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Development of a Mathematical Model for the Calculation of the Tool Appropriation Delay depending on the Tool Inventory

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Compliance with punctual delivery under the high pressure of costs can be implemented through the optimization of the in-house tool supply. Within the Transfer Project 13 of the Collaborative Research Centre 489 using the example of the forging industry, a mathematical model was developed which determines the minimum inventory of forging tools required for production, considering the tool appropriation delay.

Keywords: production planning and controlling, production management, tool inventory reduction, operating resource management, forging companies.

1 INTRODUCTION

1.1 INITIAL SITUATION

In order to satisfy and to enable them to assert themselves in global competition, companies must continuously optimize their internal processes. The production's logistical performance, measured by adherence to delivery dates and order quantity with respect to the customer, is of essential importance in this case. Via the tool supply process for production in forging companies, the latter is directly depending on the logistics performance of the tool circuit, in which the forging dies are tested after employment, reprocessed and provided again in commissioned tool sets.

Forging companies are exemplified, because in comparison with other provided materials and operating resources for production, forging tools are goods with a high monetary value. Therefore, the stocking of a large number of tools leads to high circulating-stock costs. As a result of the high proportion of tool costs in the product costs, the logistic optimization of the tool supply in the forge industry carries a great potential for saving [Sil03].

In order to do this, positioning between logistics performance and tool circuit costs in an ideal manner is challenging. The tool-type-related tool inventory can be considered representative for the logistics costs. While too few tools can lead to more frequent equipping through distribution of the production lots and to associate increases in setup times of up to 30% in the production [Boh06], process uncertainties result from excessive tool inventory through the increase of the circuit throughput time and an increased scattering of the same [Mat77].

Another characteristic of tool circuits in the forging industry is a relatively short operating time compared to other process times. Furthermore, a production order can only be approved, if a complete lot of tools is provided by the tool appropriation.

Bearing in mind those characteristics, the results of this research can also be applied in other industries and stock inventory considerations, which focus on the improvement of the logistics performance and costs. Therefore, the surveyed stock has to meet similar requirements in order to allow a reasonable application of the developed model. It is important that the selected stock is flowing in a closed loop. Thus, the amount of objects circulating within main and support processes is constant while process delays in one loop of an item can cause further delays in subsequent loops. Besides, focusing on the logistics performance and costs, the selected stock also must have a high impact on the product costs itself or being time critical. Otherwise, there is no prior need in optimization of that inventory.

1.2 STATUS OF RESEARCH

SELAOUTI [Sel10, Sel11] describes the effect of a great number of influence variables on the tool availability. The simulation-supported and empirically developed method for the tool-type-related evaluation of the tool supply for more than one tool in forge companies represents an event-oriented modeling approach. In the model developed by SELAOUTI, the logistics performance is measured by the tool appropriation delay arising in production. The tool appropriation delay describes the timespan between nominal and actual appropriation deadline for a tool or a tool set. The costs, dependent on the tool inventory in the tool circuit, are used as a measure of the logistics costs. Furthermore, the model is adaptable to different general conditions and represents the dynamic system characteristics of the tool supply with the use of job-progress records. However, the high level of complexity and the large number of input parameters complicate an application in operational practice.

Further research studies in the area of the tool sector mostly pursue a very specialized objective. In this case it often involves complex planning and control methods implemented in software for the tool flow, which are adaptable to a limited degree only and register the tool circuit incompletely only [cf. Eve91, Fra10, Fu95, Gay87, Jen07, Kri95, Mar92, Mue04, Mum98, Pau92, Rom92, Zip94]. The most important of these research studies are presented below:

Thus, for example JENDOUBI [Jen07] describes a computer based information gathering concept on an operational equipment level, which acquires the status and position of tools. However, this equipment managing concept cannot be used to determine the necessary number of circulating tools. KRISHNASWANY [Kri95] on the other hand developed a tool management system for planning and scheduling adapted to the requirements of the automotive industry. It serves for work scheduling within a defined time horizon and accesses average process values. Since those values withstand a statistical variation and other influences are not included, the developed tool management system is not sufficient. There is also a parameter based information system for the operative and strategic use deduced by MARTENS [Mar92], which does not measure the temporal scope of the appropriation delay's impact und hence does not describe the relation between the tool stock inventory and the appropriation delay. Likewise, the measure catalogue for tool management by MUMM [Mum98] includes the analysis of influences on the tool supply and the current system state, but can also not be used to plan and control the tool supply. Another approach has been made by ZIPPER [Zip94] by developing a complex cross-departmental information technology system to avoid order throughput failures by misinformation. It does not enable the planer to evaluate planning decisions and also describes the tool circuit incompletely by not considering the tool making.

VRECER and CUS [Vre03] describe an ordering model for the tool transportation problem, wherein the planned tool consumption is determined by order scales. This model helps to minimize tool transportation and holding costs. However, a calculation of the tool appropriation delay depending on the number of tools in the circuit is not taking place.

VEERAMANI [Ver94] presents an integration of cutting-tool management in flexible machining systems. In order to minimize the tool inventory he proposes to classify tools by the number of times the tools in each group were used. On one hand this approach is oriented towards the past and on the other hand it is not possible to calculate the needed number of tools in the circuit.

The stock optimization of a single or a chain of operating systems can be modulated significantly and practically relevant by Logistic Operation Curves. Those curves have been developed with a deductive-experimental approach, which is verified by variety of simulations and industrial projects [Nyh09]. Still, there has been no application for the closed looped material flows. The tool supply in forging companies is only one example for a closed loop material flow, e.g. the circulation of production accessories for manufacturing or assembly processes, other materials or by-products, or a reworked and reprocessed product itself. Analysing those closed loops, the output of the material circuit impacts the input. Hence, an undersupply within the material circuit leads to self-enhancing material shortage in production, followed by a fast increasing loss of the logistical performance.

In science, there are a lot of capabilities and methods for the optimization of stock inventory. The creation of an optimization model represents one of these capabilities. However, these optimization models require a large number of constrains and in some circumstances more input parameters to calculate an optimum. Furthermore, the constraints are usually company-specific and thus cannot lead to generally valid solutions. Simulation models can also be used to optimize stock inventories in companies. These are, however, as well as the approaches of operations research, enterprise-related and their development and execution is very time-consuming.

As shown above, in science, there is no mathematical model which describes the interconnection between the number of tools in a tool circuit and the tool appropriation delay. Thus, there is a need for a practicable method to determine the ideal operation point between logistics performance (i.e. punctual availability of tools) and costs (i.e. tool stock costs).

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1.3 Objective

Due to these existing deficits, a deductive mathematical model was developed within the framework of the Transfer Project 13 of the CRC 489, which uses the example of the tool supply in forging companies to relate the appropriation delay and the stock inventory in closed loop material circuits. It assists in determining the optimum number of inventory in a material circuit like forging tools for production in a tool circuit. The model enables a practical application, since it is based on fundamental data, which already exists in operational practice. In addition, it is adaptable to special general conditions and influences in the tool circuit. Here, in order to guarantee the transferability and to avoid faulty interpretations of relationships and causality, already proven procedures and approaches are referred back to in case of the derivation.

2 Development of a Mathematical Model

The model aims at the description of the interconnecting effects between mean appropriation delay and the total number of tools in the circuit. For the derivation, the system considered is isolated and described. Then, based on that, the minimum inventory is derived for the tool circuit, as well as the connection is established between tool appropriation delay and number of tools. In advance to this, term delimitations are carried out and references are established for the basic theory.

In the following chapters, important terms are defined and basic literature on the matter is pointed to (cf. chapter 2.1). After that, the tool circuit is described as well as the assumptions that have been made during modelling, in particular of the tool issuing store and the components of its safety stock level (cf. chapter 2.2). Based on that model delimitation, the minimum tool inventory is induced step by step. After introducing the process caused inventory (cf. chapter 2.3.1), the inventory from influences is described with an overview of factors, which cause additional stock (cf. chapter 2.3.2). The inventory from storage (cf. chapter 2.3.3) is added with a focus on compensating deviations with a safety stock level. Afterwards, the derivation of the appropriation delay follows. It is structured in two parts, the derivation of the interconnection of the mean appropriation delay and the number of tools in the tool circuit itself (cf. chapter 4.1) and the application of the results for inventory optimization (cf. chapter 4.2).

2.1 Term Delimitation and References to Theory

The **status quantity** of a tool represents to the number of work pieces which can be produced with this tool in a defined quality. The total status quantity corresponds to the status quantity which exists during manufacture, up to the decommissioning of a tool. The employment status quantity is generated in the tool manufacture and reprocessing. The remaining status quantity corresponds to the status quantity before the employment of the tool in production, minus the status quantity required in employment.

Status quantities can be regarded as being distributed statistically. The nominal status quantity corresponds to the mean employment status quantity. The influence variables to be considered for the tool availability are the nominal status quantity and its scattering. They influence the employment, as well as the reprocessing frequency and the scope. Scattering of the status quantity arises either from the technology or through the in-service conditions, and lead to an inferior planning capability of the tool employment, as well as the reprocessing of tools. The reduced response capability resulting from this leads to increased tool inventories.

The **appropriation delay (AD)** of tools in the production (of forged work pieces) can be referred to as a measurement for a lacking tool supply. An appropriation delay always occurs when the tool issuing store cannot supply the production with tools. In this case, the actual output of the stock does not agree with the nominal output.

$$AD = stock\ output_{actual} - stock\ output_{nominal} \quad (1)$$

During the consideration of the appropriation loss a **differentiation between the logistics performance of the production of forged parts and the tool circuit** must be carried out. The reduction of the logistics performance in the tool circuit caused by excessive tool inventories and failures, as a result of the tool appropriation delay, directly affects the logistics performance of the production and also reduces it.

In the following, ideal and real conditions for the tool supply are differentiated. Under ideal conditions, the working systems in the tool circuit do not have to wait for orders and have sufficient capacities available for the processing of the orders. Thus, no waiting times arise. Furthermore, no deviations from the plan occur within the system, as a result of which the planned throughput time corresponds to the actual throughput time (TTP).

The applied tool circuit is modeled on the basis of a company survey of 27 companies of the German forge industry [Sel13] and with the aid of throughput elements [Nyh09]. Furthermore, for the illustration of the tool appropriation delay, reference is made to the existing delivery delay curves [Gla95] and the characteristic curve theory in general, as well as to the derivation of the ideal minimum inventory in case of production systems [Nyh09].

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2.2 System Delimitation

After the delimitation of elementary terms, this chapter focuses on the description of the tool circuit and its processes and storages as well as it outlines basic assumptions made during modelling. This includes especially the modelling of the tool issuing store and its safety stock level.

The tool circuit taken as a basis represents the individual processes with the aid of throughput elements (cf. Figure 1). Every element consists of throughput-time and interoperation time (TIO) elements. There exists a linear, directed material flow. For the purpose of simplification, in case of processes which consist of a series of linearly-concatenated sub-processes, the intermediate waiting times and the associated scattering are neglected.

For every special case of application, further simplifications can be applied for the tool circuit, such as e.g. the elimination of transit times for processes which are located in spatial proximity to each other. As for the modeling, a stable system is assumed, in which the capacity offer is adapted to the loading of the working systems. The decommissioning rate corresponds to the manufacture rate of new tools and thus, the number of tools in the system remains constant in a steady state.

The tool making contains of two processes "maintenance" and "reprocessing". Reprocessing is performed demand-independent after a certain tool undercuts a predefined respective threshold value (minimum permissible remaining status quantity). If the remaining status quantity is larger than the threshold value, only maintenance of the tool is performed.

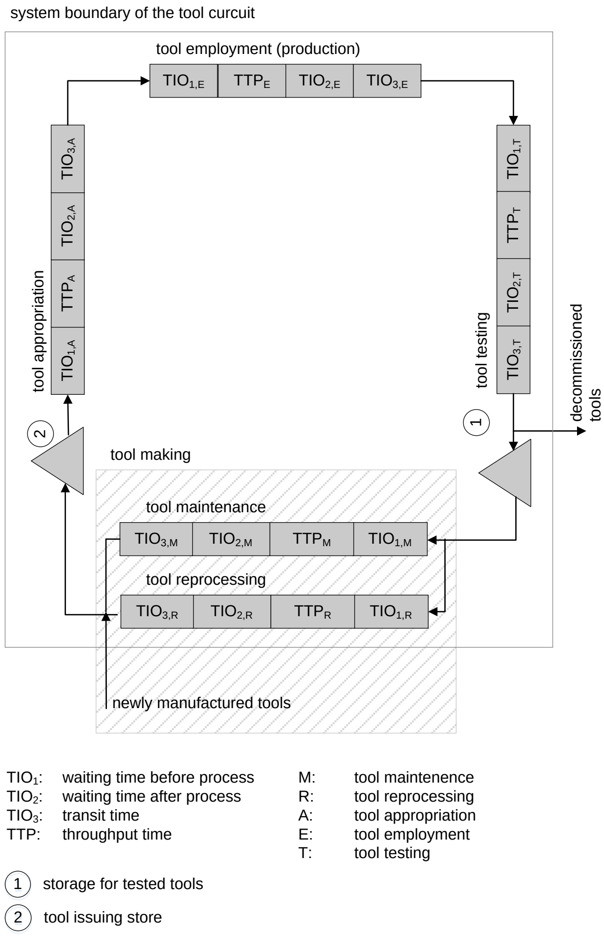

Figure 1: Modeled tool circuit

Scattered values of the tool status quantity of a technological nature (e.g. tool-work piece combination) can be neglected by the consideration of only one tool type and the specific processes and parameters associated with this. The nominal status quantity that is added to a tool of one tool type through reprocessing is also assumed as constant. Appropriation date and quantity variations for tools, which arise from scattering in orders in the production of the forged parts, are considered in the determination of the security stock level (SSL).

The number of tools to be provided for employment depends on the lot size of the production order and the status quantity of the tool. The tool issuing storage itself has continuous receipt of tools, however the issuing of tools takes place in lots of one or more tools or tool sets (cf. Figure 2). Under the assumptions made, it can be adopted that the input-goods rate from the tool making corresponds to the mean requirement rate.

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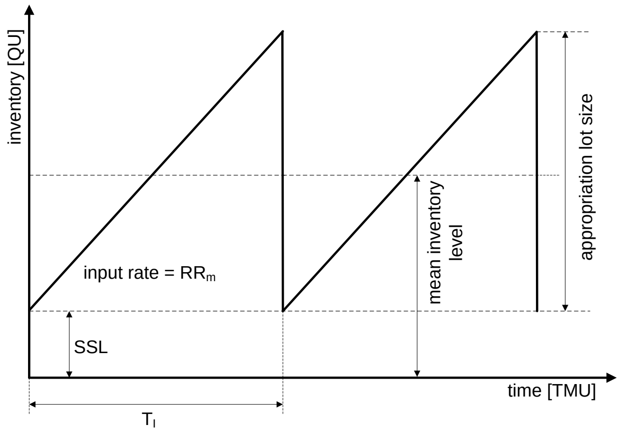


T_l: production cycle
RR_m: mean requirement rate of tools / tool sets
SSL: safety stock level
QU: quantity units
TMU: time measurement units

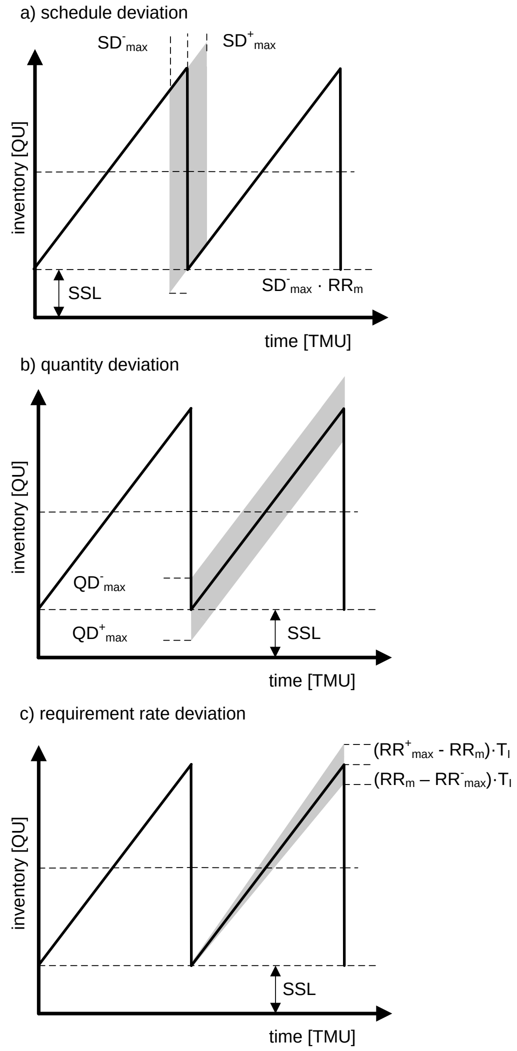
Figure 2: Modeling of the tool issuing store

Under ideal conditions, the tool issuing storage does not require any safety stock level, since no deviations from the plan occur in this case. Accordingly, the mean inventory in the tool issuing store ($I_{m,TIS}$) corresponds to half the appropriation lot size (Q_{app}). Under real conditions, however, following NYHUIS [Nyh09] the mean inventory is composed of the mean appropriation lot size as well as a necessary safety stock level.

$$I_{m,TIS} = \frac{Q_{appr}}{2} + SSL \qquad (2)$$

The safety stock level in the tool issuing storage enables the equalizing of deviations from the plan. These deviations from the plan can occur both incoming-sided as well as outgoing-sided and have the effect of reducing or increasing the stock level respectively (cf. Figure 3 and chapter 2.3.3). They can arise because of the following three reasons:

- As a result of new scheduling and rescheduling, the appropriation must be time-related postponed in the production (cf. Figure 3a).
- The number of tools required by the production varies, for example due to changes of the production quantities (cf. Figure 3b).
- The tool issuing storage is supplied with tools which are ready for action with a supply rate of the tool making deviating from the expected status (cf. Figure 3c).



SSL: safety stock level [QU]
SD^-_{max}: maximum negative schedule deviation of the tool requirement [TMU]
SD^+_{max}: maximum positive schedule deviation of the tool requirement [TMU]
QD^-_{max}: maximum negative quantity deviation of the tool requirement [QU]
QD^+_{max}: maximum positive quantity deviation of the tool requirement [QU]
RR^+_{max}: maximum positive requirement rate deviation of tools [QU/TMU]
RR^-_{max}: maximum negative requirement rate deviation of tools [QU/TMU]
RR_m: mean requirement rate in tools [QU/TMU]
T_l: duration of a production cycle [TMU]
TMU: time measurement unit
QU: quantity unit

Figure 3: Deviations from the plan in the goods incoming and outgoing of the tool issuing store

2.3 DERIVATION OF THE MINIMUM TOOL INVENTORY

Based on that model delimitation, the minimum tool inventory is deduced in this chapter. In a first step, inventory from process is recognized (cf. chapter 2.3.1). Then the inventory from influences is summed up including an overview of factors, which cause additional stock (cf. chapter 2.3.2). The inventory from storage (cf. chapter 2.3.3) is added afterwards with a focus on compensating deviations with a safety stock level.

The derivation of the minimum inventory of tools for the tool circuit ($I_{min,tools}$) is implemented assuming an ideal tool supply and is attributed to the interconnections for the ideal minimum inventory in work centers in the production [Nyh09]. With a sequence of i processes, e.g. of tool maintenance or tool reprocessing, and k storage areas in the tool circuit, it is defined as the sums of the individual minimum inventories ($I_{min,pro,i}$ and $I_{min,sto,k}$). Tool inventories related to j further (external) influences ($I_{min,inf,j}$) are added, such as e.g. scattering of the sojourn times in the tool issuing store through the tool selection principle.

$$I_{min,tools} = \sum I_{min,pro,i} + \sum I_{min,inf,j} + \sum I_{min,sto,k} \quad (3)$$

2.3.1 Minimum Inventory from Processes

The tool circuit, as described above, does not indicate any waiting times under ideal conditions (cf. e.g. Figure 1: $TIO_{2,M}$). However, as well as the actual processing times, non-negligible times, such as e.g. transit times must also be considered. The required minimum inventory of tools for a process i is calculated as the product of minimum process throughput time ($TTP_{min,i}$) and the mean requirement rate (RR_m).

$$I_{min,pro,i} = RR_m \cdot TTP_{min,i} \quad (4)$$

2.3.2 Minimum Inventory through Influences

As well as process-related minimum inventories, further minimum inventories result, which arise from non-negligible influence variables, such as e.g. the scattering of the transit times in the tool making, as well as through increases of the throughput time in the tool making caused by the tool selection principle. These are considered by the resulting time contents analogous to the process-related inventories (cf. scattering content of minimum inventories in [Nyh12]).

In his dissertation, Selaouti [Sel13] gives an overview of influences on the appropriation delay, which includes the variation of the throughput times of the cycle, but also tool specific tribological influences, as well as influences on the systems' offered capacity. The following passages outline, whether and how the single influences were considered in the model.

The variation of the throughput time in the tool circuit can be reduced to the variation of the throughput time in tool reprocessing on one hand and variations of transit times on the other. The reprocessing of tools is modelled independently of the demand. It is performed for tools that come below a fixed tribological limiting value. Under ideal conditions, there are no variations in reprocessing throughput time. If the times vary significantly under real conditions, they have to be included into the model statistically. Variations of the transit times between the single reprocessing steps on the other hand are neglected, because a continuous flow is assumed. But variations in the tool making order can have an influence on the throughput time. The resulting varying lay times lead to varying transit times and thus, have to be considered (consideration of the variation of the mean transit time).

In case of tool specific reprocessing, there can be variations in the tool operating life. The tool operating life is depending on the wear of the tool and denoted as the number of tool operations (per work piece) until the tool has to be reprocessed. It is assumed that the technological influence (used material, tool and work piece combination, tolerances and surfaces, processes) on the tool operating life is constant and therefore irrelevant due to the analysis of one specific tool type.

The influence of schedule variations as well as appropriation date and quantity variations is considered in the safety stock level.

2.3.3 Minimum Inventory for Storage

The minimum inventory of tools in storages of the whole tool circuit results from the sum of the minimum inventories for the individual storage areas. In the above-represented tool circuit, these are the tool issuing storage as well as the storage of the status test.

$$\sum I_{min,sto,k} = I_{min,TIS} + I_{min,ST} \quad (5)$$

With consideration of the minimum inventory of the tool issuing storage, ideal and real conditions must be differentiated between. As follows from Equation 1, the mean inventory in the tool issuing storage ($I_{m,TIS}$) corresponds in the ideal status to half the appropriation lot size. The stock in the status test is neglected under the assumptions made.

Under real conditions, on the other hand, the tool issuing storage must carry a safety stock level, in order to temporarily compensate deviations from the plan. Due to the deviations from the plan, stock-reducing or stock-increasing effects can arise incoming-sided and outgoing-sided [Nyh09] (cf. Figure 3).

Schedule deviations in the outgoing goods of the tool issuing storage arise e.g. from order rescheduling in production (cf. Figure 3a). If the maximum possible schedule variation of the too-early tool request occurs, the storage must have more tools in reserve at this time in order to balance the time-related deviation over the safety stock level. The number of additionally required tools in this case results from the maximum negatives, i.e. too early schedule deviation and the rate with which the tools required by the tool making are provided. Under the assumptions made, this access rate corresponds to the mean requirement rate. The safety stock level caused through schedule deviations is as follows:

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$$SSL_{SD} = SD^{-}_{max} \cdot RR_m \tag{6}$$

A further possible goods outgoing-sided deviation from the plan is the deviation of the appropriation quantity. This is caused by requirement variations in the production (cf. Figure 3b).

The safety stock level caused through quantity deviations must correspond to the maximum deviation of the requisition quantity:

$$SSL_{QD} = QD^{+}_{max} \tag{7}$$

A further deviation from the plan can be implemented at the incoming goods' side through fluctuations of the requirement rate of the tool making in the overall observation period (cf. Figure 3c). The required safety stock level for the compensation of fluctuations of the requirement rate results from the difference between mean and minimum requirement rate, multiplied by the order time (TO) for the manufacture of the tool:

$$SSL_{RD} = (RR_m - RR_{min}) \cdot TO \tag{8}$$

For the calculation of the total safety stock level, it is assumed that the considered deviations from the plan are statistically independent. In other words, the mean stock inventory is dependent on the schedule deviation, the quantity deviation and the requirement rate deviation of the production. The maximum impact of each influence is considered in the corresponding safety stock levels (equations 6-8). Statistical speaking, the above mentioned deviations can be considered as uncertainties (also errors). These effects can reinforce but also compensate each other [Nyh09]. Based on statistics, the total safety stock level must consider the occurrence of all deviations from the plan. Therefore the following association can be established for the total safety stock level (see [Sac03]):

$$SSL = \sqrt{SSL_{SD}^2 + SSL_{QD}^2 + SSL_{RD}^2} \tag{9}$$

2.4 Tool Appropriation Delay

In the preceding section, the derivation of the minimum inventory of tools in the total tool circuit was demonstrated. In the following, a quantitative interconnection between the inventory actually present in the tool circuit and the tool appropriation delay resulting from this is derived. In a first step the derivation of the appropriation is deduced by describing stockout quantity areas and stock inventory areas geometrically in the throughput diagram. The resulting equation and curve for the appropriation delay is then described and its application possibilities for optimization are explained.

2.4.1 Derivation of the Appropriation Delay

The mean tool appropriation delay (AD_m) is defined as the relationship of the stockout (A_{SO}) and the total number of tools provided ($Q_{app,total}$) in an observation period:

$$AD_m = \frac{A_{QL}}{Q_{app,total}} \tag{10}$$

Based on the geometrical relationships (cf. Figure 4), stockout- and stock inventory areas can be considered in the throughput diagram of the ideal tool issuing storage for the derivation of the mean tool appropriation delay (cf. [Gla95]). The throughput diagram of the tool issuing storage is used for this, in which both the input curve, as well as the outgoing goods curve, are plotted (cf. Figure 4).

The stockout quantity area and stock inventory areas for a production cycle T_I in the interval $0 \le x \le T_I$ are determined by means of the control variables x (measurement for the overlap of the input and appropriation curve). For that reason, simple geometrical relationships are applied. The area A of a right-angled triangle corresponds to the half of the product of the right-angled triangle legs (a and b).

$$A = \frac{a \cdot b}{2} \tag{11}$$

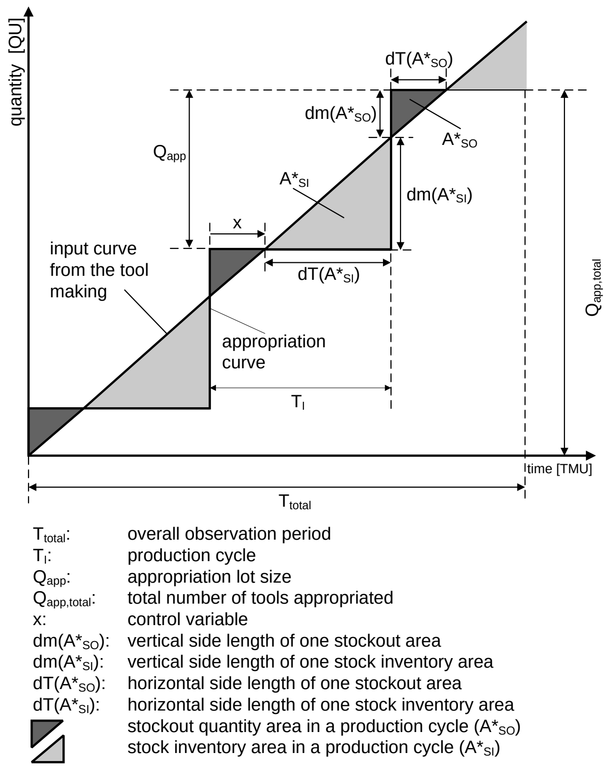


Figure 4: Geometrical relationships in the throughput diagram of the tool issuing store

Both for the individual stockout area A_{SO}^*, as well as for the individual stock inventory area A_{SI}^* the side length can be read off in horizontal direction directly from Figure 4. For the stockout area A_{SO}^*, it corresponds to:

$$dT(A_{SO}^*) = x \quad (12)$$

For the stock quantity area A_{SI}^*, it corresponds to:

$$dT(A_{SI}^*) = T_I - x \quad (13)$$

The side length in the vertical direction can be determined over the known slope m of the stock receipt lines. This corresponds to:

$$m = \frac{Q_{app}}{T_I} \quad (14)$$

Thus, for the side length of the triangle in the vertical direction of the stockout area A_{SO}^* follows:

$$dm(A_{SO}^*) = \frac{Q_{app} \cdot x}{T_I} \quad (15)$$

And for the stock inventory area:

$$dm(A_{SI}^*) = \frac{Q_{app} \cdot (T_I - x)}{T_I} \quad (16)$$

With the aid of Equation 11, as well as the values for dT and dm from the Equations 12 and 15, the size of the stockout area finally is:

$$A_{SO}^* = \frac{Q_{app} \cdot x^2}{2 \cdot T_I} \quad (17)$$

Analogous to this, the stock inventory area can be calculated with by means of the Equations 13 and 16:

$$A_{SI}^* = \frac{Q_{app} \cdot (T_I - x)^2}{2 \cdot T_I} \quad (18)$$

For the overall observation period T_{total} $(= T_I \cdot n)$ with n equally long continuous production cycles, the stockout area A_{SO} is:

$$A_{SO} = A_{SO}^* \cdot n = A_{SO}^* \cdot \frac{T_{total}}{T_I} \quad (19)$$

Furthermore, the assumption can be made that the mean inventory corresponds to the inventory in the tool issuing storage $I_{m,AS}$ in the ideal status during a production cycle:

$$I_{m,WIS} = \frac{A_{SI}^*}{T_I} \quad (20)$$

Thus the inventory-dependent appropriation delay follows from Equations 10 and 17-20 in Equation 21:

$$AD_m = \frac{T_{total}}{Q_{app,total}} \cdot \left(\frac{Q_{app}}{2} + I_{m,TIS} - \sqrt{Q_{app} \cdot 2I_{m,TIS}}\right) \quad (21)$$

for:

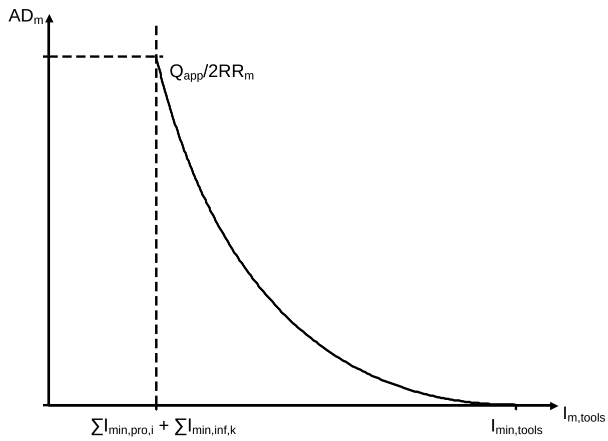
$$0 \leq I_{m,TIS} \leq \frac{Q_{app}}{2}$$

As shown, Equation 21 establishes a connection between mean tool appropriation delay and the inventory in the tool issuing storage. However, the objective of the research project is to represent the appropriation delay dependent on the tool inventory in the overall tool circuit. The connection between mean tool issuing storage level $I_{m,WIS}$ and the minimum inventory of tools in the tool circuit $I_{min,tools}$ is used for that (cf. Equation 3). It follows:

$$AD_m = \frac{1}{RR_m} \cdot \left(\frac{Q_{app}}{2} + \sum I_{min,sto,k} - \sqrt{Q_{app} \cdot 2\left(I_{min,tools} - \sum I_{min,pro,i} - \sum I_{min,inf,k}\right)}\right) \quad (22)$$

The characteristic curve resulting from this for the mean appropriation delay is represented in Figure 5. It has a zero point with a tool inventory of $\sum I_{min,pro,i} + \sum I_{min,inf,k} + \frac{Q_{app}}{2}$, which corresponds to the tool minimum inventory in the circuit ($I_{min,tools}$) under ideal conditions. It does not cut the Y-axis, since it is not defined for inventories below $\sum I_{min,pro,i} + \sum I_{min,inf,k}$.

The derivation of the appropriation delay is based on ideal conditions for simplification. Hence, under real condition the safety stock level has to be added to the minimum tool inventory. This results in a shift of the curve along the X-axis by the magnitude of the safety stock level. Apart from that, there is no impact on the curve.



AD_m:	mean appropriation delay
$I_{m,tools}$:	mean tool inventory in the tool circuit
Q_{app}:	appripriation lot size
RR_m:	mean requirement rate of tools / toolsets

Figure 5: Interconnection between mean appropriation delay and the number of tools in the tool circuit

2.4.2 Application of the Appropriation Delay Curve

The developed curve can be used to determine the minimum tool stock inventory, in which no appropriation delay occurs. . In case of a higher tool stock inventory, an appropriation delay does not occur, however, there are also high costs related to the higher inventory. Starting at that point, a first optimization can be made by reducing the tool stock to the minimum inventory (see Figure 5: zero point of the curve). This leads to lower costs while maintaining the same logistical performance.

Additionally, a production planer can use the curve to determine the occurring appropriation delay at a certain tool stock. This can be used for further optimization:

As seen above, the calculated minimal tools stock inventory can be a decimal. In order to avoid appropriation delay, the calculated number of tools always has to be rounded up to the next whole number. Hence, the determined minimal tool stock inventory is higher than the actually needed inventory for a delay free appropriation of tools. Because the slope of the curve is relatively low near the zero point, the appropriation delay is comparably small for a reduction of a single tool. Therefore, it can be considered to reduce the inventory on purpose and accept a slight delay, which will be compensated by other scheduled times (e.g. idle times).

Another reason to reduce the amount of tools can apply for a production mix with different product variants that need different tool types. In that case the interval for the appropriation extends by the change of the variant. Besides that, production control measures, like using a one-piece-flow in appropriation instead of the assumed lot-by-lot basis, can also extend the interval till the next appropriation. The planer can determine this interval exactly in both cases and reduce the tool stock inventory by equalizing the interval with the measured appropriation delay.

3 Conclusions

In this article the development of a mathematical model was presented, which represents the connection between mean appropriation delay and the number of tools in a tool circuit.

With the aid of the model, the minimum inventory of tools required for the production can be determined and the effects of an inadequate tool supply as a result of tool appropriation delay can be assessed. The subsequent adaptability and transferability of the model to changed conditions in the tool circuit are enabled by the general formulation of the characteristic curve for the description of the mean appropriation delay. The modeling of the tool issuing storage under real conditions, with inclusion of deviations from the plan, considers the required safety stock level of tools.

The model represents the first part of a higher-level, deductive-experimental evaluation method, which assesses the logistic performance capability of tool supply in forge companies. The higher-level objective is to develop a method for employment in business practice which allows an assessment of the processes of the tool supply with regard to the pursued monetary and logistic target variables.

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