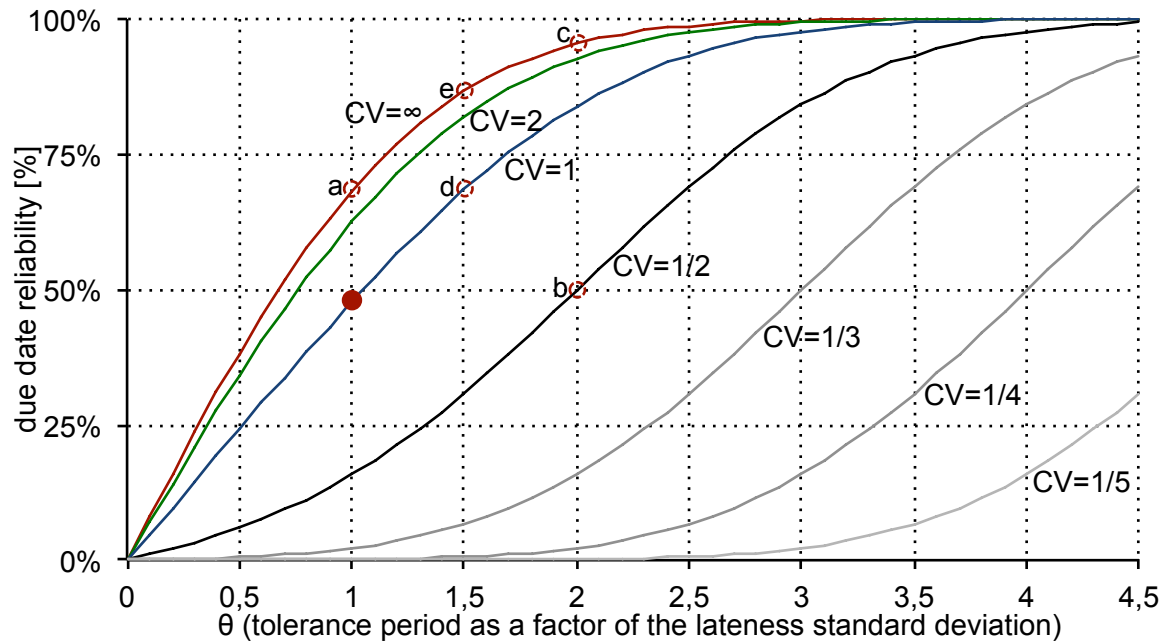
This equation allows a direct quantification of the effect of improvement measures such as planned lead time adjustments on the resulting due date reliability. Hence, the four schematic scenarios presented in Figure 3.3 can be easily quantified. Table 6.2 shows these exemplary options and compares the resulting due date reliability with the initial situation, for which the values were chosen randomly. It can be seen that each option leads to an increase in due date reliability in this set of examples. By setting reasonable planned lead times or adjusting the capacity to decrease the difference between planned and actual lead times leads in Option (a) to a significant increase of DR by 21%. Option (d) shows that a less restrictive tolerance period also significantly increases due date reliability. However, the tolerance period should be defined by the process characteristics and company goals rather than only by the attempt to increase due date reliability. This example shows the effects of each option, revealing that a measure to decrease the mean and variance of lateness leads to the best results. Moreover, the feasibility of a more strict tolerance period for an improved lateness distribution can be quantified in advance, as shown in Option (e).

Table 6.2 also includes the calculation of the coefficient of variation of lateness, which is a normalized measure of the dispersion of the probability distribution. It further includes the calculation of an independent variable θ , which is defined as the ratio of the tolerance period to the lateness standard deviation. Figure 6.10 shows a plot of the due date reliability for seven exemplary coefficients of variation over the corresponding independent variable. More specifically, the figure shows the due date reliability depending on the defined tolerance period and the lateness distribution. For this visualization a normal distribution was assumed for lateness. If the mean actual and the planned lead time match ($L_m=0$; $CV=\infty \rightarrow$ red curve), due date reliability reaches 95% for tolerance periods that exceed two times the value of the given standard deviation ($\theta=2$), and almost 100% for $\theta>3$. The position of the exemplary initial situation presented in Table 6.2 is represented by the red dot. Thus, having a mean lateness of two SCDs with a standard deviation of two SCDs (coefficient of variation: $CV=1 \rightarrow$ blue curve) and a tolerance period of ± 2 SCDs that is equal to the standard deviation of lateness ($\theta=1$), a due date reliability of 47% can be assumed. The five simplified options that could result from measures

taken by production planners are also marked in the figure by red circles. They show the main advantage of the presented approach: It allows visualizing and directly comparing the options to one another in a quantitative way. Thus, the anticipation of an expected due date reliability enables a more precise setting of improvement measures by production planners. Depending on the preferred business strategy, planners now can pick the optimal measure rather than choosing based on the gut feeling. Moreover, the expected due date reliability improvement can be compared to the required time, effects on quality, and costs of the implementation for each option.

Table 6.2. Example of instant due date reliability improvement measure quantification.

	L_m [SCD]	L_{sd} [SCD]	Coefficient of variation [$-$] ($CV=L_{sd}/L_m$)	Tolerance period [SCD]	θ [$-$] (tolerance period/ L_{sd})	Due Date Reliability [%]	Change of DR [%]
Initial situation	2	2	1	± 2	1	47	
Option a: Decrease mean lateness (e.g. adjust WIP or tl_p)	0	2	∞	± 2	1	68	+21
Option b: Decrease variance of lateness (e.g. avoid rush orders)	2	1	1/2	± 2	2	50	+3
Option c (a&b): Decrease mean and variance of lateness	0	1	∞	± 2	2	95	+48
Option d: Adjust tolerance period of lateness (in consultation with customers)	2	2	1	± 3	3/2	69	+22
Option e (c&d): Decrease mean and variance & adjust tolerance period	0	1	∞	$\pm 1,5$	3/2	87	+40



● initial example situation ○ resulting operating points for exemplary options

Figure 6.10 Due date reliability as a function of the tolerance period and the coefficient of variation (V) of lateness³⁹

The presented methodology for quantifying and anticipating the resulting due date reliability after adjustments of, e.g., planned lead times or capacities directly supports planners in the decision-making process and reduces the probability of wrong decisions based on gut feelings. Therefore, it is another component of a roadmap that merges all presented methodologies to avoid the LTS in practice. This roadmap is summarized in the following section.

6.4 Merged Roadmap of Strategies: A Methodology to Avoid the Lead Time Syndrome in Practice

The previous sections presented methodologies to mitigate the LTS. Thereby, the aim was to transfer the results from theory into practice by finding answers to each of the questions *when, how often, and on which value should planned lead times be adjusted*. To obtain and maintain the maximum performance of a work system a roadmap has to merge all presented methodologies and approaches to support the decision-making process of planners. The following approach provides a list of steps to maximize system performance in practice in the scope of the LTS. Following the process of knowledge discovery in databases (KDD) presented in Section 5.1.2, (I.a) initially the relevant data has to be selected, prepared, and transformed to enable the analysis and interpretation of the system state. (I.b) In addition, delay and fluctuations should be minimized independently of the choice of the control strategy. This choice depends on the relationship between the actual adjustment frequency

³⁹ The graph is independent of the numeric value of the standard deviation, since the independent variable is the ratio of the tolerance period to the lateness standard deviation.

and the value of a suitable adjustment frequency, (II.a) which is therefore determined first. (II.b) Then, the appropriate control strategy can be selected including (II.c) the definition of the optimal parameter settings. These steps are explained in more detail below.

I. Preparation

- a Collect and prepare all relevant system information*
- b Minimize delay and reduce fluctuations*

II. Choice and determination

- a Define a suitable adjustment frequency and (if necessary) calculate the magnitude of response*
- b Check which control strategy is appropriate*
- c Calculate optimal parameter setting (i.e., planned lead time or actual capacity)*

(I.a) Before starting to adjust values initially all actual system KPIs have to be given to enable further evaluations and determinations in the following steps. Exemplary, as proposed by Nyhuis (2009), a logistic analysis could be applied to collect and prepare manufacturing feedback data to calculate company specific KPIs such as due date reliability, actual lead times, etc. In addition, information such as date and magnitude of the last planned lead time adjustment, actual latency period, and the short-term and long-term capacity flexibility⁴⁰ have to be available. This initial step requires a good quality of the feedback data (Eversheim 2000; Hopp 2008; Nyhuis 2009b). If it is not given, the data may not reflect current system states and could lead to overreactions or wrong decisions (Moscoso 2011).

(I.b) The presented control theoretic research results indicate that both control strategies obtain higher system performances for decreasing information delay (see Section 6.1.3). Moreover, a reduction of the processing delay reduces the time period until adjustments affect the monitored system and the resulting KPIs. The research results in Section 6.1.3 also indicated that the maximum achievable system performance increases with decreasing fluctuations (i.e., decreasing input variability). This proposition is confirmed in literature as it has been shown that low lead time fluctuation is a key factor in decreasing safety stocks or safety times (Zipkin 1986) and that it improves the performance of production systems (Erlebacher 1999). Reducing lead time length and variability in production systems enables constant flows and a higher due date reliability (see also ninth basic law of production logistics (Nyhuis 2009b)).

(II.a) It is essential for the selection of an appropriate control strategy to define a suitable adjustment frequency that determines the minimal adjustment period length for which impacts of the LTS are avoided. The LTS is triggered according to

⁴⁰ See also theory of envelope curves for a definition of capacity flexibility in different time horizons (Breithaupt 2000a; Wiendahl 2001).

Proposition P_2 if the adjustment period length is shorter than the latency period. If the new adjustment period length is shorter than the latency period, a suitable magnitude of response may have to be calculated to damp the LTS (see Section 6.2).

(II.b) Based on the defined and calculated system characteristics the appropriate control strategy has to be selected. Capacity control should be selected, if the adjustment period length is shorter than the latency period and a suitable magnitude of response is below a level of 0,05. Furthermore, the results of the control theoretic investigation in Section 6.1.3 support the conclusion that planned lead time control is more suitable to control systems in the long-term, while capacity control is superior in the short-term. Thereby, adjustment period lengths that are shorter than the planned lead times can be defined as short-term adjustments.

(II.c) Finally, with the choice of a control strategy, the optimal parameter settings have to be calculated that lead to the maximum performance increase as measured in due date reliability. If planned lead time control is selected, the optimal new planned lead time has to be calculated as defined in Section 6.3. If capacity control is selected, the actual capacity has to be adjusted according to the definition in Section 6.1.1. Finally, to anticipate the resulting due date reliability after implementation the methodology presented in Section 6.3 can be applied.

The presented steps for maximizing system performance transfer the theoretical results into practical application. However, the roadmap focuses on the adjustment of planned lead times (indirect order release control) and the planned capacity (capacity control), thus excluding the sequencing and order generation tasks of manufacturing control (see Section 2.2.2). Hence, further research is needed on the effects of other order release principles, sequencing rules, capacity control strategies, and methods of order generation on the applicability of this roadmap (see also Section 7.2 for a discussion of further limitations).

6.5 Summary of the Methodology Development

The aim of this section was the development of a roadmap of strategies to avoid the LTS in practice. Therefore, the previous sections presented methodologies to mitigate the LTS that were based on the research results presented in the mathematical, control theoretic, and case study research on the LTS interactions. These sections focused on the questions (1) *when*, (2) *how often*, and (3) *on which value should planned lead times be adjusted*. These methodologies were (4) finally transferred into a merged roadmap.

(1) To answer the first question a control theoretic model of a work system with capacity control was developed to test if capacity control provides an alternative control strategy to planned lead time control. In summary, the results indicate that an increase in due date reliability can be observed if planners are able to maintain a

high adjustment frequency and decrease information delay. More specifically, capacity control obtains a higher performance at work systems with a higher capacity flexibility and a low reaction time to adjust capacities. The improvement and provision of both of these characteristics is expensive in practice, which has to be considered when choosing capacity control (see also (Breithaupt 2000a)). The comparison of planned lead time control and capacity control showed that planned lead time control is preferable for adjustment period lengths that were longer than the underlying planned lead time. Thus, capacity control only obtained higher performances for shorter adjustment period lengths. Unexpectedly, this correlation remained unchanged for all simulated information delays and input fluctuations, which led with increasing values to lower system performances as measured in due date reliability.

(2) To answer the second question it was necessary to determine a suitable adjustment period length for which the LTS is avoided. It was found that the LTS is avoided if the adjustment period length is longer than the expected latency period, which is the sum of information and processing delays. If shorter adjustment periods become necessary, the magnitude of planned lead time adjustment has to be reduced to damp the LTS. For this scenario a calculation methodology to determine a suitable magnitude of response was presented.

(3) Based on the definition of how often planned lead time should be adjusted, it was defined in a second step how to set new planned lead times in practice, thus on which value planned lead times should be adjusted. For this purpose a calculation methodology for a new optimal planned lead time was defined that maximizes the resulting due date reliability for the given system state. In addition, upper and lower limits for system specific maximum and minimum planned lead times were defined, which guarantee that the system is operated in the transition area of the Logistic Operating Curves. Finally, a methodology was presented for quantifying and anticipating the resulting due date reliability after adjustments that supports planners in the process of decision-making.

(4) In the final section all presented methodologies and approaches were merged into a roadmap. This roadmap supports planners to obtain and maintain the maximum performance using planned lead time control or capacity control of a work system in the scope of the LTS.

The next section sums up the research results throughout this work and defines limitations and possible extensions for further research on the LTS.

7 Conclusions and Implications for Further Research

This final chapter aims at summarizing, discussing and critically examining the presented research results, which finally leads to the derivation of implications for science and practice and further research questions in the scope of the LTS. Thus, initially Section 7.1 summarizes and discusses the research results obtained to achieve the objectives defined in Section 1.2. Then, research assumptions, limitations and the generalizability and transferability of the results are presented in Section 7.2. Section 7.3 points out implications for science and practice of the research results on the LTS. Finally, some possible starting points are given for further research to better understand the LTS interactions (Section 7.4) and to investigate the influence of human behavior in scope of the LTS (Section 7.5).

7.1 Summary and Discussion of Results

The aim of this thesis was to investigate the influence of the LTS of manufacturing control on the logistic target achievement to validate the syndrome interactions and to develop a methodology to avoid it in practice. To approach the guiding research question six objectives were defined in this thesis that served as milestones for the investigation of the LTS. The remainder of this section will summarize and finally start with a discussion of the results that were gained during the research to achieve each of the objectives.

Objective one: Validate the line of argumentation of the Lead Time Syndrome.

The mathematical model quantified the effect of a planned lead time adjustment on other logistic key figures and eventually on the resulting due date reliability. It was shown that a planned lead time adjustment leads to a short-term decrease of the actual due date reliability. If planners overestimate this decrease and think that the observed decrease is due to other reasons, renewed adjustments are likely. The increasing complexity of networked manufacturing systems can make it impossible for decision-makers to estimate impacts of their own planned lead time adjustments on the resulting KPIs correctly. Summing up, the mathematical model of the LTS steps validated the correctness of the LTS line of argumentation presented by Mather and Plossl (1977). Moreover, it provided the fundamentals for achieving the second objective of determining the main triggers of the LTS drawbacks.

Objective two: Reveal interactions that trigger the Lead Time Syndrome.

In the mathematical model two triggers of the LTS were identified that lead to a reduced performance as measured by due date reliability. The first trigger is the negative correlation between due date reliability and lead time standard deviation.

The three factors backward scheduling, disturbances, and planned lead time adjustments were thereby identified as main triggers of increasing lead time standard deviation in the scope of the LTS. In this context, the increase in standard deviation was identified as both cause and effect of the LTS, which leads to a reinforcing effect if planned lead times are adjusted again⁴¹. This correlation revealed the second trigger of the LTS; if adjustments are performed before the system reaches a steady state, effects overlap and lead to the LTS. Thus, it was concluded that the impact of the LTS effects is higher (leads to a lower logistic performance), if the adjustment period length is shorter than the latency period of adjustment implementations. However, both propositions had to be validated, which was the third objective.

Objective three: Validate the derived interactions of the mathematical investigation of the Lead Time Syndrome.

A control theoretic model was developed to derive LTS interactions and triggers that validate the derived interactions of the mathematical investigation. It was shown that the LTS leads to an unstable system in which WIP level and lead time oscillate with a building amplitude. The results revealed that the LTS is triggered if the adjustment period length is too short in proportion to the given information delay, or if the magnitude of response to fluctuations is too high. In this case the system is not able to reach a steady state before the next planned lead time adjustment is implemented. Further simulation runs were then evaluated to analyze these interactions in more detail to enable the derivation of strategies to avoid the LTS.

Objective four: Define strategies to avoid the Lead Time Syndrome.

To derive strategies to avoid the LTS various input variances, adjustment period lengths, information delays, and magnitudes of response were simulated. The evaluation revealed that planned lead time control triggers the LTS if the adjustment period length is not longer than the information delay. Based on this relationship, another strategy was developed to dampen the LTS for scenarios in which the adjustment period length is not longer than the information delay. It was shown that the impact of the LTS could be damped significantly if the magnitude of planned lead time adjustments is reduced. The resulting ideal levels of reduction in various simulation scenarios were then transferred into an initial approach to calculate a suitable magnitude of response depending on the ratio of adjustment frequency and information delay. In addition, it was also found that the overall target achievement increases with a decreasing input variance.

Objective five: Evaluate and confirm the derived propositions in a real system.

To evaluate and confirm the derived propositions a case study of a real manufacturing system was presented. The underlying feedback data enabled the

⁴¹ This behavior is similar to the situation of positive feedback as described in Section 2.2.3.

investigation of two situations: (1) no transparency and (2) full transparency of actual system states. (1) It was shown that the first case led to the worst case steady state of the LTS with long and erratic lead times, high WIP levels, and a low due date reliability. Thereby, planners had to set planned values based on their gut feelings and experience. (2) In the situation of full transparency a PPC IT-System provided all relevant system information such as throughput diagrams, KPIs, and lateness distributions. The result was a significant performance increase in comparison to the situation of no transparency. However, it was observed that planners tended to set initial planned lead times too long, thus including buffers of safety lead times. Moreover, in situations of decreasing due date reliability they tended to adjust planned lead times instead of adjusting capacities. The determination of new planned lead times overstrained planners, as the complexity of available information was too high for them. Thus, preferred KPIs and diagrams (not necessarily the most relevant) were used in the process of decision-making to determine new planned lead times. Besides these observations, the impact of planned lead time adjustments on the resulting due date reliability was analyzed. It was shown that a planned lead time adjustment leads to a sudden decrease in due date reliability, followed by a gradual increase. Thus, the LTS would lead to a decrease in performance if planners adjust planned lead times in this latency period. The presented research results evaluated and illustrated the effects of the LTS, confirmed the propositions, and once again suggested that the LTS line of argumentation of Mather and Plossl (1977) is valid.

Objective six: Develop a roadmap of strategies to avoid the Lead Time Syndrome.

The investigation of the impact of planned lead time adjustments on the resulting due date reliability provided the fundamental knowledge and understanding of the LTS interactions for developing a methodology for mitigating the LTS in practice for different environmental conditions. Therefore, a roadmap was presented that answers the questions *when, how often, and on which value should planned lead times be adjusted*. For this purpose, the performance of capacity control was compared to the performance of planned lead time control (taking into account the LTS) to answer the question of when to adjust planned lead times. It was shown that planned lead time control is preferable for adjustment period lengths that are longer than the actual planned lead time. Capacity control obtained higher performances for shorter adjustment period lengths, but requires flexible capacities that give rise to costs. To answer the question of how often planned lead times should be adjusted, calculation methodologies were developed to determine first a suitable minimal adjustment period length that guarantees the avoidance of the LTS and second a suitable magnitude of response that dampens the LTS if inevitable. Finally, a calculation methodology was presented to answer the last question (on which value to adjust). It calculates the optimal planned lead time for the given system state. Upper and lower limits were defined for system specific maximum and minimum planned lead times to guarantee that the system is operated in the

transition area of the Logistic Operating Curves. In addition, a methodology was presented for quantifying and anticipating the resulting due date reliability after adjustments to support planners in the decision-making process. To obtain the sixth objective, finally a roadmap was presented that merged all presented methodologies. Hence, a roadmap that transfers the theoretical research results into practical application to maximize system performance in the scope of the LTS.

In many discussions on the LTS topic the idea came up to implement an automated planned lead time control into the PPC IT-System. As already noted by Plossl (1988) it would be “a rational method of self-destruction at blinding speed” if the strategies to avoid or damp the LTS are not included. To answer the guiding research question (see below) this thesis presented for the first time a holistic approach to face the LTS. It was shown that the LTS affects logistic target achievement and that a lack of knowledge about the impact of the LTS might lead into poor system performance. Therefore, at first two propositions (see below) were derived in the mathematical investigation that characterize the main interactions that lead into the LTS. Afterwards these propositions were evaluated and confirmed by means of control theory and a case study. However, the presented approach is subject to assumptions and limitations. The aim of these investigations was to reveal fundamental interactions that enable to understand the LTS. Therefore, the presented models were as simply as possible to demonstrate that even under these simple conditions the negative effects of the LTS might occur for specific parameter settings. Thus, transferability and generalizability of the results is limited regarding these assumptions. These are described in Section 7.2, which also includes a more detailed discussion of the presented research results.

Guiding research question: *How does the LTS affect the logistic target achievement of manufacturing control and which methodologies can planners apply to avoid it?*

P_1 : Standard deviation: *The longer the lead time and the higher the planned lead time adjustment, the higher the lead time standard deviation, hence the lower the due date reliability.*

P_2 : Frequency of adjustments: *The LTS leads to a reduced logistic performance if the adjustment period length is shorter than the latency period (the sum of processing and information delays) of the adjusted system.*

This thesis can be considered as fundamental research on the LTS as it affects several subjects and fields of research. The presented approach used logistic equations (see Funnel Model), statistics, control theory, and a case study as main methods to derive conclusions. In each of these research fields further research is needed to confirm, challenge, or extend the presented results, which is described in Section 7.4 and Section 7.5. In summary, the research results show that the adjustment of planned lead times not necessarily leads to an improved logistic target

achievement and suggest the following points to maintain a high system performance in practice in the scope of the LTS:

- *Planners should be aware of the possible LTS effects.*
- *A reduction of disturbances and variation leads to an overall system improvement.*
- *The adjustment period length has to be set according to the given latency period.*
- *The adjustment of planned lead times should be objectively justified.*

7.2 Research Assumptions, Limitations, and Generalizability

The research results presented in this thesis were subject to assumptions and limitations. First, this section summarizes these assumptions and limitations for each of the presented methodologies and, second, classifies the generalizability and transferability of the research results.

Mathematical model of the LTS

The logistic equations that were used for the mathematical modeling of the LTS are based on the Funnel Model (see (Nyhuis 2009b)). These equations are used to calculate systems' behavior for steady state situations, thus for situations in which the underlying process characteristics remain the same during the reference period (e.g., maximum capacity). As the LTS results from a parameter change (i.e., planned lead time) it has to be distinguished between long-term and short-term effects. The integration of basic statistical methods enabled the determination of short-term effects such as the resulting new lead time standard deviation. However, the developed equation to calculate the due date reliability results in an anticipated value and is limited in depicting short-term impacts of variable adjustments.

In addition, it was assumed that the underlying lateness is normally distributed. The presented validation in Section 3.1.1 was able to confirm or rather accept this assumption in the scope of the LTS investigation. However, the maximum negative lateness is limited by the length of planned lead times, while the maximum positive lateness is – in theory – unlimited. Thus, other distribution functions, such as a Weibull distribution (see, e.g., (Rinne 2009)), might lead to even more precise calculations of the actual due date reliability, which has to be tested in future research.

A more differentiated analysis of the lead time elements was not part of this thesis. This assumption was made for reasons of simplification as only interoperation times are directly affected by changing WIP levels (increased waiting time). Therefore, a separated consideration of interoperation and operation times was unnecessary in terms of the investigation of the LTS interactions. However, the determination of the value on which to adjust planned lead times showed that a separate consideration of interoperation and operation times can be necessary (see

Section 6.3). The resulting lead time standard deviation is more strongly affected by the given operating times if, e.g., set-up or processing times have a high variance and interoperation times decrease to a level located in the transition area of the Logistic Operating Curves (see also (Nyhuis 2009b)). Thus, further investigations on the LTS interactions (i.e., case study, mathematical and control theoretic investigation) might also include an independent consideration of interoperation and operation times.

Control theoretic model

The presented control theoretic model of the LTS is subject to several assumptions and limitations for simulating planned lead time control and enabling the initial investigation of fundamental LTS interactions. The most significant limitation is the simulation of only one work system. Depending on the desired focus, the modeled system can represent one machine, a machine group, a self-contained production area, or the entire factory (Petermann 1996). However, the simulation did not model a network of work systems, with material flows between them. Thus, the presented results reflect the situation of a work system at the beginning of a process chain and might underestimate the impact of the delay component, as the processing delay strongly depends on the number of predecessors (i.e., the delay until (earlier released) orders reach the system).

To link impacts of variable adjustments on the emergence of the LTS stochastic elements were not included. Besides the input fluctuation, which was generated by a random source with a normally distributed fluctuation around a fixed mean, no other disturbances or fluctuations were simulated. These assumptions were made to avoid overlapping effects that would have made it difficult to distinguish between effects of the LTS and effects of disturbances. Further research might include capacity and work disturbances to model more realistic work systems and analyze, if these disturbances lead to an amplification or damping of the LTS.

Stochastic effects would have also increased the number of simulation runs that are needed to derive justified conclusions for each simulation setting. For the presented results in Chapter 4 more than 252.000 simulation runs – with some 15 seconds computation time to finish one simulation run – were carried out. Thus, it was necessary to reduce complexity. This led to the decision to set only one information delay that defined both the delay of planned lead time adjustments and the delay of order release adjustments. Hence, both values have the same length, which leads to a significant reduction of required simulation runs by a factor of ten and the number of required dimensions to evaluate the results. As both delays are independent from each other in practice, future research should also include a separate investigation. This could be supported by an equation based dynamic analysis approach that transfers the control model into differential equations of control theory. They allow a more detailed investigation of fundamental LTS interactions that would make it superfluous to run numerous simulations. Moreover, it would support the derivation of an optimal magnitude of response k_p , as the

presented methodology requires further investigations to, e.g., include the level of input fluctuations or stochastic disturbances.

Case study

The results presented in the case study were based on the feedback data of a job-oriented production environment of a division of a globally operating steel manufacturer. Thus, the transferability and generalizability of these results is limited (Voss 2002). According to Yin (2009) one rationale for a single-case design is when it meets all of the conditions for testing the theory. Thereby, the research results can confirm, challenge, or extend the tested theory (Yin 2009). Another rationale is when the single-case is representative or typical. Thus, if a manufacturing process can be considered as typical of other manufacturing processes of the same industry (Yin 2009). It was shown that the chosen case meets all of the underlying assumptions of the LTS (due date reliability as main performance indicator, planned lead time control, high fluctuations, etc.), hence fulfilling the first rationale. The second rationale is fulfilled by a definition of the field of applicability. The investigated division of a globally operating steel manufacturer processes individual customer orders separately on a given set of machines in a job-oriented production environment (see also Section 5.1.1). It can therefore be assumed that this case is representative of customer-ordered individual or small series production in which orders are processed on single machines or in manufacturing cells (see also (Schönsleben 2012; Wiendahl 2014)). Therefore, the results of the single-case are likely to be generalizable for manufacturing processes of this type, which are according to Schönsleben often found in automotive, tool making, mechanical-engineering, and electronic industries, hospital care, etc. (Schönsleben 2012). Also, the separation of the feedback data into two periods of investigation, with multiple embedded units of analysis, supports the external validity, which is the generalizability of a single-case (see (Voss 2002; Yin 2009)). However, a longer period of investigation, in which there is full transparency of current system states (by PPC IT-System), would enable the investigation of more embedded units of analysis, thus further confirm, challenge, or extend the derived propositions. An extension of the period of investigation was not possible due to time restrictions of the research project.

Roadmap

Transferring the research results of the mathematical, control theoretic and case study approaches into guidelines in practice that support planners in the decision-making process to avoid the LTS is in a (advanced) concept phase. Further research is needed on each of the presented elements that were merged into one roadmap.

The comparison of capacity control and planned lead time control is based solely on the presented control theoretic evaluation. The capacity control model is thereby subject to the same assumptions and limitations as the planned lead time control model, which were discussed above. Moreover, the compared system performances were based in the case of planned lead time control on the assumption that the LTS

can be damped by setting a suitable k_p . However, the calculation methodology of this magnitude of response needs further research (see above). The conclusion that capacity control should be preferred to planned lead time control for an adjustment period length that is shorter than the underlying planned lead time should therefore be used with caution. Although the research results support this assumption, further research is needed on this conclusion that also includes other research methodologies.

The derivation of the presented methodology of *when, how often, and on which value* to adjust planned lead times is once again subject to the assumptions and limitations of the control theoretic model and the single-case. The definition of a suitable adjustment period length that guarantees the avoidance of LTS drawbacks was based on rather inconsistent research results. The single-case suggests that the adjustment period length should at least exceed the time period until due date reliability reaches its base level again, while the control theoretic investigation suggests that an adjustment period length that is longer than the information delay is sufficient to avoid the LTS. Therefore, it was defined according to Proposition P_2 , by defining that a suitable adjustment period length should be longer than the latency period, which covers both suggestions. Thus, further research is needed on these inconsistent results to define an optimal adjustment period length in the scope of the LTS.

Transferability and generalizability of results

As discussed in Section 2.2 the LTS was first observed in systems using classical MRP. Thus, the presented validation of the LTS was limited to manufacturing control systems using backward scheduling to determine planned order release dates. Hence, the emergence of the LTS still has to be tested for other manufacturing control methods, such as workload control or load oriented order release (see also (Lödding 2013) for an extended list). In particular, the LTS was validated in this thesis for push systems⁴². Thus, the effects of the LTS are not directly transferable to systems using, e.g., pull-oriented manufacturing control systems such as CONWIP, Kanban (see also (Pettersen 2009; Hopp 2008; Lödding 2013)) or mixed principles such as the Push-Pull-Principle (Perdaen 2008). It can be summarized that the research results on the LTS are transferable to manufacturing companies that use basic MRP II and ERP concepts for PPC. These concepts are according to Schönsleben (2012) frequently used in batch production systems for all plant layouts except continuous production (see also (Wiendahl 2014)).

The impact of the LTS on the logistic target achievement was also limited to the four targets of low WIP, high capacity utilization, low lead times, and in particular high due date reliability. However, high quality, low costs or other targets might be more important for some companies, thus limiting the generalizability of the presented results.

⁴² MRP systems are frequently described as push systems (Bonney 1999; Hopp 2004).

The presented research assumptions and limitations as well as the generalizability of the research results reveal that further research in the scope of the LTS is required (see Section 7.4 and Section 7.5). However, the research results also have some implications for science and practice, which are presented in the next section.

7.3 Implications for Science and Practice⁴³

The research on the LTS interactions aimed at answering the questions of how a planned lead time adjustment affects due date reliability and how possibly wrong decisions of planners to adjust planned lead times can be avoided. The knowledge gained from the research results on the LTS interactions has some implications for practice, science, and software developers that are presented next.

Implications for practice

The investigation of the LTS interactions revealed that the LTS is able to lead to a situation with low logistic target achievement in terms of low due date reliability, high WIP levels and long and erratic lead times. Thus, planners should be aware of the syndrome when adjusting planned lead times. This especially concerns the observed effect that it takes some time until planned lead time adjustments take effect (latency period), thus until the desired due date reliability is reached (see Observation 3 in Section 3.3.2). The problem is thereby that due date reliability can decrease significantly directly after the adjustment, thus leading to misinterpretations and renewed adjustments. Another problem that was addressed in this regard is the anticipation of the resulting due date reliability after adjustments. Based on the developed equation to calculate due date reliability as a function of the due date tolerance and mean and standard deviation of lead times a methodology of how to anticipate the resulting due date reliability after adjustments was presented (see Section 6.3). This methodology allows to forecast and compare future scenarios in a quantitative way. For example, if the actual lead time standard deviation is reduced by 10%, due date reliability will be increased by 6%. Anticipating the expected due date reliability supports production planners in the decision-making process for selecting improvement measures. Moreover, the expected due date reliability improvement can be compared to the required time and effort of implementation for each option.

As discussed in Chapter 6, PPC-systems often lack the support to define and maintain planned values (Nyhuis 2010). The roadmap presented in Section 6.4 supports planners in defining suitable planned lead times. This also includes on one hand the information of how often to adjust at maximum (suitable adjustment frequency) in order to avoid the LTS and on the other hand for which situations capacity control would be preferable. Moreover, it can be assumed that a reduction in information delay and fluctuations significantly increases the logistic target achievement. These results can be applied to manufacturing systems with customer-

⁴³ Parts of this section have been published in similar form in (Knollmann 2014c).

ordered individual or small series production in which orders are processed on single machines or in manufacturing cells (see Section 7.2). Thus, if planners follow the recommendations, it can be assumed that drawbacks of the LTS interactions are avoided and that the logistic performance is significantly improved.

Implications for science

The roadmap developed in Section 6.4 supports planners obtaining and maintaining the maximum performance of a work system in the scope of the LTS. However, if planners refuse to believe the presented results or decide to adjust planned lead times according to their gut feelings, the LTS may be triggered. This example once again shows that human behavior is a key element to be considered in manufacturing control in order to maintain a high logistic target achievement.

Research on human behavior has a long tradition in anthropology, psychology, and sociology (Berelson 1964). In the past decades also other research disciplines integrated the effects of human behavior into their studies. Exemplary, cognitive biases were investigated in the context of the strategic decision process of high-level management (Das 2002). Cognitive biases challenge the assumptions made in rational-choice models and show that if humans deal with complexity and uncertainty they systematically go wrong (Kahneman 2002a). In the recent past, research on human behavior has made considerable progress in economics and led to the creation of the field of behavioral economics (Tokar 2010). Despite the fact that logistic models are limited if behavioral realities are not integrated, cognitive biases and human behavior are still open research questions in logistics (Weber 2008; Tokar 2010).

The observations made during the research project in the manufacturing company (see case study in Chapter 5) support the conclusion that further research is needed in the field of human behavior in the scope of the LTS. Thus, to answer the questions why or when planners overreact in practice and repeatedly adjust planned lead times. These investigations could lead to the determination of requirements for the visualization of, e.g., system states in manufacturing control systems. Therefore, Chapter 7.5 gives a brief introduction into the research on human behavior in the field psychology to show starting points for possible further research approaches in scope of the LTS. A first attempt to develop a user interface to support planners in the process of decision-making is presented next.

Implications for software developers

The next step to avoid the LTS in practice will be to develop a software tool to support production planners in the process of decision-making. Hence, to further develop the roadmap described in Section 6.4 and to take human behavior into consideration. In the following an initial concept of a visualization methodology is presented that is supposed to support planners and minimize the probability of wrong decisions in terms of a decreased system performance.

Figure 7.1 shows a screenshot of a first attempt to develop an interactive user interface. Initially a user has to choose between the two control options ‘planned lead time control’ and ‘capacity control’ and move the handle of the particular controller to the desired position. The tolerance period controller affects the results of both control strategies. A more strict due date tolerance would lead to a more sensitive system behavior in terms of disturbances. Also, the integration of a KPI summary would give an overview of the actual logistic performance.

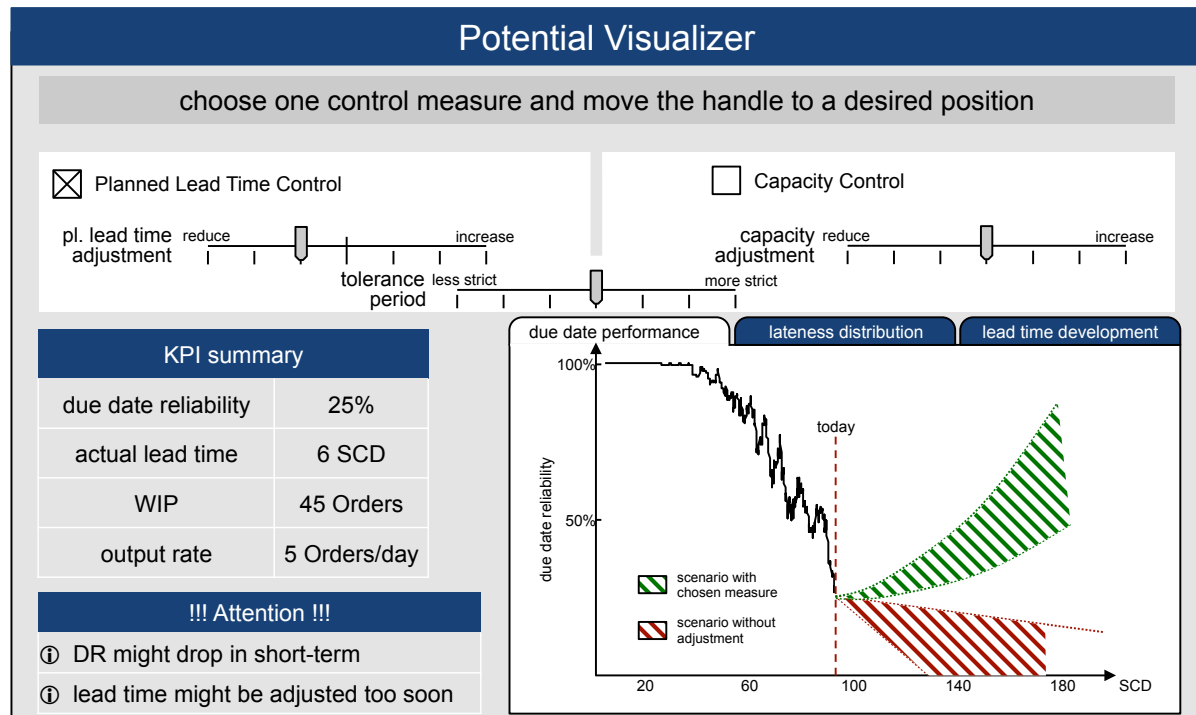


Figure 7.1 Screenshot of a user interface with real time scenarios of anticipated KPI-developments

The most attention should be placed on the instant feedback box in the lower right corner of the user interface. Exemplary, three values were chosen to demonstrate the choice of the user between different visualization options. Here, the due date performance development is shown over time until ‘today’. Depending on the chosen control strategy and the desired adjustment, an instant scenario corridor would visualize the most likely development of the value⁴⁴. This corridor could be upwardly limited by a maximum boundary, which represents the optimal parameter setting for the given system state. For a more visual differentiation also a corridor of the anticipated KPI development could be integrated to show what happens if no control actions are taken. Both corridors are so far schematic drawings without underlying calculations. Taking into consideration the likelihood of triggering the LTS, special care has to be taken to visualize or inform a user about possible risks or other issues that should receive attention. This is implemented in the ‘attention’ box, which would display necessary information depending on the choices of a user. Another strategy would be to directly implement limits in the adjustment

⁴⁴ A calculation approach to anticipate such due date reliability developments is presented in Section 6.3.

controllers, e.g., by making it impossible for a user to adjust too often or to choose illogic or infeasible values (e.g., if a capacity adjustment would exceed the maximum capacity). Potentially, a variable color scaling of the controllers would also help. Also, pop-up windows could be integrated to give more information when a user clicks on a value or a word. However, the biggest benefit of the presented methodology would be the anticipation of future states rather than only presenting the actual or past situation. The interactivity moreover would give instant feedback to a user about what is likely to happen if an adjustment is performed with his current choices. Such a user interface could support planners in the process of decision-making and prevent accidentally wrong adjustments that lead to a decrease in performance.

It has to be clarified for the development of such a user interface which information is needed by planners and if there are requirements to display them. Thus, further research is needed on human behavior in the scope of the LTS, which is discussed in Section 7.5. Also, further research on the LTS interaction is required to define, e.g., upper/lower limits of suitable planned lead time adjustments.

7.4 Further Research on Lead Time Syndrome Interactions

This thesis validated the LTS line of argumentation and developed methodologies for avoiding it in practice. However, further research is needed to better understand the LTS interactions and to further develop appropriate methods for avoiding it. This section lists some possible starting points from which some arise from the limitations presented in Section 7.2.

In the control theoretic simulation a constant input rate with three different input variances were sufficient to validate the LTS. Nevertheless, further research might also simulate seasonal fluctuations by simulating a shifting mean, e.g., by implementing a sine function. Also, more simulation scenarios would confirm, challenge, or extend the definition of a suitable magnitude of response. The differentiation between short-term and long-term capacity flexibility would lead to a more realistic simulation of capacity control as defined by the theory of envelope curves (see (Breithaupt 2000a; Wiendahl 2001)). This is due to the fact that capacity adjustments require both flexible workers and flexible machines (Lödding 2013), which gives rise to additional costs that have to be considered when comparing both control strategies.

As the LTS line of argumentation was used by several researchers to introduce measures to overcome selected negative LTS interactions (see Section 2.4), further research might also focus on the question of whether these methods are able to avoid the LTS in practice. Thus, e.g., how planned lead time adjustments affect the performance of bottleneck control, if other sequencing principles (e.g., Least Slack principle) affect the emergence of the LTS, or if due date based order release is able to avoid the LTS (see also Lödding (2013) for other methods of manufacturing

control). This also includes the question whether the LTS can be observed in a pull production. Thus, if the LTS can be observed in manufacturing systems that implemented, e.g., Kanban or CONWIP (Hopp 2004).

Also, a control model of a network of manufacturing systems would better reflect reality and would enable the investigation of more complex interactions and dependencies. Moreover, it would be interesting to compare the obtained system performances with a combined control strategy of long-term planned lead time control and short-term capacity control, as the research results support the conclusion that planned lead time control is more suitable to control systems in the long-term, while capacity control was superior in the short-term. Overall, further investigations on the LTS interactions would be supported by an equation-based dynamic analysis approach that transfers the control model into differential equations of control theory. This would enable a more detailed investigation of fundamental interactions and facilitate transferring control strategies to damp fluctuations or mitigate positive feedback by, e.g., increasing the damping ratio or determining parameters of a PID controller (see, e.g., (Bubnicki 2005; Nagrath 2006)).

The single-case study that was analyzed was sufficient to illustrate, evaluate, and confirm the derived LTS interactions, but additional units of analysis would give more insights into the impact of planned lead time adjustments on logistic performance. Thus, e.g., an extended period of investigation with more work systems in which planned lead times were adjusted or other case companies to enable evaluating observed similarities and differences. This would also include the integration of other targets such as quality and costs, other manufacturing systems such as flow production, and other methods of manufacturing control as mentioned above.

In addition to further investigations on LTS interactions, further research might also focus on human behavior in terms of when and why planners tend to misinterpret system states and to repeatedly adjust planned lead times in practice, which is described in the next section.

7.5 Further Research on Human Behavior in Scope of the Lead Time Syndrome⁴⁵

The mathematical investigation in Chapter 3 showed that the revealed interactions only lead to a decrease in due date reliability for a defined time period (latency period) and that the LTS is only triggered if planners adjust planned lead times during this time period – without consideration of the methodology presented in Section 6.4. The case study presented in Chapter 5 showed that in practice planners often misinterpret system states. Hence, in order to improve logistic

⁴⁵ Parts of this section have been published in similar form in (Knollmann 2014c).

performance planners could decide to adjust planned lead times again and again, which – against their expectations – leads to a decrease in due date reliability and into the LTS. Thus, further research is needed to avoid the LTS in practice. This section gives a brief review of the research on human behavior and cognitive biases such as mistakes by overreaction or misinterpretation of decision-makers from the field of psychology and shows that such behavior can also be observed in the scope of manufacturing control and the LTS and should be considered in future research.

The investigation of the case company presented in Section 5.2 showed that the intention of planners to increase due date reliability is – with a lack of transparency about actual system states – likely to lead to a situation of low performance including low due date reliability. Although the observed initial situation depicted the worst case steady state of the LTS some general problems of human behavior became apparent in the observed manufacturing system:

- Even if planners are aware of the LTS and know that due date reliability might decrease due to too frequent adjustments they propose planned lead times adjustments as method of choice.
- A lack of transparency about current system states makes workers prone to high work in process levels in order to have a ‘guarantee’ of enough work in the following periods (observed during the worst case situation of Section 5.2) (see also ‘dilemma of operations planning’ (Gutenberg 1951)).
- Without planning and sequencing of orders, workers tend to follow their own sequencing rules (e.g., the most interesting or biggest orders first)(observed during the worst case situation of Section 5.2)
- Workers do not always report order completion times (i.e., date and time) directly. Rather, finishing times are often entered into the IT-system at the end of a shift or at the end of a working week (Nyhuis 2009b).
- With full transparency about current system states (including charts, diagrams and KPIs) workers see the planned work for the following periods. As they previously were accustomed to extremely high WIP levels some feel uncomfortable with low WIP levels that correspond to their capacities. Thus, the phenomenon was observed that some workers slowed down the output rate of a work system to artificially increase WIP levels by retarding orders (Lödding 2013) (also observed during the situation presented in Section 5.3).
- With full transparency planners are often incapable of coping with the amount of information and pick preferred KPIs or diagrams for optimization (e.g., due date reliability) (Fernandes 2006) (also observed during the situation presented in Section 5.3)

This partial list is based on observations made during the research project on which the single-case study is based. They show that either accidental or intentional misbehavior of workers and planners could decrease the logistic target achievement. However, it should be assumed that workers do not intend to decrease the performance, but rather fall victim to cognitive biases. Cognitive biases and human behavior are still open research questions in logistics (Weber 2008). Tokar (2010) provides an overview of potential benefits of behavioral research in logistics and

supply chain management, stating that robustness, predictive accuracy and overall usefulness of logistic models are limited if behavioral realities are not integrated. Furthermore, the author suggests that behavioral research should be promoted due to the practical nature and the large number of human interactions in logistics (Tokar 2010).

To develop a methodology that prevents human mistakes of overreaction and misinterpretation, initially cognitive biases in the scope of the LTS have to be identified. Kahneman (2002a) explored the psychology of intuitive beliefs and choices and developed a map of bounded rationality that is presented in following paragraphs⁴⁶. Brief summaries of the findings of Kahneman are presented, which are then individually transferred into the context of the LTS or decision-making in general to point out potential fields for further research on the LTS.

The two-system view of cognitive systems

Decisions are often based on beliefs regarding the possibility of uncertain events such as election results or the development of stock prices (Tversky 1974). In these studies of judgment under uncertainty it was distinguished between the cognitive processes *intuition* and *reasoning* (Stanovich 2000; Kahneman 2002a). Stanovich and West categorized the characteristics of these two cognitive processes, which were labeled System I and System II. The operations of System I (Intuition) are relatively fast, parallel, automatic, emotionally charged, effortless and difficult to control or modify. The operations of System II (reasoning) are deliberately controlled, effortful, rule-governed, flexible and relatively slow (Stanovich 2000; Kahneman 2002a). A comparison of the generated effort of the mental processes indicates to which system they can be assigned.

Based on this two-system view, Kahneman and Frederick suggested that *impressions* are generated in System I, while all *judgments* are generated in System II (Kahneman 2002b). They also suggest that the process of monitoring of judgments by System II is quite lax. That the process of cognitive self-monitoring may be lacking was shown for example in the ‘bat and ball’ problem (Frederick 2005):

“A bat and a ball cost \$1,10 in total. The bat costs \$1,00 more than the ball. How much does the ball cost?” (Frederick 2005)

Around half of the respondents answered “10 cents”. This example shows that intuitive judgments are likely to be expressed, even if they are erroneous. People are often content to trust plausible judgments that quickly come to their minds as they are not accustomed to think hard. It can be concluded that judgment errors are always errors in System II, which are likely to occur in decision-making due to the lack in self-monitoring.

For example, in the context of the LTS planners intuitively think – without further justification – that frequent planned lead time adjustments lead to an

⁴⁶ Kahneman (2002) also presents findings of other authors that are referred to below separately.

increase in due date reliability. Decisions have to be made quickly with limited information, which are often based on intuition and anticipations of future system states. More specifically, if planners blindly trust their intuition, judgment errors are even more likely.

Accessibility of information

While intuitive thoughts come to mind spontaneously, other thoughts might not be accessible for individuals. Therefore, the accessibility of information is defined by the ease with which a mental content can be activated (Higgins 1996a). Figure 7.2 shows two examples of differential accessibility according to Kahneman (2002).

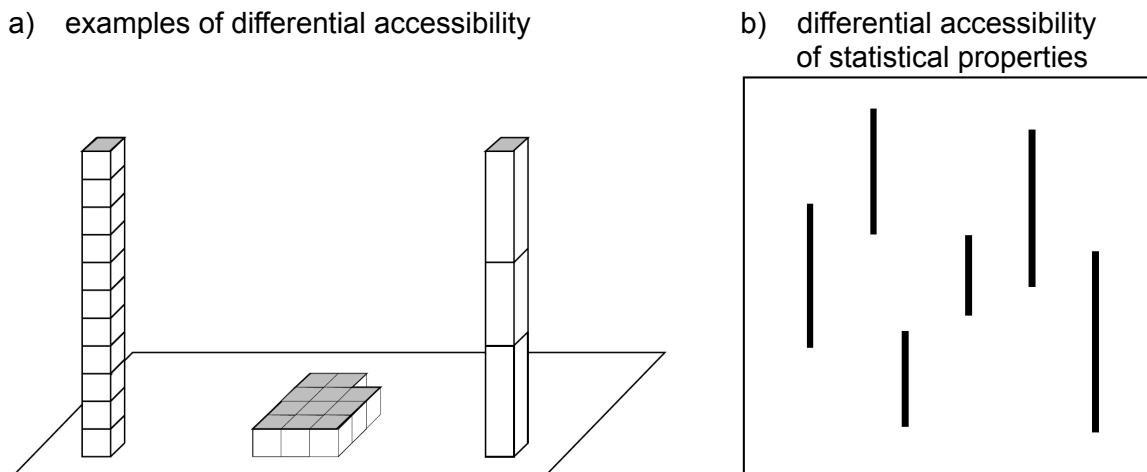


Figure 7.2 Differential accessibility of information (Kahneman 2002a)

While we have an intuitive impression of the height of the left tower (part (a)) and the area of the top block, a quantification would need deliberate operations. This also applies for the other two block structures. While the middle structure gives an immediate impression of the total area, the height of all blocks stacked is not directly accessible. Also, the left and the right tower are different, but more similar to each other than to the middle one. Another example is given in part (b). Here, the question regarding the average length of the lines can be more easily answered than the question of the total length of all lines. The accessibility of information can be increased through experience and skill. This can be illustrated by the simple example of a trained chess player that intuitively predicts chances during a game.

The problem of accessibility leads in the process of decision-making to situations in which highly accessible information is given more weight than information with low accessibility, which is also likely to be ignored. To gain knowledge about actual system states, diagrams such as production operating curves (see (Nyhuis 2009b)) or lateness distributions have to be interpreted correctly. Furthermore, not only the knowledge about calculated KPIs has to be given, but also they have to be understood and they have to be seen in relation to each other (e.g., Flow Rate and lead time (Ludwig 1995)). Thus, it is theoretically likely that planners put more weight on favored, but possibly less relevant KPI values, when it comes to decision-

making. This behavior is often observed in practice. For example, if students have internalized during their studies that a maximum capacity utilization is essential, they primarily try to optimize this value when they are production planners (Weber 2008). Another example can be given by the observations during the case study (Chapter 5). Planners initially named a high due date reliability as main target without knowing the exact definition of the value, as they used ‘on-time production’ and ‘due date reliability’ synonymously and furthermore did not define tolerance periods (see definition in Section 2.1.2). However, consultancy projects and coaching are able to continuously improve the skill to access more process relevant information⁴⁷ (Kahneman 2002a).

Framing effects

A significant aspect of rationality is the invariance of preferences, which means that changing irrelevant features should not change any preferences (Tversky 1981). The cognitive bias of framing effects violates this aspect of invariance. One example is the experiment of the so-called “Asian Disease Problem”, in which two alternatives are given to respondents to combat it. Different formulations of the alternatives lead to the choice of the risk averse option for one case and the risk-seeking option for the other. Thus, certain outcomes were preferred to outcomes with a medium or high probability. More specifically, framing effects contribute to risk aversion when people are confronted with choices including sure gains and to a risk seeking behavior when choices include sure losses (Kahneman 2002a).

Framing effects can be observed in the process of decision-making when alternative descriptions of a problem highlight different aspects of the resulting events. Hence, it has to be considered that different visualizations or representations of the same information could lead to different decisions. Exemplary, a visualization of the actual lead time over time will be interpreted differently for different scalings of the vertical axis (e.g., a minimum of zero or the minimum measured actual lead time, and specifying in percent or absolute numbers). Thus, data have to be prepared and presented in a transparent way to avoid framing effects.

Changes or states (Prospect Theory)

The perceptual systems of a human being have the general property that they are designed to increase accessibility of changes and differences (Palmer 1999). Perception is reference-dependent as “the perceived attributes of a focal stimulus reflect the contrast between that stimulus and a context of prior and concurrent stimuli” (Kahneman 2002a). One simple demonstration was given by the example of three buckets of water (left=cold; middle=tepid; right=hot). Immersing the left hand in the cold water and the right hand in the hot water leads to an intense perception of heat and cold. This sensation gradually wanes. Putting both hands afterwards into the bucket with the tepid water leads to the ambivalent impression of both heat (left hand) and cold (right hand). The idea of reference-dependence is

⁴⁷ This effect was also exemplary shown in a consultancy project presented by Nyhuis (2009).

conflicting with the assumption in Utility Theory⁴⁸ that decisions are independent from the initial state. However, the experiments of Kahneman showed that when subjects are offered two choices between two gambles, decisions are made based on the changes of wealth, losses or gains, not the expected states of wealth after the gamble. Based on this theory, which is termed Prospect Theory⁴⁹, one could also expect the evaluation of decision outcomes to be reference-dependent. Decision makers are often confronted with uncertainty during the process of decision-making and therefore will be strongly influenced by their evaluations and perceptions of losses and gains. Moreover, decisions cannot be separated from emotions, which are caused by changes. A model that excludes feelings such as pain or regret of losses or mistakes would be unrealistic (Kahneman 2002a).

The problem of changes or states demands visualization of variable developments over time because this would make changes more transparent. Such a visualization would also reduce framing effects. The complexity of production networks makes it impossible for an individual to anticipate effects correctly. Thus, in addition a visualization of anticipated future KPI developments would mitigate this cognitive bias. Moreover, personal interests and feelings of decision maker could be integrated by involving them in the definition of options by choosing optional control measures to be predicted and visualized.

Anchoring and Adjustment Heuristic

During the process of decision-making people start with an initial estimate (anchor) and adjust it until the final answer is reached (Tversky 1974). However, the adjustments rarely lead to the correct answer. One example by Tversky and Kahneman (1974) is the estimation of the product of $A=8\cdot7\cdot6\cdot5\cdot4\cdot3\cdot2\cdot1$ in comparison to the calculation of $B=1\cdot2\cdot3\cdot4\cdot5\cdot6\cdot7\cdot8$. The estimation of the solution under time pressure leads to higher values for the first case (median of estimates for A : 2250; B : 512). Sterman (1989) gives a more practical example by the so-called ‘Beer Distribution Game’. The participants had to estimate parameter settings rather than calculate exact solutions due to a lack of time. It was shown that the anticipated delay between order placement and receipt was generally underestimated. Hence the participants adjusted the desired stock levels each period to compensate these underestimations (Sterman 1989). These adjustments were strongly influenced by the initial levels (anchor). In this example planning instabilities, local optimization, and the misconceptions of feedback data lead to the so-called ‘bullwhip effect’, which in turn leads to poor system performance (Moscato 2011; Sterman 1989). The misperception of feedback was particularly notable because the participants assigned the observed fluctuations to external events rather than to their own actions. This means that they were not able to account for their own control actions, which were initiated previously but had not yet affected the observed values (Sterman 1989).

⁴⁸ The “study of quantitative representations of people’s preferences and choices” (Fishburn 2006).

⁴⁹ A theory that describes the behavior of how people choose under risk (Kahneman 1979).

The misperception of feedback once again demands more transparency to avoid sudden overreactions as a result of short term disruptions or fluctuations. Particularly, the anchoring and adjustment problem describes the situation observed in the LTS. Planners tend to adjust planned lead times instead of entirely reconsidering the magnitude of the value. Moreover, in case of the LTS external influences are held responsible for the in-fact delayed due date reliability decrease that seemingly demands another planned lead time adjustment. The complexity of production networks makes it impossible for planners to anticipate their own impacts on the overall system and in particular on the adjusted system.

The presented cognitive biases that were described and mapped by Kahneman (2002) show that the rationality of decision makers is bounded. They often have to deal with uncertainty due to the fact that only past data of system states such as WIP levels or capacity utilization levels are exact, which is also only given if feedback data are correct. In addition, future demands are subject to predictions and disturbances are mostly unpredictable, such as quality problems, breakdowns, unexpected maintenance, illness etc.⁵⁰. Thus, decisions have to be made quickly with limited information, which are often based on intuition and anticipations.

Therefore, further research on the LTS should consider human behavior and in particular cognitive biases in the decision-making process. The brief introduction into the research on human behavior revealed the strong influence of intuition on the decision-making process, which also includes judgment errors. Thus, further research is needed to derive guidelines in the field of production logistics that deal with the problem of cognitive biases. In scope of the LTS, further research is needed to specify the elements of a user interface of the potential visualizer in more detail (see Section 7.3). This also includes the next step of developing and implementing a functional software application that is tested in IT systems of manufacturing companies.

⁵⁰ See also Table 3.3 in Section 3.3.1 for an extended list of possible disturbances.

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Appendix

The attached DVD includes the datasets on which the presented results are based. The following list shows the structure of the folders that are saved on the attached DVD:

- Control model of planned lead time control
 - Simulink control model
 - Simulation feedback data
- Control model of capacity control
 - Simulink control model
 - Simulation feedback data
- Case study
 - Manufacturing feedback data
 - Master data
- Figures (PowerPoint)

The following code shows the implemented MATLAB function to calculate actual lead times in the control theoretic model of the LTS (see Section 4.1.2):

```
function [ leadtime ] = LeadTimeCalculation()
leadtime = 0;
j = 0;
load('KumOutF');      %Excel file that lists the total work out of each period
KumOutF = KumOutF';
k = size(KumOutF);
if k(1) > 0
    wo = KumOutF(k(1),2);
    load('KumInF');    %Excel file that lists the total work in of each period
    KumInF = KumInF';
    run = size(KumInF);
    for i = run(1):-1:1
        if KumInF(i,2)< wo
            j=(k(1)-i-1)/10;
            break
        end
    end
    leadtime = j;
else leadtime = 0;
end
end
```

Statutory Declaration

I, Mathias Knollmann, hereby declare that I have written this PhD thesis independently, unless where clearly stated otherwise. I have used only the sources, the data and the support that I have clearly mentioned. This PhD thesis has not been submitted for conferral of degree elsewhere.

Date

Mathias Knollmann