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Anticipatory Inventory Management For Realizing Robust Production Processes In Engineer-To-Order Manufacturing: A Modeling Approach

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Abstract

At ever shorter intervals, manufacturing and processing companies of all industries are confronted with external or internal disruptions and crises that need to be managed. Consequently, a corporate focus on robust supply chains and processes is essential. At the same time, crises and their impact on supply chains cannot be predicted. To be able to act anticipatively, it is necessary to link product and production system design to take suitable measures to safeguard production at an early stage. In this context, a monetary conflict of objectives arises concerning when a company should position itself robustly and when it is sufficient to react flexibly to disruptions. The production planning and control (PPC) task inventory management is an essential lever for realizing robust order fulfilment processes. Inventory management aims to ensure that production and assembly within the company are supplied in the right quantities and without lateness. In particular, companies that operate according to the engineer-to-order strategy (ETO) face specific challenges in dimensioning stocks for materials or components - for example, due to the low level of standardization or lack of supplier diversity. This paper presents an approach for anticipatory inventory management using product portfolio characteristics. A new modeling approach for dimensioning safety stocks under the increasing influence of crises is also developed and integrated into the process.

Keywords

Production planning and control (PPC), Inventory Management, Safety stock, Robustness, ETO

1. Introduction

Increasing dynamics and volatility in the global business environment lead to rising uncertainties for companies in every sector. As a result, future market developments and resulting supply chain disruptions are more challenging to anticipate and cannot be predicted with sufficiently accurate probability. [1,2] Companies must therefore create robust processes which, despite these developments, enable on-time deliveries to customers and, in turn, sustainable competitiveness. In recent years, the planning and design of supply chains have been primarily characterized by cost optimization and profitability [3]. Current crises (e.g., the COVID-19 pandemic, the Suez Canal blockage, and uncertainty in the financial markets) illustrate how unpredictable the business environment is becoming and how susceptible the widely interlinked supply chains react to such disruptions. Additionally, companies are being affected by crises/disruptions and associated material shortages with increasing frequency and intensity [4]. This poses particular challenges for ETO-manufacturer (e.g., Aircraft or shipbuilders). The high level of customer influence throughout the production process leads to additional uncertainties [5] and requires close cooperation with suppliers. In some cases, joint development and design work is

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carried out with suppliers, which must have appropriate certifications (e.g. regarding safety and quality). In crises, therefore, manufacturers cannot necessarily switch suppliers to counteract supply bottlenecks. At the same time, stocking certain materials or components for complex products is associated with high costs. These constraints require a closer link between the early development phase and production system design, including procurement and production planning and control (PPC). An important task within the PPC is inventory management. The main challenge is dimensioning the safety stock depending on the service level to be realized. Safety stocks are considered suitable for avoiding supply bottlenecks [6]. Since crises/supply chain disruptions cannot be predicted, it is hardly possible for companies to realize necessary inventory increases in time. This paper defines anticipatory inventory management as a link between product and production system design. It enables companies to identify materials/components in early planning phases that require higher risk hedging, e.g., through higher stock levels, due to their high importance regarding complexity, price, or multiple uses. Previous approaches hardly examine how the product structure or standardization characteristics influence the decision regarding safety stock dimensioning [4] and how companies can assess potential delivery quantity deviations logistically and economically during crises [7].

This paper develops an approach to mathematically model delivery quantity deviation as a safety stock component. This model is integrated into an analysis procedure that supports companies in selecting materials for which robust inventory dimensioning is appropriate. Section 2 presents the state of the art for safety stock dimensioning. In Section 3, the research methodology used is described. Section 4 describes the mathematical model for dealing with delivery quantity deviations and the analysis procedure for anticipating inventory management before Section 5 provides a summary and outlook for future research activities.

2. State of the art

2.1 Fundamentals of stock dimensioning to deal with uncertainties

Various properties of production systems for dealing with uncertainties exist. The property of robustness aims to avoid disturbances from the outset. In the case of unexpected disruptions, robustness will minimize the influences in such a way that the functionality of the production system is maintained. [8,9]. In contrast to the reactive resilience strategy, robust stock sizing is a proactive strategy since the system is designed anticipatively - i.e., before a disturbance - so that corresponding properties take effect when the disruption occurs [10]. For example, multiple-sourcing strategies are generally more robust than single-sourcing strategies. In the case of a supplier breakdown, the entire supply chain is not jeopardized since if the other suppliers for this material remain able to deliver, production can continue at least for a certain time without any significant loss of performance [11].

Robust production systems are insensitive to external and internal influences and thus continue to perform in the event of unexpected disruptions [8,12]. One important supply chain element for absorbing these influences are warehouses, which enable decoupling in terms of time and quantity and supply subsequent processes with materials, semi-finished products, or tools. Inventory dimensioning focuses on the trade-off between low inventory costs (e.g., resulting from capital commitment and floor space costs) and a high level of service. The service level indicates the share of demand the available stock can serve in terms of quantity and time [13,14]. The basis for the approaches of stock dimensioning described below is the general REFA inventory model, which represents the stock development of an article or material over time. The safety stock is used to achieve a high level of service despite deviations from the plan concerning dates, quantities, and requirements [7]. The dimensioning of the safety stock is based on three essential components, shown in Figure 1 [15].

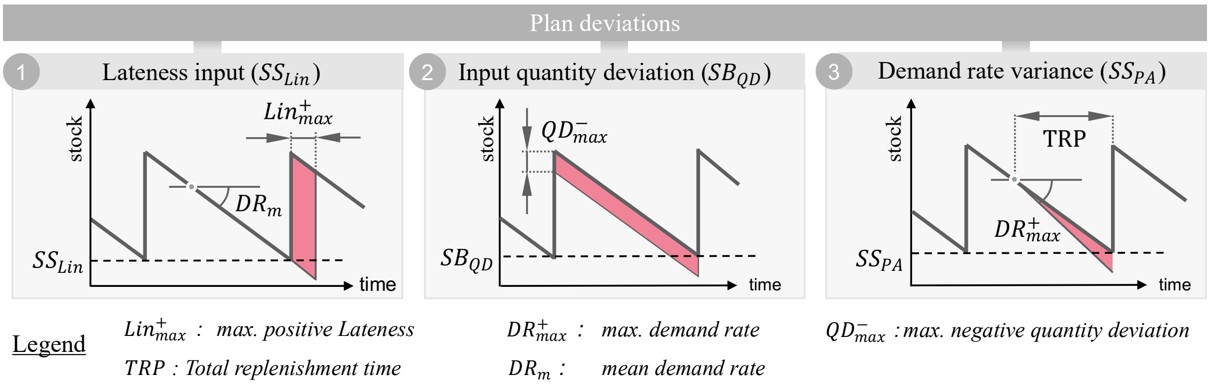


Figure 1: Three components for dimensioning the safety stock due to plan deviations

The first component takes into account schedule deviations in stock inbounds. Here, the stock is increased to such an extent that the demand can still be met for the duration of the maximum positive input lateness (Lin^+_{max}). **The second component** focuses on the quantity deviation from the planned input to the warehouse. The safety stock required for this (QD^-_{max}) results from the maximum negative quantity deviation to be assumed. **The third component** of the safety stock represents demand rate deviations that occur within the replenishment time. For this purpose, the difference in the maximum demand rate deviation $DR^+_{max}$and the mean demand rate (DR_m) is formed. Given that the individual components can add up and compensate, which is the case if stochastic independence is assumed, the minimum safety stock is calculated according to formula 1 [7]. BECKER evolves this formula by taking into account seasonal fluctuations in demand or offtake rates [16] so that a time-dynamic calculation of the safety stock is possible.

$$SS_{\min} = \sqrt{(Lin^+_{max} \cdot DR_m)^2 + (QD^-_{max})^2 + ((DR_{max} - DR_m) \cdot TRP)^2} \qquad (1)$$

$$SS_{min,i} = \sqrt{\left(\sum_{t=i+1+TRP}^{i+TRP+Lin^+_{max}} DF_t\right)^2 + \left(QD^-_{max}\right)^2 + \left(FD^+_{max} \sum_{t=i}^{i+TRP} DF_t\right)^2} \qquad (2)$$

with

$SS_{min,i}$	Minimum safety stock at the time i / QTY
Lin^+_{max}	Maximum positive lateness to be assumed / SCD
QD^-_{max}	Maximum negative delivery quantity deviation to be assumed / QTY
FD^+_{max}	Maximum positive forecast deviation to be assumed / %.
DF_t	Demand forecast for the time t / QTY
TRP	Total Replenishment time / SCD

2.2 Approaches to take into account product structure properties in safety stock dimensioning

The literature review by GONÇALVES ET AL. shows that only a few relatively old papers deal with how product structures and standardization affect the dimensioning of stock [4]. COLLIER develops a formula for safety stock calculation that considers an analytical metric based on the bill of materials (BOM) to measure the degree of commonality in a product family. This formula was validated using simulation. The results indicate that increasing the degree of component commonality leads to lower safety stocks while maintaining the same service level [17]. GRUBBSTRÖM'S approach aims to determine a safety stock in the case of demand uncertainty for planned production flows in single-stage product structure systems. The annuity flow is used as the evaluation criterion instead of the usual average cost approach [18]. CARLSON AND YANO calculate a heuristic upper bound for safety stock dimensioning for each component of a product structure with periodic and replanned production schedules under stochastic demands. Using simulation, the authors demonstrate the approach's potential by comparatively evaluating different stock levels using the inventory cost criterion. In another paper, the authors investigate how the frequency of replanning affects safety stock decisions for a single product and its product structure. [19,20] In developing their solution, PERSONA ET AL. consider the benefits of modular product design and Super-BOMs, which were created by combining multiple BOMs of similar products. In the paper, cost-based analytical models are developed, evaluated, and applied to quantify the optimal safety stock for modular subassemblies and components. In doing so, the authors focus on the requirements of a make-to-order and assemble-to-order strategy [21]. The approach developed by HERNÁNDEZ ET. AL. also deals with calculating and reducing safety stocks for modular product structures in the context of make-to-order strategies. In addition to safety stock reduction by commonality in modules and components, a substitution factor revised from group technology theory is also considered. Using fictitious examples, different scenarios for inventory dimensioning are tested (e.g. with and without high commodity), and it is shown that safety stocks could be reduced by applying the developed model [22]. The literature analysis shows that only a few approaches deal with the interface of product and production system design. None of the methods considers the three components of the safety stock (cf. section 2.1) and focuses on modeling quantity deviations due to increasing disruptions.

3. Research Methodology

The variety of interdependencies and the technical and organizational influencing factors that must be considered while integrating predictive inventory management into ETO production require a model-based approach to structure and solve the problem. A deductive-experimental research approach was chosen to develop a generally applicable model for inventory dimensioning. In doing so, argumentative-deductive analysis achieves inferences from issues or facts through reasoned argumentation. The research is construction-oriented and qualitative. The hypotheses created about specific real-world points using deduction will then be examined by observations and experimentations to confirm or disprove them. (cf. [7]). If the limits of analytical methods have been reached, if complex cause-effect relationships are involved, or if experiments on the real object of investigation are challenging to perform, experiments can be carried out with the help of simulations. The results presented in this paper are based on the deductive modeling approach. An experimental investigation of the interrelationships is focused on in following papers.

4. Anticipatory inventory management for ETO processes

4.1 Modeling assumptions

Section 2 shows the components of the safety stock for static and dynamic cases. The impact of delivery date variances is related to inventory inputs, and the effect of demand rate or forecast variances is connected to inventory outputs. Quantity deviations as an additional safety stock component should only be considered if the replenishment time is higher than the period between two planned deliveries. [7] The modeling approach presented in this paper is based on the assumption that if a crisis occurs, the availability of certain materials is abruptly reduced while demand remains constant. If the availability of materials decreases, suppliers may no longer be able to deliver the contracted quantity of materials within a specified replenishment time. As a result, at certain measurement times after the crisis has occurred, there are deviations in the delivery quantities of materials that are affected by the corresponding bottleneck situation and, therefore, cannot easily be compensated by subsequent deliveries, e.g. from other suppliers. In that case, companies whose safety stocks were already replenished in adequate quantities before the first signs of demand availability problems will realize a higher service level for a more extended period in the event of supply shortfalls. For anticipatory dimensioning of safety stocks, business parameters such as increased storage costs or loss of revenues due to opportunity costs must be considered when determining the added value of an early increase in safety stock.

4.2 A mathematical model for robust dimensioning of safety stock as a result of crises

To make crisis-related inventory adjustments, it is generally not necessary to anticipate the exact time a crisis will occur. Instead, it should be determined how many and which deliveries (cf. section 4.2) could be affected by the availability problems. Therefore, it is essential to make accurate predictions about the length of the crisis and the number of deliveries that occur during the crisis. Furthermore, similar to the demand forecast from BECKER'S approach (see section 2.2), it must be predicted how significant the quantity deviations of the deliveries will be during the crisis. If this can be estimated separately for each delivery, a more accurate calculation of the costs arising from the safety stock increase can be made. However, the method is only effective if the average deviation values in delivery quantity are calculated. If the crisis impacts many deliveries, an average value simplifies the calculations significantly.

The number of affected deliveries is calculated from the estimated duration of the crisis and the time between two deliveries or the original replenishment time. All deliveries between the last complete delivery before the occurrence of the crisis and the first full delivery after the occurrence of the crisis are considered affected deliveries:

$$n_c = \left\lceil \frac{D_c}{TRP} \right\rceil \tag{3}$$

With	n_c	Number of deliveries affected by crisis *c*
	D_c	Expected duration of the crisis *c* / SCD (supply calendar days)
	TRP	Replenishment time / SCD

The minimum theoretical safety stock level is the cumulative shortfall forecast over the crisis duration. These can be determined both via the averaged forecast quantity deviations of individual deliveries and via the forecast availability level:

$$SS_{QD,c} = \sum_{l=1}^{n_c} p_{QD^-,l} \quad = D_c \cdot DR_m \cdot (1 - p_{a,c}) \tag{4}$$

With	$SS_{QD,c}$	Component of safety stock due to quantity deviations resulting from crisis k / QTY
	DR_m	Mean demand rate / QTY per SCD
	$p_{QD^-,l}$	Predicted negative quantity deviation from delivery l / QTY
	n_c	Number of deliveries affected by crisis c
	D_c	Expected duration of the crisis c / SCD
	$p_{a,c}$	Mean availability forecast of the affected item for crisis c / %.

The safety stock component calculated in this way represents the quantity of a material/article by which the safety stock must be increased before the crisis occurs to survive the crisis without reducing the service level. The safety stock component calculated in equation (3) considers the shock's intensity and duration of the availability crisis. In principle, it can be assumed that no two crises are alike. Furthermore, a crisis does not necessarily have identical effects on companies. For example, particularly cooperative relationships with a supplier can mean that a company can better overcome a crisis than other competitors. The impact of crises on the procurement situation of a company must be understood as a multi-factorial result, which must be analyzed separately for each crisis. Therefore, the theoretically necessary safety stock component $SS_{QD,c}$ (see formula 3) is extended by four additional factors. The **adjusted** safety stock component is calculated with consideration of all factors as follows:

$$\widetilde{SS}_{QD,c} = SS_{QD,c} \cdot F_O \cdot \frac{F_R}{F_I} \cdot F_A \tag{5}$$

With	$\widetilde{SS}_{QD,c}$	Adjusted component of safety stock due to quantity deviations resulting from crisis k / QTY
	$SS_{QD,c}$	Unadjusted component of safety stock due to quantity deviations resulting from crisis k / QTY
	F_O	Factor for the probability of occurrence
	F_R	Factor for the relative order quantity
	F_I	Factor for the importance of the order/customer
	F_A	Factor for alternative procurement options and the procurement strategy

The **factor probability of occurrence** of the crisis indicates the extent to which the forecast delivery quantity deviations are actually to be expected. The second factor is the **size of the order quantity**. The larger the order quantity, the greater the probability that delivery will not be complete in the event of availability problems. In this context, **the customer's economic or strategic importance or the supplier's order** must be considered as a factor, too: As a rule, customers who regularly purchase large quantities are of greater importance than customers whose order quantity is significantly smaller. The supplier, therefore, endeavours to serve large orders as fully as possible to ensure the satisfaction of essential customers. Given the factor described above, customers whose vast order quantities should receive as complete deliveries as possible. However, this isn't easy to achieve precisely because of the large quantities involved. In times of availability problems, other customers may no longer be able to be supplied. In contrast, smaller purchase orders from customers of lesser economic importance can be served more readily. It can therefore be assumed that these effects offset each other to a certain extent (see formula 4).

In addition to the factors already mentioned, it must be examined **which procurement strategy** is being pursued and to what time alternative procurement options can be activated for the article concerned. In the most unfavourable scenario for the company F_O, F_A and the ratio $\frac{F_R}{F_I}$ assumes the value 1. In this case, the necessary adjusted safety stock ratio $\widetilde{SS}_{QD,c}$ corresponds precisely to the forecast shortfall $SS_{QD,c}$. accumulated throughout the entire crisis. The necessary safety stock component is reduced if at least one factor is smaller than 1. As a result, the theoretically required safety stock percentage calculated based on intensity and duration cannot increase any further, taking equation (4) into account. In order to determine these factors for the respective (crisis) situation, an evaluation table can be used as a decision-making aid based on the factor evaluation within the framework of a Failure Mode and Effects Analysis (FMEA).

To integrate the determined safety stock component $\widetilde{SS}_{QD,c}$ into equation (2), it must first be noted that the forecast and delivery date deviations components refer to the following replenishment time. $\widetilde{SS}_{QD,c}$, on the other hand, refers to a crisis that occurs within the following replenishment time. However, the determined inventory share refers to the duration of this crisis, which can cover several replenishment times. If $\widetilde{SS}_{QD,c}$ should be used for QD_{max}^{-} in equation (2), this would result in the compensation effects of geometric addition only acting on the additional quantity deviation-related safety stock level required in the first replenishment time, so an excessively high safety stock level would be calculated. Therefore, it is necessary to consider the compensation effects for the entire crisis period. If it were possible to replenish the safety stock during the crisis, the safety stock required at the beginning of each replenishment period would be calculated according to equation (5). This requires demand forecasts for the entire crisis period. These are then assumed to remain constant during the crisis period.

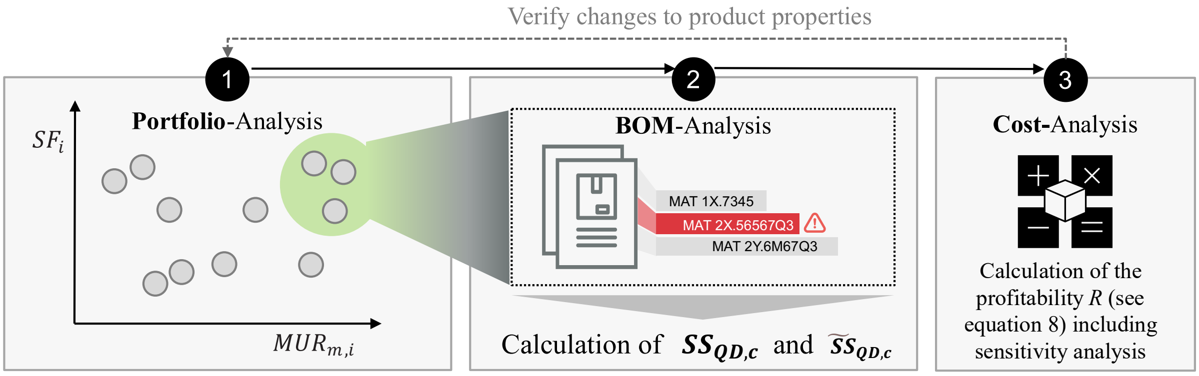
$$SS_{min,i} = \frac{1}{n_c}\sqrt{(n_c \cdot \sum_{t=i+1+TRP}^{i+TRP+Lin^{+}_{max}} DF_t\,)^2 + (\widetilde{SS}_{QD,c})^2 + (n_c \cdot FD^{+}_{max} \sum_{t=i}^{i+TRP} DF_t\,)^2} \tag{6}$$

With

$SS_{min,i}$	Minimum safety stock at the time i / QTY
Lin^{+}_{max}	Maximum positive lateness to be assumed / SCD
$\widetilde{SS}_{QD,c}$	Adjusted component of safety stock due to quantity deviations resulting from crisis c / QTY
DF_t	Demand forecast for the time t / QTY
FD^{+}_{max}	Maximum positive forecast deviation to be assumed / %.
TRP	Total Replenishment time / SCD
n_c	Number of deliveries affected by crisis *c*

4.3 Procedure for anticipatory inventory management

In designing, planning, and controlling production systems, ETO manufacturing focuses mainly on the product. Decisions in the context of product development are primarily made for design- or customer-oriented reasons. The challenges this creates in the individual production stages, assembly, or procurement and provision are only considered to a limited extent. The realization of a high logistic performance (e.g. a high service level in the warehouse) is thus made more difficult. The three-stage procedure developed here (see figure 2) starts at this point and focuses on the interface between driver variables of the product structure and inventory dimensioning.



Legend

$MUR_{m,i}$:	*Mean degree of multiple use of the material numbers of product i / -*
SF_i:	*Sales forecast for product i*
R:	*Profitability of the safety stock increase / €*

Figure 2. Approach for anticipatory inventory management

In the first step, the product portfolio is analyzed about the driver parameter of the degree of multiple uses of the material numbers[23].

$$MUR_{m,p} = \frac{1}{n_{Prod}} \cdot \frac{\sum_{j=1}^{n_{Mat,p}} MU_j}{n_{Mat.p}} \tag{7}$$

With

$MUR_{m,p}$	Mean degree of multiple uses of the material numbers of product p / -
n_{Prod}	Number of all products in portfolio / -
p	Product *p* / -
$n_{Mat.p}$	Number of all material numbers of product p (*j* = 1, ... *J*) / -
MU_j	Number of products in which material number *j* is used / -

As stated by KÄMPFER & NYHUIS [23], the frequency of usage can be utilized to calculate the proportion of the portfolio in which the material numbers of a product are used on average. If the information on the multiple usage levels within the (future) portfolio is linked with corresponding key figures on the sales forecasts per product p, a description matrix can be created (cf. Figure 2; left block). This makes it possible to identify materials in the early development phases for which robust safety stock dimensioning appears worthwhile from an economic and logistical point of view. This form of product representation allows materials to be identified for which robust inventory dimensioning offers a powerful lever for safeguarding production against potential disruptions. **The second step of the procedure** involves the application of the modeled formula presented in the previous chapter (see formula 5 in section 4.1.) for the robust dimensioning of safety stock, which takes into account delivery quantity deviations depending on crises at the time *i*. The first step is selecting materials for which robust stock dimensioning is a significant lever for safeguarding production against potential disruptions. After selecting materials suitable for robust stock dimensioning, this approach phase assists with the question of "how robust should the company set itself up to be". After dimensioning has been carried out for one material or component, the profitability (R) of the safety stock increase due to quantity deviations should be finally evaluated. For this purpose, the following calculation logic is integrated into the **third step of the procedure**:

$$P = S - \Delta C_l - \Delta C_{exp} = (P_c - P_b) \cdot \widetilde{SS}_{QD,c} - \frac{P_v \cdot \Delta SS_m{}^2 \cdot (z_{IR} + k_{CW})}{DR_m \cdot 36000} \tag{8}$$

With	P	Profitability of the safety stock increase / €
	S	Savings of the safety stock increase / €
	ΔC_I	Additional inventory costs / €
	ΔC_{exp}	Additional costs due to interest expenses / € (opportunity costs)
	P_c	Price level during the crisis / € per QTY
	P_b	Price level before the crisis / € per QTY
	$\widetilde{SS}_{QD,c}$	Adjusted component of safety stock due to quantity deviations resulting from crisis c / QTY
	ΔSS_m	Mean additional safety stock throughout the crisis / QTY
	DR_m	Mean demand rate / ME per SCD
	z_{IR}	Opportunity interest rate p.a. / %
	k_{CW}	Warehousing costs p.a. / %

It is assumed that although it is possible to purchase a required quantity at a higher price during the crisis, this should be avoided by adjusting the safety stock beforehand. It is also assumed that the relationship between the price level during and before the crisis is equivalent to the balance of the material availability level before the crisis (around 100%) and during the crisis. The price difference multiplied by the amount of additional safety stock $\widetilde{SS}_{QD,c}$ represents the savings *S* that the anticipatory stock increase can achieve. Additional inventory costs and opportunity costs reduce this saving. The additional inventory cost is obtained by multiplying the value per item, the average additional safety stock, the storage period, and the storage cost rate per day. Other costs that must be considered are interest expenses arising from the additional capital.

5. Conclusion

In this paper, a procedure for anticipatory inventory management was developed to link product and production system properties. The modeling approach integrated into the process can be used to quantify how robustly a company should position itself concerning relevant materials/components, depending on the predicted duration and intensity of a crisis. Future research could address determining factors to adjust the safety stock level due to quantity deviation. As indicated in section 3, testing and validating the modeling approach presented here is necessary using, e.g. simulation experiments to meet the requirements of the deductive-experimental research approach. The extent to which a rating scale for the factors and their mathematical modeling is meaningful must be answered in future research based on simulation studies. The mathematical model assumes that reordering in increasingly volatile environments cannot cover the quantity deviations. The developed model-theoretical representation of several successive supply quantity deviations during a crisis can be a starting point for further research. For example, future approaches should address the adjustment of safety stock levels in simultaneous uncertain replenishment times and demand rates. Here, it is essential to investigate how the compensation effects behave. Converting the model presented here into a model-based systems engineering approach would enable a systematic representation and interdisciplinary use of the information in product development and production system design. Stock dimensioning is one possible measure to realize robust production systems. Different properties, such as resilience, are also available for designing and planning production systems. Depending on the evaluation of the given uncertainty, it needs further research activities to identify the right combination of measures.

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Biography

Alexander Wenzel, M.Sc. (*1992), studied industrial engineering with a focus on production and systems engineering at Technical University Braunschweig. Since 2020, he has been a research associate in production management at the Institute of Production Systems and Logistics (IFA) at the Leibniz University Hannover.

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Prof. Dr.-Ing. habil. Peter Nyhuis (*1957) studied mechanical engineering at Leibniz University Hannover and subsequently worked as a research assistant at the Institute of Production Systems and Logistics (IFA). After completing his doctorate in engineering, he received his habilitation before working as a manager in the field of supply chain management in the electronics and mechanical engineering industry. He is heading the IFA since 2003. In 2008 he became the managing partner of the IPH - Institut für Integrierte Produktion Hannover GmbH.