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# Logistics-Oriented Production Configuration Using the Example of MRO Service Providers

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**ABSTRACT** Providers of maintenance, repair and overhaul (MRO) services for complex capital goods, such as aircraft engines, which are indispensable for the customers to perform their services, are facing increasing market dynamics as well as constantly growing, diversifying customer requirements. The ability to achieve (the required) high logistics performance is greatly determined by a suitable production configuration. From the strategic definition of goals to the design of suitable supply chain structures as well as planning, controlling and monitoring mechanisms, a multitude of interdependent configuration decisions must be made on different organisational levels at various points in time. At the same time, numerous internal and external influencing variables must be taken into account, observed and continuously examined for configuration-relevant changes. If necessary, suitable reconfiguration measures must be initiated. This article presents an approach to production configuration based on logistics modelling. To handle the multitude of effects and interactions they are translated into a framework for efficient and sustainable production configuration. It consists of four successive levels for the initial configuration as well as an additional module for long-term production configuration monitoring. It serves to review pre-existing configurations in the context of reorganisation projects and enables the target-oriented configuration of internal supply chains.

**INDEX TERMS** Supply chain management, production planning and control, MRO, reference modeling, production configuration.

## I. INTRODUCTION

Achieving logistics objectives like short delivery times and a high degree of schedule reliability while keeping logistics costs as low as possible requires a holistic production configuration adapted to the specific company's requirements and harmonised along the entire supply chain [1]. 'Holistic production configuration' encompasses all configuration decisions starting with the design of the value creation structure at the strategic level down to the configuration of production planning and control (PPC) at the tactical and operational level. Since the focus of this paper is on holistic production configuration, in the following, we will refer to 'production configuration' synonymously with 'holistic production configuration'. It consequently distinguishes from '(holistic) production systems' that represent methodical sets of rules and principles for the design, optimisation and standardisation of order fulfilment processes as well as relevant support processes in order to increase a company's productivity [2]. However, these rules do not guide how supply chains and individual process steps must be arranged, (de-)coupled and parameterised [3]. Implementing a target-oriented and efficient production configuration requires the consideration and anticipation of a multitude of (multidirectional) interdependencies between individual configuration decisions to be made across the different configuration levels. Neglecting or even ignoring the important interactions between these individual configuration decisions consequently bears the risk of serious losses in production logistics efficiency [4], [5]. Despite its enormous potentials, systematic production configuration is rarely implemented because of financial and logistics performance risks of complex long-term production configuration projects [6]. Instead, many companies stick to historically developed production configurations and frequently do not exploit the efficiency potentials of target-oriented production configuration. They often also lack the

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necessary expert knowledge to properly assess the consequences of production configuration decisions for the performance of production logistics [7]. Among other things, this is reflected in the fact that the selection and parameterisation of the procedures used in PPC are only rarely scrutinised - partially due to employees' limited understanding of the overall system [7], [8].

The multitude of interactions along the supply chain makes production configuration a highly complex task [5], [9]. Due to this, a quantitative assessment of individual configuration decisions is neither possible in an efficient and generally valid manner nor is it verifiable in or relevant to practice. Existing approaches tend to have a limited scope and hence do not provide a holistic view [10]. Most of the work focuses on the selection of individual configuration options (for a detailed overview, see [9]), their design for specific applications [11] or describe the basic architecture and tasks of PPC [6], [12]. The multitude of interdependencies from the strategic to the operational level are not seamlessly described nor structured by any approach so far.

This conceptual paper aims to further develop the theoretical foundations of supply chain design and production configuration theories. Our study combines methodological principles of corporate strategy and supply chain design, PPC configuration, and production monitoring into a holistic framework utilising logistics models. This framework can be used to structure supply chain design or restructuring projects fundamentally as well as to develop suitable controlling mechanisms for an ongoing production configuration control. It closes the research gap by aggregating the results gained from two research areas, i.e. logistics modelling and cause-effect-relation based production control. To narrow the research gap, we focus on developing a conceptual management decision framework as a guideline for proactive production configuration incorporating reactive real-time production configuration controlling.

With regards to research methodology and logic, this contribution is rooted in conceptual research. Based on a literature analysis and an analysis of approaches to production configuration, we derive a generic framework for production configuration, which is finally transferred into a cybernetic control loop for ongoing production configuration control. The presented methodology provides integrated, practice-oriented guidance for production configuration without requiring complex and customised simulations or mathematical models. It does not aim to deliver quantitative evidence on the benefits of individual configuration decisions. Instead, it brings together knowledge from a wide range of scientific literature with observations from practice in an argumentative way. In order to provide specific examples for some of the relevant decisions, the use case of a maintenance, repair and overhaul (MRO) service provider is applied throughout the paper. The MRO branch represents a logistically highly demanding industry, ensuring applicability in less demanding environments. The use case is introduced as part of the theoretical background in section II. Section III describes argumentative reference modelling as the research methodology applied in this paper. Section IV presents the framework for production configuration, structured across four levels and comprising an overall controlling process. These also represent the structure for the respective subsections. Section V sums up the extensive descriptions, while section VI gives conclusions and outlines potential future research topics.

## II. THEORETICAL BACKGROUND: DYNAMIC-INDUCED CHALLENGES IN PRODUCTION PLANNING

The following section provides the theoretical background for further discussion. It is split into a brief description of the use case of the MRO service provider and an overview of logistics models as tools for production configuration, as well as existing research on the configuration of production planning and control.

### *A. USE CASE OF AN MRO SERVICE PROVIDERS*

Production configuration is highly dependent on industry- and company-specific boundary conditions and corresponding influencing factors, particularly important for companies exposed to high market and process dynamics facing significant uncertainty of information along the order fulfilment process. Specifically, this applies to regeneration or MRO services providers for complex capital goods such as aircraft or their sub-systems (aero engines, etc.). The purpose of these MRO services is to preserve the residual value of the capital goods at the end of a use phase and to transfer it to a further use phase [13]. After disassembly and a detailed inspection, reliable information about the repair measures required for regeneration and spare parts needed is available. Once all components are ready for installation, the capital goods are reassembled and quality assurance can be completed [14]. Despite increasing condition monitoring parallel to operation, there still remains high uncertainty of information regarding the actual damage patterns, a strong customer influence during order processing, frequent changes in the work content or scope, and a high level of information uncertainty regarding the expected capacity and material requirements [15]. These factors lead to significant production logistics turbulence and significantly increased process variance [16], [17]. These can cause massive process disruptions or inefficiencies if production configuration is not consistent or capable of handling them [18]. MRO, which comprises maintenance, repair and overhaul, including all technical aspects of repair of both planned and unplanned work, is to be distinguished from the closely related term of remanufacturing. Although remanufacturing also focuses on restoring used products to as-new condition, it is normally carried out for an anonymous market. Consequently, the goods are bought back for this by the remanufacturer from the customer [19]–[21]. In contrast, in case of MRO, the customer remains owner of the goods even during regeneration and thus is directly bound to their regeneration processes and the logistics performance achieved here [18].

A further differentiation is necessary with respect to recycling. This is characterized by the original product and the actual functionality is completely given up. The aim of recycling is to recover individual materials from which the original products were made and to make them usable for the production of new products [22].

### *B. LOGISTICS MODELLING AS AN ENABLER FOR CONFIGURING THE COMPANY'S INTERNAL SUPPLY CHAIN*

To enable a quantitative description and analysis of interdependencies between actuating variables, control variables and objectives along the company's internal supply chain, an abstraction of the production processes using logistics models is very helpful. These allow for a target-oriented positioning between conflicting logistics objectives like short throughput times and high utilisation of capacities. Further, it is required to determine the effects of decisions in the context of PPC on the supply chain structure as well as to be able to evaluate general interdependencies within the company's internal supply chain independently of its actual state [12], [23]. To apply such analyses, it is advisable to subdivide the company's internal supply chain into individual macro processes that can be coupled with each other. Each of these macro-processes itself consists of one or more elementary supply chain components. These generally represent storage levels, work systems as well as completion points where different material flows converge [24]. Within these, different, sometimes contradictory objectives can be described [1], [25], [26]. While activities are performed in work systems and completion points serve to merge multi-component orders, storages are usually used to establish a decoupling in material flow. Decoupling can be established along three dimensions: time, quantity and quality [27]. An exclusively time-related decoupling is called *buffering* and is often realised as a queue between two processes. An additional decoupling between incoming and outgoing material quantities constitutes *storage*. One example is the continuous removal of material from a warehouse that is cyclically filled in batches. In case of an additional decoupling through quality, the decoupling is referred to as a pool. Qualitative decoupling is achieved by combining at least two pooling stages separated by a quality-influencing production process [27].

Within internal supply chains, cause-effect relationships can be derived and described using logistics models. As mentioned earlier, these are mathematical models that describe fundamental cause-effect relationships in supply chain elements between actuating variables, control variables and objectives in a universally valid and easily applicable manner. By adjusting the parameters contained therein, they can be adapted to match the current state of a supply chain component [1]. Coupling the models via variables such as schedule deviation enables modelling of the supply chain components and estimating the effects of structural changes and decisions in production planning and control on the degree of achievement of the logistics objectives [28].

Using the example of MRO service providers, the whole supply chain (Fig. 1) can be composed by the macro processes of disassembly and inspection, repair, as well as the final reassembly, including quality assurance - each comprising one or more elementary supply chain components [29]. Disassembly and the subsequent inspection represent the starting point of the exemplary internal supply chain for MRO services. For better readability, these will be summarised in one macro process subsequently. The same applies to reassembly and quality assurance. In addition, up to two pool stages and new parts procurement are established in many MRO supply chains [13], [14], [18], [30].

Fig. 1 also adds examples of potential applications of logistics models along the internal MRO supply chain. Components leaving the macro process Disassembly and Inspection usually are transferred to the following repair process. In production areas like these and at individual work systems, there is a fundamental conflict of objectives between the level of WIP and the logistics objectives of a short throughput time and a high output rate, as shown by the production operating curves (a) [1]. Furthermore, (b) the chosen sequencing procedure [31], [32] and (c) possible prioritisations of rush or fast-track orders have an impact on throughput time (variability) and schedule deviation characteristics [33]. The prioritisation offers the possibility to accelerate material supply for downstream processes actively. One example is the prioritisation of severely damaged components during disassembly to enable the earliest possible start of subsequent repair processes [34]. As shown in Fig. 1 (c), non-accelerated jobs are slowed down with a growing number of the accelerated 'rush orders' if these share the same production capacities. After a successful repair, the now serviceable components feed the completion point before assembly. For the completion point, the supply diagram (d) visualises how a non-functional ('disturbed') inventory results from an asynchronous provision of components, which is significantly influenced by the schedule deviation of the upstream supply processes [25]. In this context, 'Disturbed' refers to WIP that cannot be processed in downstream processes due to missing components. Assembly and quality assurance can be modelled analogously to the disassembly and repair processes. Reassembly can start once all required components are supplied. At two pool stages, up- and downstream to the repair process, the central conflict of objectives occurs between the desired service level and lateness (e) or the level of disrupted WIP (f) and the respective inventory required on hand [27], [35]. By decoupling up- and downstream macro processes from each other using these pools, repairable (RA) or serviceable (SA) components can be supplied to downstream processes from the pools (e) or storages (f) without having to wait for the upstream processes to be completed - assuming that the required parts are available in storage. The procurement of new parts (g) supplies both the pool/storage stages and the completion with procured components. Here, a conflict of objectives arises

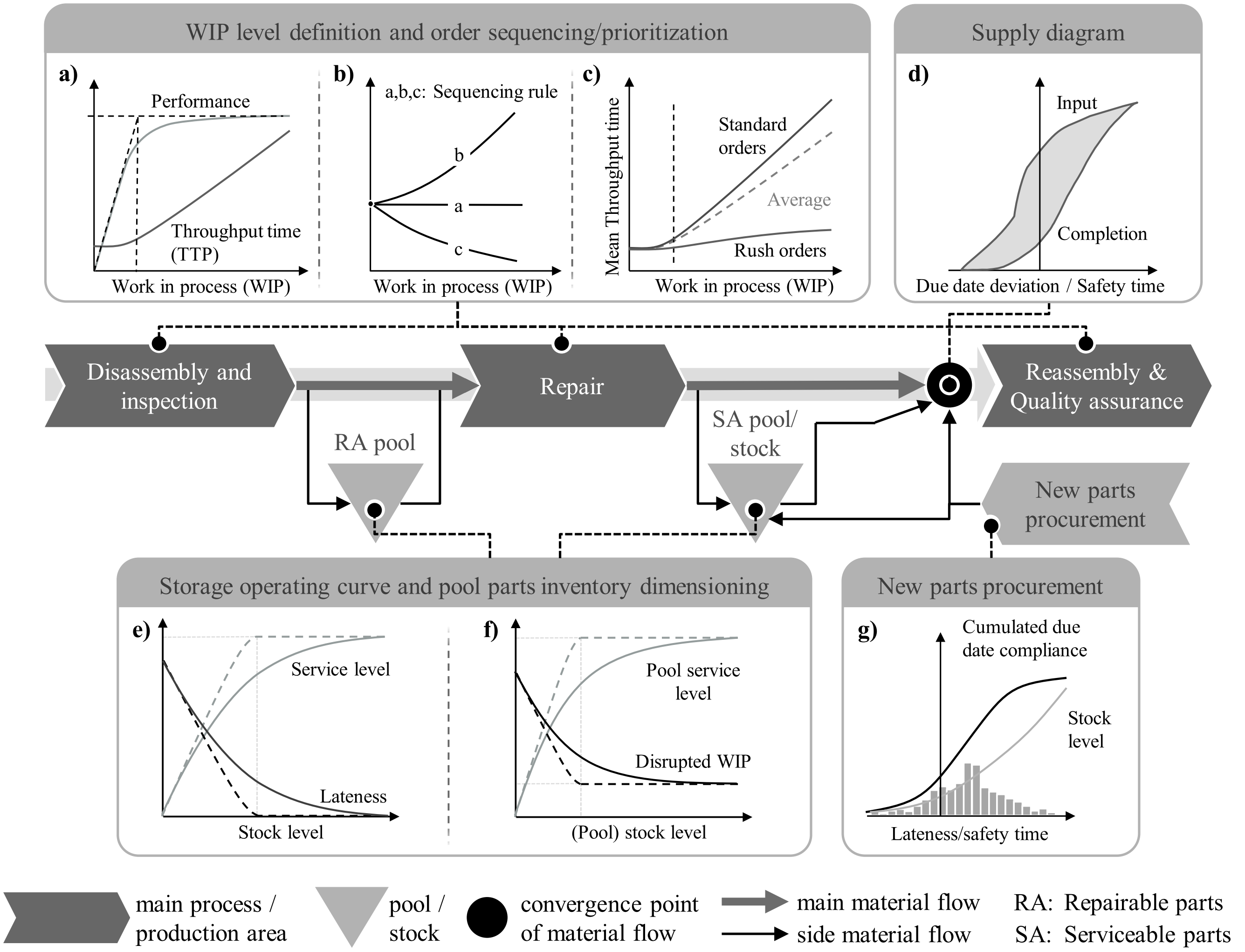

**FIGURE 1.** Exemplary applications of logistic models within the MRO supply chain [14] using a) Nyhuis and Wiendahl [1]; b) Mütze and Nyhuis [32]; c) Trzyna *et al.* [33]; d) Schmidt *et al.* [36]; e) Lutz and Wiendahl [35]; f) Kuprat [27]; g) Nyhuis, Beck, and Schmidt [25].

from the implementation of safety times to increase schedule adherence while at the same time causing increased inventory costs [36].

These examples provide a brief overview of conflicting objectives along the (MRO) supply chain. The logistics models presented support balancing these as well as their representation in production configuration. Furthermore, benefits and use cases of logistics models for structural analysis of internal supply chains and a basis for generating and selecting configuration alternatives are demonstrated.

### *C. APPROACHES TO THE CONFIGURATION OF PRODUCTION PLANNING AND CONTROL*

When configuring PPC, i.e. selecting and parameterising procedures to fulfil PPC tasks during order processing, the interdependencies between actuating and control variables and objectives, as well as existing conflicts of objectives, must be taken into account [23]. For example, controlling the input of production (actuating variable) impacts the work-in-process level (control variable) and, thus, the objectives of throughput time and capacity utilisation. A fundamental dilemma in the design of PPC systems is the inability to plan the entire production while simultaneously being aware of heterogeneous production organisational conditions and dependencies, while not neglecting the interdependencies resulting from the joint use of resources by several orders. Nevertheless, it is often necessary to plan, control and optimise multi-stage and interlinked value-adding processes without negatively influencing each other in terms of the overall logistics performance of the company. Thus, to derive a suitable PPC systems architecture, Drexl *et al.* [37] formulated guidelines for designing capacity-oriented PPC systems. These embrace structuring supply chains into individual linked macro processes, vertically layering decentralised cross-functional planning modules combined with central coordination instances and a segment-specific selection of proper planning and control instruments.

In literature, there are many conceptual frameworks for a universally valid description of PPC as well as basic, limited in scope approaches to derive a company-specific PPC configuration [9], [23]. Likewise, there are branch-specific frameworks for PPC configuration, such as the work of Sendler [38], giving an overview of possible PPC configuration options for MRO service providers.

Examples of superordinate conceptual frameworks for the general description of the processes in PPC are the PPC model according to Hackstein [39] and the (extended) Aachen PPC model built on its basis [6]. In addition, some frameworks provide a detailed description of one or a branch of PPC main tasks and the effects of various procedures on production logistics performance. A typical example is the model of manufacturing control of Lödding [40], focussing the task production control. The Hanoverian Supply Chain Model developed by Schmidt and Schäfers [12] (Fig. 2) incorporates the aforementioned conceptual models and links the process-oriented perspective of PPC with the company's internal supply chain processes.

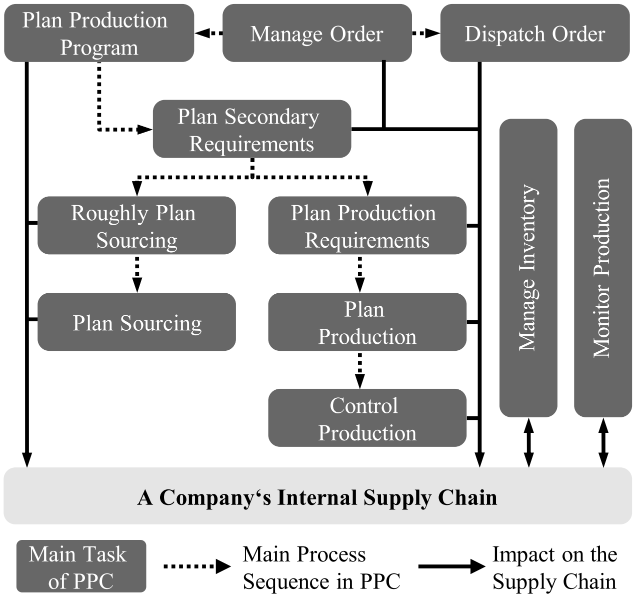

**FIGURE 2. The Hanoverian supply chain model (HaSupMo) a framework for production planning and control: An overview based on Schmidt and Schäfers [12].**

In this way, the effect of specific PPC tasks (e.g. order release) on actuating variables in the supply chain and ultimately on the logistics objectives (e.g. work-in-process) is consistently modelled for the entire PPC. Therefore, the Hanoverian Supply Chain Model serves as the conceptual basis for configuring PPC as part of production configuration.

Besides the conceptual frameworks, there are various concepts for the systemic and practical solution of the production planning and control problem. These differ particularly in whether decisions are made centrally or decentrally and in the degree of integration for determining a suitable solution for the PPC problem [5], [41], [42]. Thus, the approach of simultaneous planning as a highly integrated approach, which so far fails due to the power of the planning problem to be solved, and the rigidly directed little integrated successive planning as extremes of integration are to be distinguished from each other [42]. Well-known concepts of successive planning are the MRP logic according to Orlicky [43] and its further development (MRP II) according to Wight [44]. Concepts or approaches that tackle the problem of pure successive planning are the Hierarchical Production Planning (HPP) [45] and the use of Advanced Planning Systems (APS) [46]. For a more detailed overview and discussion of these concepts of PPC systems, reference is made to Missbauer and Uzsoy [47].

In summary, it can be stated that promising approaches exist at both the conceptual (e.g. selecting procedures) and the systemic level, which enable a target-oriented configuration of PPC in the context of a holistic production configuration. However, it is to be noted that there is no approach so far that links conceptual and systemic aspects and embeds the configuration of PPC in an overall framework to production configuration.

### D. INTIRIM CONCLUSION

By classifying the logistics challenges of businesses with a particular focus on MRO service providers and providing an overview of the tool of logistics modelling as well as current conceptual and systemic approaches for describing the tasks, processes within and the organisation of PPC, the necessary basis for a deeper understanding of the present work is created. It is shown that there are excellent approaches for configuration decisions for specific logistics elements (e.g. dimensioning of work-in-process at a work system) and the basic configuration of PPC.

While in industrial practice, production configuration and the space of possible and expedient solutions are often limited by various constraints or conditions. For example, these may include the product or service portfolio and the production technologies applied [14], [48]. Nonetheless, there remains a multitude of configuration options covering the selection of specific production principles for each section of the supply chain or the number and position of decoupling points along the order fulfilment process [49] as part of the supply chain structure design. In addition, further degrees of freedom open up by configuring production planning (e.g. capacity planning) as well as production control and processing strategies. To the best of the authors' knowledge, no existing approach supports an integrated and holistic view on production configuration ranging from the overarching corporate strategy to a detailed operational perspective. Consequently, this paper aims to solve the problem of holistic production configuration by applying a multi-level framework.

## III. DESIGN SCIENCE RESEARCH STRATEGY AND RESEARCH METHOD

This article, as already described in the introduction, uses a conceptual research approach. The applied research strategy follows the approach of application-oriented science

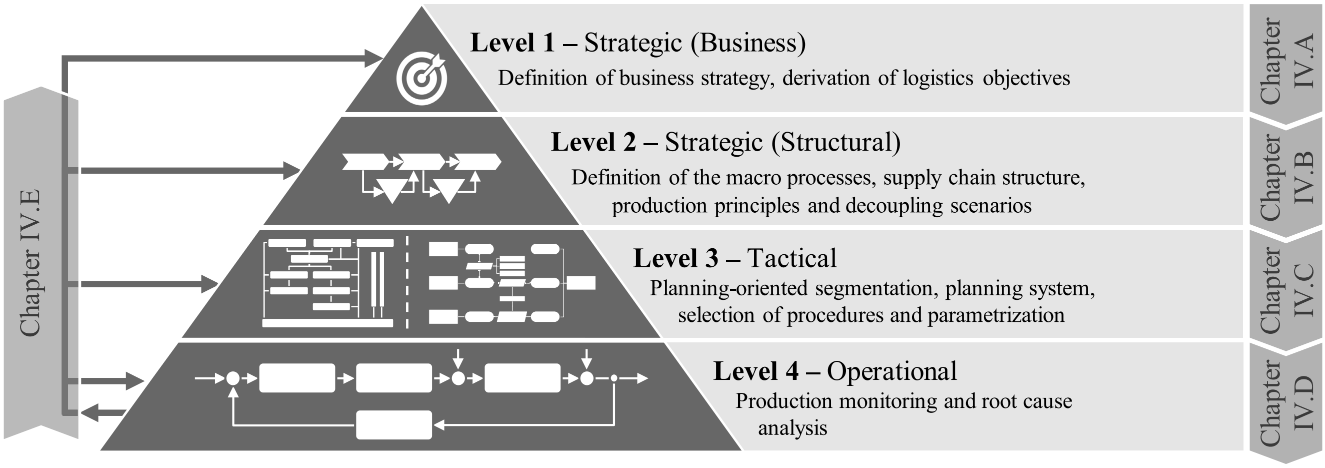

**FIGURE 3.** The four levels of production configuration.

according to Ulrich [50] and is methodologically based on logical-argumentative reference modelling to find suitable solutions. Reference modelling in this context shall be defined as the inductive or deductive creation of usually simplified and optimised depictions (ideal concepts) of systems, deepening existing knowledge and generating design patterns upon it [51], [52]. This research methodology allows approaching the problem of production configuration in the most efficient way possible in the sense of Weick's [53] notion of 'sensemaking', emphasising the relevance of a valid system's understanding instead of exhaustive quantitative studies on hardly constrained use cases. Thus, by defining a multi-stage procedure enclosed by a control loop, a model is developed that enables practical users to increase their understanding of the system. Overall, the research approach does not pursue a quantitative description of the interdependencies of various configurations but aims at a qualitative, process-oriented and model-based procedural description for the practice-oriented support in holistic production configuration.

## IV. FOUR-LEVEL PROCEDURE TO PRODUCTION CONFIGURATION

The procedure for deriving a suitable and application-specific production configuration is subdivided into strategic, tactical and operational levels following Anthony [54]. As mentioned earlier, it also incorporates the guidelines for designing PPC system architectures according to Drexl *et al.* [37]. The fundamental structure is shown in Fig. 3. It provides support for necessary configuration decisions and can be adapted to any company-specific challenges.

Strategically, as a basis for the selection and orientation of all further configuration decisions, company-wide logistics objectives must be defined and projected onto the subordinate areas (chapter IV.A). In addition, a suitable production system for order processing (see [2]) and the structure of the company's internal supply chain must be derived (chapter IV.B). This determination includes defining the macro processes involved in the product creation process, determining decoupling points and selecting the production principles to be applied. For this purpose, two strategic levels (business and structural) are differentiated.

The subsequent design of the logistics interactions among the process elements within the company's internal supply chain takes place at the tactical level of production configuration (chapter IV.C). In this context, the definition of planning segments and their organisational (de-)coupling must be carried out. By selecting and parametrising suitable procedures for PPC, the planning segments are to be positioned according to the previously defined, sometimes contradictory corporate and divisional objectives (e.g. utilisation vs. WIP). On the operational level, adherence to the procedural regulations and parameter specifications must be checked during operation. If necessary, regulatory measures must be initiated to ensure target-oriented operation (chapter IV.D). Chapter IV.E concludes by describing a cross-level control loop for deriving and allocating reconfiguration needs as a comprehensive methodology.

The entire procedure for production configuration thus shows which tasks have to be carried out at the different levels and links them in a general framework. Each of the tasks to be fulfilled can be supported by a variety of tools and methods, such as logistics models (see chapter II.B), but also tools of the Lean philosophy (e.g. Hoshin Kanri or Muda), which will not be discussed in detail in the following.

### A. STRATEGIC LEVEL: STRATEGY DEVELOPMENT AND DERIVATION OF OBJECTIVES

The basis for economic success is the development and definition of a competitive market or corporate strategy adapted to the business model. Following Porter [55], in general, three types of a corporate strategy can be distinguished: overall cost leadership, differentiation and focus. In addition to defining the range of products or services offered to the market, the differentiation between different strategies can also be applied to the range of logistics performance offered to customers. More and more, companies are differentiating themselves based on their logistics performance by offering, for example, shorter delivery times or special supply commitments. Overall, four central logistics objectives have to be balanced with each other: Inventory/Work-in-Process, Capacity Utilisation, Delivery/Throughput Time and Schedule Reliability [1]. The logistics models presented in chapter II.B can be used for assessing the logistical impact and dimensioning of resources and mechanisms required accordingly. For example, the preferred service levels to be provided to the market can be compared with the necessary inventory and the associated capital commitment on the basis of the inventory operating curve (cf. [35]). Using the example of MRO service providers, this can be transferred to the quantity of pool components held in stock for spontaneous maintenance demands [56]. Once the strategy has been defined by balancing the logistics objectives and shaped at the corporate level, it can be broken down into single divisions. This subsequently serves as a strategic guideline for the single macro processes of the company's internal supply chain [57].

In order to support the achievement of strategic objectives, corresponding indicators must be derived and their target values set. For this purpose, various KPI systems for production already exist, which can serve companies as a reference for setting up their own customised KPI system. Examples are provided by VDI-Norm 4400-2, VDMA-Guideline 66412 and the SCOR-Model [57]–[59]. A good overview is also provided by Gottmann [60]. Due to the focus of this paper, reference will be made here to these and the works cited therein. No further detailed consideration is given.

## B. STRUCTURAL LEVEL: STRUCTURAL DESIGN

Once the strategy and the objectives have been defined, the structure of the internal supply chain needs to be designed to support the defined objectives and the company's overall strategy. Besides the decisions at the superordinate level, additional influencing factors need to be considered as well [61]. These include the product-related complexity within the spectrum of orders, the logistics-relevant customer requirements and the logistics service portfolio. This second level of the overall procedure of production configuration also marks the central link to factory planning, providing several mutual interactions that are highly dependent on the respective type of structuring scenario (new planning or restructuring/reorganisation) [62]. Due to the scope and diversity of these interactions, they will not be discussed in depth in this paper.

Starting with the structural design, an essential driver is the diversity of variants in the product or service portfolio and the related complexity of the material flows. Among other things, these have a considerable influence on the choice of production principles as well as their configuration and parameterisation [63], [64]. For example, this is observable by capacity utilisation losses due to excessively heterogeneous product portfolios in automotive assembly lines [65]. Taking logistics-related customer requirements into account - e.g. specific delivery times - or offering shortened delivery times to the market, as discussed in section IV.A, have an additional impact. Depending on the share in the overall portfolio as well as the strategic importance, decisions related to logistics processing, e.g. in the form of separate fast lanes for rush orders [33], or a change in the order processing strategy, e.g. from a Make-to-Order to a Make-to-Stock strategy [66], have to be made during structural design.

### 1) PROCEDURE FOR DERIVING A STRUCTURE

The macro processes necessary for order processing can be identified based on the product or service portfolio, the business model, and the logistics portfolio. This macro process structure (cf. chapter II.B using the example of the MRO supply chain) needs to be further detailed based on the production programme derived from the sales forecast. In addition to the determination of the production technologies necessary for order processing, this also includes the forecast of resource requirements and the associated fundamental decisions regarding the resource structure to be implemented. Among others, this includes the number of machines, the basic shift model, or the production principle to be applied. The selection of the production principle, as well as the consideration of possible mixed or hybrid forms, strongly depends on the variance in the product creation process (number of variants, differences in work content, resulting material flow complexity, etc.) as well as on the planned vertical segmentation of production [63], [65]. According to Wildemann [67], vertical segmentation describes the number of parallel product-oriented production areas within a single macro process and thus the decomposition of the supply chain sections for different products. Using the example of MRO service providers, process-related variance essentially results from the composition of different types of capital goods with varying damage patterns or repair work scopes and customer- and order-specific contract characteristics [68], [69]. If orders with identical or similar work contents and processes can be bundled within a closed segment, flow-oriented manufacturing principles, such as flow line production, can offer productivity advantages. While the work systems within flow line structures are usually strictly linked to each other without any time buffer, other manufacturing principles such as job-shops offer the possibility of loosely linking processes.

The vertical segmentation, as well as the type of linkage of the macro processes to be passed, allow the derivation of possible material flow-oriented decoupling scenarios between the macro processes. These decoupling scenarios include the type, number and location of the decoupling points (cf. chapter IV.A) implemented along the supply chain [49]. Also, many consequences need to be taken into account when deciding whether or not to decouple [70]. For example, production processes can be decoupled from long replenishment times of required pre-products by holding these in stock and consequently avoiding material bottlenecks that would extend the overall throughput time. Thus, decoupling can open up the potential for throughput time and thus delivery time reduction [27], [49].

In the MRO context, load flexibility enabled by decoupling with pool stages additionally allows the compensation of the particularly high level of information uncertainty regarding the capacity and material requirements to be expected from a customer order compared to conventional production processes by keeping spare parts in stock [13]. In conjunction with the use of capacity flexibility (e.g. using overtime), this enhances the supply chain's robustness against unanticipated disruptions.

The need for robustness is mainly dependent on the remaining, not anticipated (load) uncertainty left in the process. A reduction of this uncertainty is, among others, possible by analysing load data from previous orders or field data using modern methods of predictive data analytics [15], [71]. The remaining load uncertainty that cannot be eliminated until the start of order processing can be modelled as a statistical distribution and thus enables the derivation of different load scenarios [72]. A successful and early reduction of uncertainty reduces the number of pool components and other flexibility measures that need to be maintained to cover process disruptions. Overall, on this level, the macro processes, their type of linkage, and corresponding decoupling points need to be defined. The procedure can be transferred to various company-specific use cases and forms the basis for any configuration on tactical or operational levels.

### *C. TACTICAL LEVEL: CONFIGURATION OF PRODUCTION PLANNING AND CONTROL*

After the derivation of the logistics objectives for production from the corporate strategy and the definition of a suitable supply chain structure, a compatible configuration of PPC needs to be developed at the third, the tactical level of production configuration. To do so, coherent planning segments must be formed first. In this paper, the formation of planning segments is defined as the aggregation of supply chain components that can be planned and controlled using a uniform system. For each of these planning segments, it must be determined which and to what extend decisions in the organisational process are already defined and included in planning. Also, the degrees of freedom remaining for production control must be assessed. In the context of this paper, this is described as the degree of integration, following Steven [41]. The selected degree of integration has a strong influence on both, the subsequent selection of procedures and the parameterisation (PPC configuration) as well as on the range of influence and decision-making of the respective PPC tasks in the entire PPC system. This paper will mainly focus on a fundamental approach for deriving the overall planning system. It is discussed using the example of (in-house) production planning and production control (see also Appendix).

#### 1) MODELLING OF PLANNING SEGMENTS AND THEIR (DE-)COUPLING

Besides the decoupling in material flow, the consideration of the possibility or necessity of (de-)coupling in terms of planning between areas within the supply chain that are connected by interdependencies is of particular importance for the design and configuration of PPC. Here, decoupling implies the possibility to plan and control production areas separately, forming so-called individual planning segments. It includes, for example, the autonomy of PPC procedure selection and parameterisation within one segment in contrast to a detailed consideration of mutual dependencies of several segments. Consequently, the planning segments have to be formed in a way that the interdependencies are maximised within the segments but minimised between the individual segments [37], [41]. Depending on the degree of interdependency, the coupling of areas can generally be fixed, flexible or non-existent/loose. Examples of a fixed coupling are heat treatment and coating processes requiring the heat of predecessor processes to be reused for economic reasons and adhere to metallurgically defined cooling corridors. As a result, the planning of both, the process and the predecessor process has to be coordinated in one planning segment and cannot be carried out separately. A flexible coupling, on the other hand, generally allows couplings of variable intensity. Here, both loose and fixed coupling can be realised. Exemplary indications for flexible coupling points between production areas are boundaries of macro processes or order decoupling stages. For visualisation purposes, loose and fixed couplings between production areas can be modelled abstractly as springs and rods (see Fig. 4), providing an easy-to-understand tool for forming aggregable planning segments.

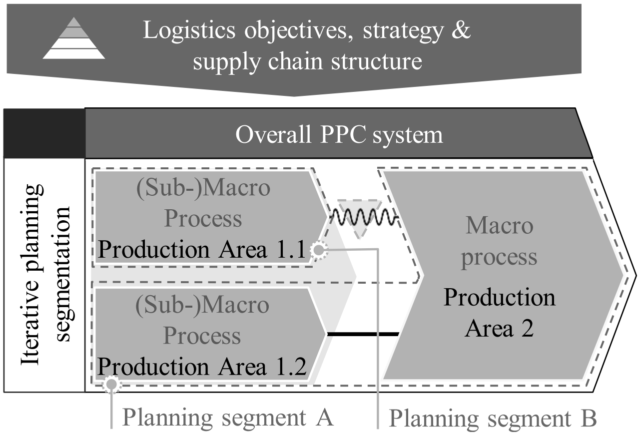

**FIGURE 4.** **Differentiation of planning segments in the overall planning system.**

#### 2) PROCEDURE FOR DERIVING AND DELIMITING PLANNING SEGMENTS

An iterative procedure is usually necessary to identify and delimit planning segments and determine the type of coupling between production areas. It can be stated that dependencies in planning usually exist between production areas connected via material flows, which converge in at least one point in the downstream product creation process or compete for limited resources. However, it should be noted that dependencies between two production areas detached from each other can also occur indirectly via other production areas. Therefore, the already examined macro process level can often be used as a starting point for the initial clustering of decoupled planning segments. Among other things, the macro process level contains information on the number and position of so-called (customer) order decoupling points in the material flow (cf. [49]). Depending on the level of detail and resolution of the macro process landscape, it may also be helpful or necessary to additionally include deeper (sub-)process levels to identify order decoupling points.

Physically, order decoupling points are usually realised as storage to achieve a temporal and quantitative decoupling of material or product requirements (cf. chapter IV.A). They also represent a typical indicator for production area relationships with loose coupling. Other indicators for the existence of an order decoupling point can be a change in the product or order structure level or the convergence of several material flows - e.g. before an assembly. In the MRO context, such a change occurs at the transitions from the disassembly of a capital good to the repair of the disassembled single components and the downstream reassembly of the capital good.

The result of this step should be an initial segmentation of the company's internal supply chain into production areas and planning segments, which serves as a starting point for further segmentation iterations. The planning segments delimited by the described procedure form the basis for their respective PPC configuration.

### 3) DETERMINATION OF THE PLANNING SYSTEM

Following the derivation and definition of planning segments, a decision on the applicable planning system and a target-oriented selection of procedures for the PPC tasks to be fulfilled must be carried out for each of the tasks, referred to as PPC configuration [11].

An ideal configuration of the PPC in these planning segments needs to anticipate all internal and external influencing factors and should be focused on meeting the divisional targets derived from the corporate objectives [73]. This means that the requirements for the granularity to be achieved in planning, the planning horizon to be depicted and the logistics objectives to be pursued must be met. At the same time, both the given planning prerequisites and the compatibility of the selected procedures with each other (cf. section Target-oriented selection of PPC procedures) must be taken into account.

As mentioned in section II.C, a distinction can be made between rather successively phase-oriented or integrated-iterative approaches when designing the planning system. In general, the phase-oriented, successive execution of PPC results in strongly directed information flows between the tasks. Thereby, each PPC task relies on the results of its predecessors. Deviations are usually met with countermeasures inherent to the respective PPC tasks and within the predecessor's 'guard rails' set. In contrast, an integrated approach allows the integration of vertical planning levels and thus the consideration of decisions at upstream or downstream planning levels along rolling planning horizons [41]. Thereby, the advantage of ideally integrated approaches is a central planning and decision-making process that simultaneously considers and combines all available fields of action and measures using the current system status provided by data integration (see e.g. [74]). Depending on the intended logic to trigger a rescheduling (rolling, event-triggered, done by machine learning or hybrid [75]) and the related planning frequency, the planning grid can be theoretically minimised until the actual plan represents a virtual image of the current production status at any time.

Both approaches presented may be understood as extremes on a scale of planning integration with an almost unlimited number of gradations and mixed forms being conceivable (see Fig. 5). According to Steven [41], a degree of integration of '0' indicates an entirely successive planning system, while a degree of integration of '1' classifies a complete integration of all planning activities into a central, simultaneous decision-making process. Neither of both has proven to be a suitable form in practice [42]. While completely successive planning usually leads to suboptimal planning results due to the lack of information backflow, a complete integration of all planning decisions in a central unit cannot be implemented efficiently due to the multitude of interdependencies that have to be taken into account simultaneously.

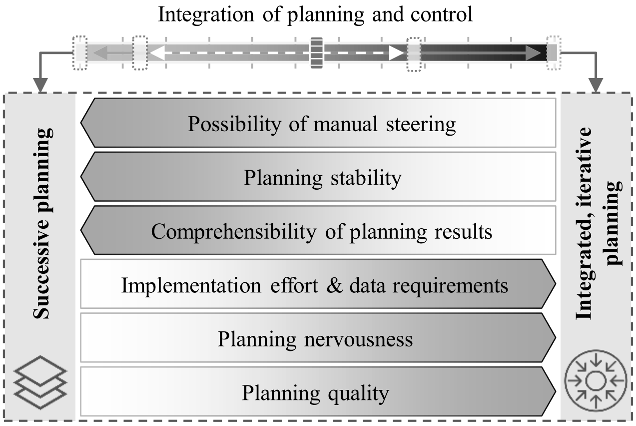

**FIGURE 5. Characteristics of the PPC depending on the degree of integration.**

Whereas in the past companies often tended to adopt comparatively less costly successive approaches due to the lack of data and computing capacity, integrated, iterative approaches are becoming increasingly important in the wake of increasing digitalisation in the manufacturing industry [76], [77]. Nevertheless, this should not be interpreted as a universal recommendation for or against a high degree of planning integration.

When designing the planning system and assessing the availability of required information and the effort required to obtain it, various other internal and external influences can affect the stability of the process and hence must also be taken into account. Fundamentally, it can be presumed that better consideration of short-term status changes or disruptions in the planned system can be achieved on average with increasing planning frequency. However, the continuous adjustment of planning also leads to less traceability of the planning processes and increases 'nervousness' in the areas of the supply chain that have to realise the planning. This nervousness is often counteracted with the introduction of so-called 'frozen zones'.

In order to derive a suitable planning system for each planning segment, the planning and control-oriented characterisation approaches by Große-Oetringhaus [78], Schuh and Stich [6] or the Key Manufacturing Characteristics according to Lödding [40] can be used as a basis. Nonetheless, a planning and control-oriented typology that comprehensively covers all relevant aspects is not available in the literature yet and needs to be developed in future research to provide a holistic PPC morphology.

#### 4) TARGET-ORIENTED SELECTION OF PPC PROCEDURES

As already mentioned in section II.C, many approaches assist the selection of suitable procedures for the PPC tasks. In order to enable a consistent and target-oriented production configuration, it is necessary to consider higher-level upstream configuration decisions and anticipate downstream configuration decisions as good as possible, which is not provided by existing approaches. Thus, the planning system (planning segments and degree of integration) envisaged in the previous sections must be considered.

In order to meet the overall requirements, the final selection of PPC procedures needs to be done, taking into account the multidirectional interactions between PPC tasks and procedures, e.g. by integrating logistics models into the analysis [9]. If the selection is conducted isolated and without a holistic view on PPC and production configuration, there is a risk of locally optimising a single supply chain's component or area. As a result, the logistics potentials of a holistic configuration would remain unused. A first qualitative approach to reduce complexity and provide a generally valid description of the interdependencies between procedures of PPC tasks and their effect on logistics objectives is provided by Schäfers [23] with a focus on (in-house) production planning and control. The clustering of PPC procedures and the development of a basic model for describing interdependencies of actuating variables, control variables and objectives with the tasks of production planning and control in the form of an integrated network effectively reduces the complexity in the selection of suitable procedures and demonstrates cause-and-effect relationships in a generally valid manner. The basic model of Schäfers can be found slightly modified in the appendix (Appendix 1). In addition to Schäfers' model [23], morphologies and typology approaches can also be used for the target-oriented selection of PPC procedures. Thus, a profound selection of PPC procedures for production control can be found on the basis of guiding questions in accordance to Nyhuis, Münzberg, and Kennemann [11] or by using the already presented Key Manufacturing Characteristics of Lödding [40].

However, since no holistic model for the quantitative description of the interdependencies is available, providing assistance to parameterise the procedures yet, the existing approaches such as the basic model by Schäfers [23], the model of manufacturing control according to Lödding [40] as well as Hanoverian Supply Chain Model by Schmidt and Schäfers [12] must be linked with the generally valid logistics models and transferred into a unifying model to enable the target-compliant configuration of PPC within production configuration. Appendix 1 provides a first insight into interactions between PPC procedures to be considered, using the example of the PPC tasks sequencing, order release and throughput scheduling. Furthermore, the logistics models enabling a quantitative examination of the interactions are mentioned.

#### 5) SUMMARY PPC CONFIGURATION

Overall, the configuration of PPC confronts companies with a wide variety of challenges. Based on the macro processes defined during structural design, first, the planning areas have to be derived. Subsequently, the planning-oriented (de-)coupling of planning segments must be determined, enabling a planning segment-specific definition of a planning system and the corresponding degree of integration to be realised. Depending on the preceding decisions, a target-oriented selection and parameterisation of PPC procedures finally must take place. Fig. 6 provides a summary of these decisions as well as their interactions with each other.

To support users in practice, the following guiding questions offer initial assistance in delimiting basic PPC configuration options focusing on internal processes like production control.

1) What is the planning segment's main objective in the overall organisational context and which objective has to be prioritised hereby?
2) Which internal or external influencing factors (superordinate, up- or downstream decisions) must be considered?
3) Which parameters (e.g. setup costs) should be considered in the planning process and provide the necessary, appropriate information basis?
4) What planning horizon should be covered?
5) What granularity must be achieved by production planning to support the achievement of the company's objectives?
6) Which planning horizon should be 'frozen' to facilitate process stability in the supply chain?

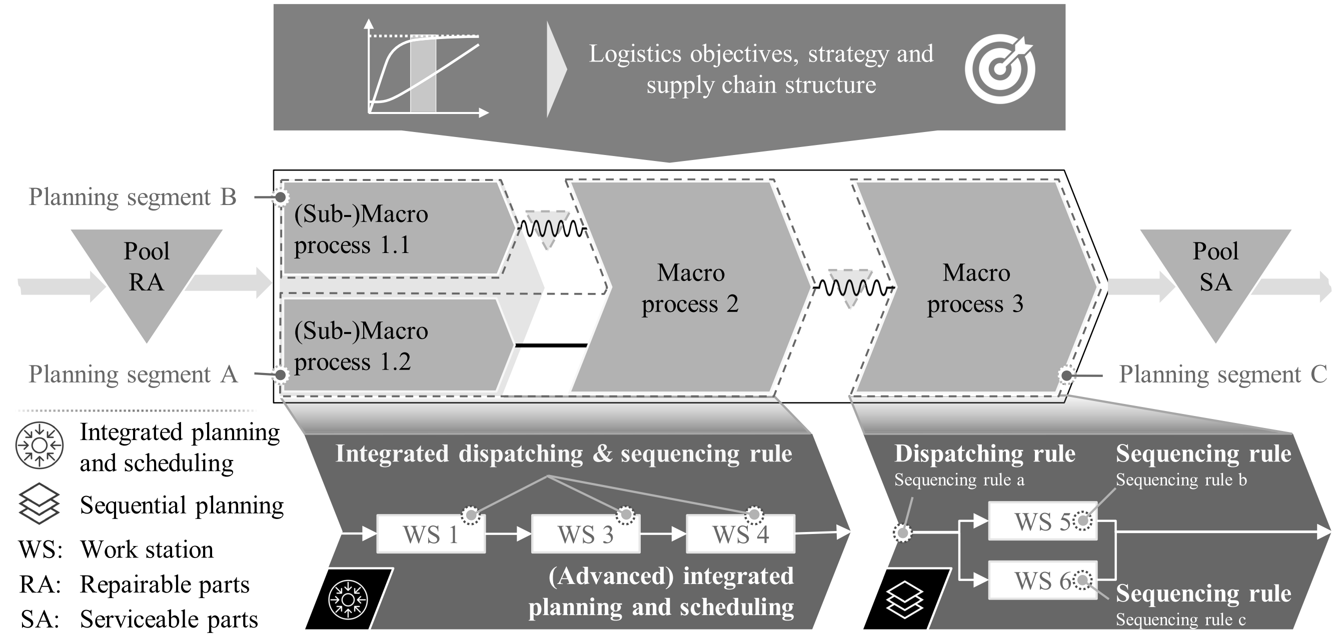

**FIGURE 6.** Overview on the result of PPC configuration.

7) Which triggers (event/time interval) should initiate a re-planning?
8) Which input data can be used for PPC, and which systemic support (IT systems) could be used?

### D. OPERATIONAL LEVEL: METHODS & PRINCIPLES FOR A TARGET-ORIENTED IMPLEMENTATION

To ensure an objective-oriented application of the production configuration in the operative business and continuously check its conformity with the overall corporate strategy, suitable methods and rules, as well as permanent monitoring of the logistics performance and logistics costs, are required. The responsive and reliable detection of changes of logistics-relevant parameters is a crucial success factor in order to be able to react to these changes immediately. This especially applies to the highly dynamic (market) environments MRO service providers are facing. A suitable approach to logistics controlling is the cybernetic control loop according to Wiener [79]. Within this approach, the actual system's performance is continuously monitored and compared to the targets and strategies at company and division level, and operationalised in KPIs and corresponding objectives, representing the reference to the cybernetic control loop. Process/production plans, derived from the configuration, serve as control parameters for the actual operations in the overall system, which is composed of individual planning areas. By comparing normative and descriptive KPIs, deviations of the actual system's status from the targeted and planned status can be detected. These, as well as changes in strategic or external reference parameters, can indicate configuration-relevant changes in the environmental conditions or the need for changes in production configuration. For a detailed discussion of the possible applications, methods and tools like a statistical machine and process monitoring (e.g. quality control charts), reference is made to Steger [80] and Gottmann [60].

If deviations of logistics objectives or parameters are identified, detecting their root cause is crucial for deriving effective and lasting countermeasures. Assistance in narrowing down potential causes is given by the logistic cause-effect relations trees by Schmidt, Maier, and Härtel [81] and Härtel [82]. Their structure combined with specific analyses of relevant KPIs allows for a systematic localisation of the root causes of deviations from their respective target or plan on the basis of generally valid multi-level cause-effect relationships. A representative example is provided by the production logistics operating curves (Fig. 1a). These allow for assessing the share of throughput time because of a high level of WIP in production systems [1]. When deviations are traced back to specific root causes (e.g. high WIP at a bottleneck work system), a critical success factor for the initialisation of effective corrective measures is the ability to distinguish between sporadic or stochastic deviations and those that are systematic or configuration-related. While sporadic deviations can usually be countered by short-term measures (e.g. non-recurring overtime), these measures may have a short-term effect in the case of configuration-related deviations as well. However, they do not lead to a long-term improvement by eliminating the respective root cause. A powerful tool to distinguish configuration-related changes in production logistics processes from typical, temporary scattering phenomena is provided by the production logistics control charts developed by Kennemann [83]. In order to integrate them into a cybernetic control loop, which is only focused on the operational application of the configuration so far, it is necessary to extend its focus to include production configuration as a whole.

### *E. CONTROL LOOP TO EXAMINE AND ADJUST PRODUCTION CONFIGURATION*

Due to the presented structure of the production configuration levels and the various corresponding cause and effect relationships, different points of intervention for deriving countermeasures result. Consequently, the cybernetic control system, which is focused on the operational processes, is expanded by three additional control loops for the two strategic and the tactical level (see Fig. 7).

The inner control loop can mostly be modelled as Ludwig's control loop for production control [84]. It can detect and handle minor deviations from targets that can be explained by temporary deviations between the objectives and the actual values, short-term fluctuations of external influencing factors, and the influences of customers during order processing that have not been taken into account or anticipated. Corresponding shortfalls regarding the logistics targets caused by natural process dispersion can usually be addressed with temporary and short-term countermeasures (e.g. shifting loads by applying component pooling and eliminating small backlogs using short-term capacity flexibility measures).

As shown in chapter IV.D, these measures usually also reduce shortfalls caused by structural misconfigurations in the short term. In this case, however, only the symptoms are temporarily addressed instead of sustainably fixing the actual causes of the logistics target shortfalls. In order to quickly derive effective and sustainable countermeasures, it is important to rapidly and reliably distinguish natural process variation induced by misconfigurations. Indicators of a need for change in production configuration can be the continuous non-achievement of strategic objectives or only achieving them by accepting high additional costs, e.g. high pool inventories. If deviations can be traced back to misconfigurations, reconfiguration is required at the tactical or strategic level. In this case, the inner control loop must be left, and production configuration controlling must be initiated. Here deviations, classified as configuration-related in production monitoring, need to be separated into those caused by PPC configuration, those caused by strategic design or structural decisions, or those arising from strategic objectives.

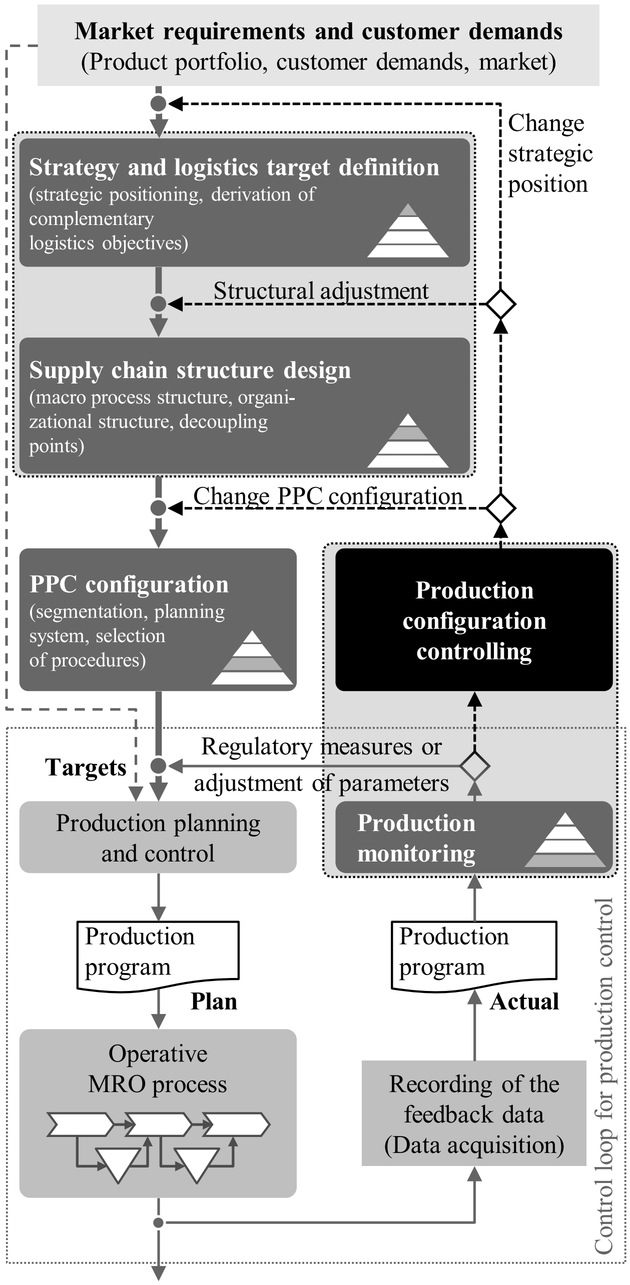

**FIGURE 7.** Production configuration control loop.

Consequently, three further feedback loops to production configuration levels 1, 2 and 3 emanate from this production configuration controlling. First, the PPC configuration must be checked (see chapter IV.C). For the selection of PPC procedures and parameterisation as well as assessing actual configurations, extensive studies can be found in the work of Nyhuis, Münzberg, and Kennemann [11], Lödding [40] and Schäfers [23]. If, even after multiple reconfigurations of the PPC, no configuration can be determined that is capable of meeting the strategic logistics objectives while maintaining the structure, a fundamental structural adjustment is required. Such adjustments may be decoupling processes into order-specific and order-anonymous sections of the supply chain or the implementation of additional work systems (e.g. exclusively for rush orders). Since structural decisions often interfere with the corporate strategy due to the required fundamental changes, a review of the strategic logistics objectives is also required. For example, adding capital bound to inventories in decoupling buffers usually requires consideration in corporate financial planning. It is evident that this breakdown can only be seen as a basic guideline for decision-making paths to identify and specify the need for reconfiguration. Nonetheless, it provides a universal framework to extend production monitoring to tactical and even strategic levels.

## V. SUMMARY

The framework for production configuration presented in this paper describes both a universally applicable procedure for initial production configuration and a methodology for production configuration controlling based on cybernetic control loops. Thus, it serves as a framework for designing efficient and competitive production structures.

The framework presented is based on a number of existing theories, models and methods, including the logistics models for positioning in production logistics target conflicts. In addition to these, a variety of approaches and methods exist, e.g. within the Lean philosophy, whose basic idea (e.g. that of Hoshin Kanri) is also foundable in the framework for production configuration. At the same time, these tools can be used to support specific activities within the different levels of production configuration. The presented framework is therefore not to be seen as a complete collection of tools and methods, but instead as an approach that describes the steps, goals, interactions, and problems to be gone through when deriving and defining a production configuration.

The starting point of production configuration is the definition of the corporate strategy and the business model pursued. These have to be translated into KPIs and corresponding target values at the corporate level and be projected to subordinate levels. The underlying supply chain structure for the order fulfilment process is fundamentally defined by the macro process structure. It is further detailed by the choice of manufacturing principles applied, the vertical segmentation of the production areas included, and the decoupling scenarios implemented. Based on this supply chain structure, the configuration of production planning and control is carried out by identifying planning areas composed of elementary supply chain components and their links to each other, defining the degree/depth of integration of the PPC tasks to be realised in these areas, and determining their configuration and parameterisation. Multiple cybernetic control loops are used to ensure the correct implementation of and compliance with configuration decisions made during operation and to check their conformity with the logistics objectives and the overall targets. Each loop is used to derive suitable corrective measures to restore overall target conformity. If 'misconfigurations' can be identified, it may be necessary not only to apply short-term measures, such as temporary capacity adjustments but also to trigger adjustments on higher configuration levels. These adjustments may include the degrees of integration of the PPC tasks selected at the tactical level, as well as the procedures and parameters selected therein, an adjustment of the supply chain structure or the company's target definition. The same applies if no combination of methods and parameters can be identified that is suitable for eliminating the identified root causes of the deviations or achieving the defined objectives. In addition to the reaction to identified shortcomings, changes on strategic configuration levels can also necessitate a reconfiguration of the production configuration. If, for example, the product portfolio is changed from very homogeneous to highly varying capacity demands per production order, a strict synchronisation/clocking of the production content in combination with the transformation to the flow production principle, which was previously introduced to increase efficiency gains, can cause significant utilisation losses.

## VI. CONCLUSION AND OUTLOOK

### A. CONTRIBUTION TO THEORY

The presented research is an extension of the existing theory in several ways. First, a definitional framework for the consideration of production configuration is presented. Furthermore, for the first time, production configuration is considered and described in a holistic form covering the strategic up the operational level, bringing mainly isolated topics and issues into connection with each other. In this way, the conducted research contributes to the theory of production organisation. Moreover, existing approaches and models are located within production configuration, and gaps in theory are identified. Due to the final definition of the production configuration control loop, the presented framework is completed by a condensed and clear model.

### B. CONTRIBUTION TO PRACTICE

Companies are facing the significant challenge to configure their production in a way that the logistics performance is in accordance with the corporate strategy. At the same time, however, there often remains uncertainty or a lack of understanding regarding the interactions and interdependencies between different decisions in production configuration. Consequently, no matter how good the choice of e.g. PPC procedures might be, it cannot compensate for a non-suitable structural design. This contribution transparently presents the issues and challenges of production configuration and translates them into a comprehensible and applicable model, which can increase the knowledge of interactions and the corresponding awareness in companies. Thus, a better understanding of the system allows them to systematically identify faults in their production configuration and initiate appropriate countermeasures to remain competitive on a sustained basis.

In the course of our research on the example of MRO service providers, further questions from a practical point of view are identified and located. Hence, this made apparent that material supply needs to be integrated into the planning and control, particularly in the case of multi-staged (pool) structures, to utilise their full logistics potential. If pooling is used as an instrument for reducing throughput times, it can only fulfil this function as long as the input schedule deviation at the reassembly does not necessitate cushioning of process scatter in material supply and thus tying up components for this purpose.

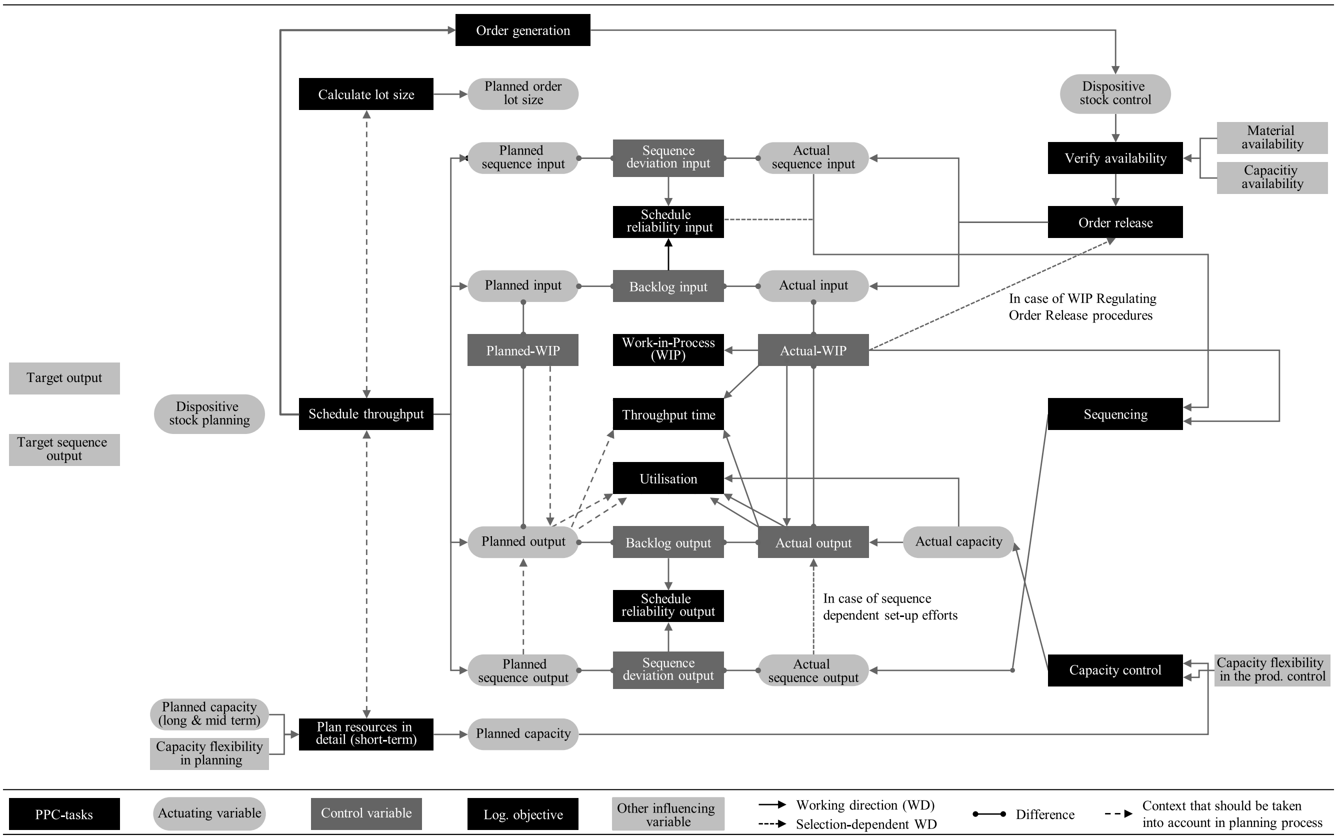

**FIGURE 8.** Basic PPC model of Schäfers [23] (slightly modified).

## C. LIMITATIONS AND FURTHER RESEARCH

The multitude of influencing factors and interdependencies along all four levels of production configuration, which can only be demonstrated in excerpts based on the examples used in this paper, makes the task of production configuration extremely challenging. The presented framework structures this complex task and establishes a long-lasting mechanism for defining and reviewing companies' production configurations. In doing so, the principal levels of consideration and their interactions can be located. However, it should be noted that the presented framework cannot replace a valid, proper and consistent understanding of the logistics system. Moreover, it became clear that there is a need for further research on the individual levels and sub-questions of production configuration, not only to provide users with the framework itself but also with corresponding tools. Furthermore, interactions between production configuration and other areas of production logistics, such as factory planning, should be taken into account to consider structural influences and restrictions in the decisions.

In order to further structure and support relevant configuration decisions, the Hanoverian Supply Chain Model mentioned above is being extended within current research activities to include cause-effect relationships at the level of the PPC tasks as well as a consistent description of the (mutual) effects of PPC procedures on each other and the logistics objectives. In addition, it is necessary to develop a methodology for deriving the ideal degree of integration of PPC tasks in the planning system, taking into account the company's individual typology and predefined strategic configuration decisions. This will form the basis for subsequent detailing of the framework presented in this paper for configuring integrated PPC systems. In doing so, the focus of previous approaches has to be broadened to include configuration decisions such as the definition and dimension of planning iterations and 'frozen zones'.

## APPENDIX
## EXAMPLE OF INTERACTIONS BETWEEN PPC PROCEDURES FOLLOWING [9]

The effect of different procedures for sequencing on logistics objectives can be well described quantitatively by logistics models (cf. section II.B) [31], [32], [85]. Thus, the selected procedure decisively determines the actual sequence in the output, which, in comparison with the planned sequence in the output, affects the control variable sequence deviation in the output and thus on the objective schedule reliability in the output [23], [40]. Consequently, the actual sequence in the output depends on the chosen procedure and, with respect to the chosen procedure, on the control variables actual work-in-process (WIP) and the actual sequence or the adherence to schedules in the input.

This is explainable because as the WIP increases, the possibility for interchanging the orders' sequence rises, and, as long as no interchanges occur, the actual sequence in the output corresponds to the sequence in the input. However, if the intention is to improve the schedule reliability in the output and to counteract previous interchanges in the input of a work system using, for example, a due-date-oriented sequencing rule, a conflict of objectives arises between the strength of the sequencing effect, which increases with increasing WIP, and the likewise increasing throughput time of the work system. According to Mütze and Nyhuis [32], a positioning in this field of tension and the necessary WIP can be determined by linking the logistics models.

The actual WIP, however, is significantly influenced by two other PPC tasks. Firstly, by order release, which can actively influence the WIP at each work system by choosing a load-oriented procedure, and secondly, by throughput scheduling, which regulates the planned WIP, the throughput time and indirectly, via order generation, the disposable stock available for order release [23], [40]. If a constant WIP at work systems is to be set, this requires a corresponding selection of procedures and parameterisation of the PPC tasks. Using the Logistic Operating Curve Theory, the effects of WIP regulation on the logistics objectives throughput time and output rate can be determined, and a positioning can be done [1].

However, as shown in Fig. 8, there are many other links between these three PPC tasks shown via different paths of actuating variables, control variables and objectives. For example, order release not only influences the WIP but also affects the actual sequence in the input, leading to further conflicts of objectives in the selection of procedures. This results from a positive effect of an inventory-regulating procedure on a stable WIP and throughput times that collides with an initial sequence deviation in the input, depending on the degree of integration of production planning and production control.

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