An approach for applying autonomous production control methods with central production planning

Sebastian Grundstein, Susanne Schukraft, Michael Görges, Bernd Scholz-Reiter

Abstract**—**Manufacturing companies must face increasingly difficult production environments. External factors such as varying product variants and varying quantities as well as internal factors such as reworking and resource breakdowns pose a high challenge for production planning and control (PPC). Dealing with such aspects of dynamics and complexity in the PPC-process is crucial for the efficiency of modern production systems. However, common central planning methods in industrial application show deficits in complex and dynamic production environments. In contrast to prevailing central planning methods, approaches of autonomous control offer the chance to cope with these dynamic conditions more efficiently. Nevertheless, there is currently a lack of knowledge concerning the interlinking of central production planning with autonomous production control. This interlinking promises the advantages of both approaches. Therefore, the interdependencies between planning and control have to be analyzed in order to combine both approaches efficiently. A successful interlinking provides production planning instruments, which create a detailed and stable production plan and are able to cope with dynamic influences.

In this context, the paper on hand describes the basic approach and potentials for the interlinking of central planning and autonomous control and gives an outlook on further research activities.

Keywords**—**Autonomous Control, Central Planning, Production Planning and Control, PPC

I. INTRODUCTION

DUE to increasing market dynamics and the resulting fluctuations in demand, the processes of production planning, optimization, and control have become more challenging for manufacturing companies [1]. This situation is characterized by growing complexity [2], which is intensified by the rising integration into global value chain networks [3]. Existing central methods for the process of production planning and control (PPC) are often not able to cope sufficiently with the increasing dynamics and complexity [4]. Unplanned disturbances of the production process can lead to deviations from the production schedule and thus to deviations from defined delivery dates. In this context, autonomous control methods are considered as a promising approach for coping with increasing dynamics and complexity in logistic processes [5]. Whereas central methods use predefined production schedules, autonomous control methods enable logistic objects (e.g. production orders) to decide depending on the current situation. Thus, central methods allow detailed and structured planning, while autonomous methods are able to cope with dynamic situations more efficiently.

However, central planning and autonomous control methods were commonly developed and evaluated independently of each other. Successfully interlinking these approaches promises the benefits both of central planning and of autonomous control.

The development of methods for the interlinking of both approaches is also of high relevance for industrial application. Nowadays, most production planning and control systems mainly process central methods which do not consider autonomous control approaches. To gain the benefits of autonomous control, it is necessary to integrate these methods into existing PPC systems. Today’s PPC system users appreciate the detailed and structured planning basis, which is granted by central planning methods. Therefore, it is crucial for the acceptance of autonomous control methods to maintain this benefit. Our current research deals with the development of methods for interlinking central production planning with autonomous control. The expected results will provide production planning instruments, which create stable plans and are able to cope with dynamic influences.

In this context, the paper on hand explains the approach for interlinking central production planning with autonomous production control.

II. CENTRAL PRODUCTION PLANNING AND AUTONOMOUS CONTROL METHODS AND MODELING

A. *Production planning and control process*

Production planning and control provides the basis for organizing and executing the production process [6]. PPC comprises the planning and control of manufacturing and

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assembly processes regarding adherence to delivery dates, production volume and capacity. Thereby, the generic aim is the efficient utilization of the production system [7].

PPC generally focuses on creating a production program for several planning periods, deducing demands of resources and afterwards realizing the program [8]. Initially, the primary demands and the production program are generated out of market and sales forecasts. The production program determines the volume of final products to be produced in each planning period. Subsequently, the demand planning process determines secondary demands in terms of material and resources for each planning period. The make-or-buy decision is also based on these primary demands. External production for example is relevant if the demands exceed available in-house production capacities. In case of in-house production, the planning and control determines batch sizes, detailed scheduling of production orders, the resource balancing of production resources as well as the order release and control [8]. These planning results determine the planned behavior of the production system as an input for the production process. The detailed scheduling comprises the allocation of production orders in terms of place and time to available production resources, e.g. in a production schedule for particular machines. This planning step considers the spatio-temporal allocation as well as planned capacities of resources [9]. There are diverse methods for supporting the detailed scheduling such as interactive control centers, sequencing rules or optimization methods. Sequencing rules and optimization methods generate production plans based on algorithms, respectively predefined rules. Control centers provide the additional possibility to check the consistency before or during the plan execution and, if required, to take appropriate corrective measures [7, 9].

The following sections present tasks and approaches of detailed scheduling from the field of central production planning as well as autonomous control approaches with their benefits. The resulting research gap and necessary work is concluded at the end of section 2.

B. Central production planning

There are various optimization methods and heuristics for the planning process depending on the production environment. This environment is among others characterized by the type of available machines and their arrangement. It is generally differentiated between single-machine arrangements, arrangements with identic parallel machines and arrangements with non-identical machines [10].

Graham, Lawler, Lenstra & Rinnooy Kan describe problem classes by type of machine environment (α), job characteristics (β) and chosen optimality criteria (γ) [11]. This (α, β, γ)-notation enables the description and classification of various production settings depending on the machine environment and considered performance figures. The machine environment comprises single machine, identic parallel machine, uniform parallel machine and unrelated parallel machine arrangements. It further distinguishes between Flow-shop, Flexible-flow-shop, Job-shop and Open-shop arrangements. Specific job characteristics describe for example varying release dates, required setup times or constraints regarding the job splitting. Optimality criteria describe possible performance indicators such as makespan or total flow-time. Combining machine environments with job characteristics and optimality criteria enables the definition of many different production problems. Especially in job shop production there are highly complex and related material flow structures, which are clustered in Flexible-flow-shop, Job-shop und Open-shop problems [12]. Already small instances of these detailed planning problems are NP-hard. This means that an optimal problem solution cannot be found analytically within adequate computing time [17]. Therefore, sequencing rules, problem-specific heuristics and meta-heuristics are mainly used for creating production plans.

In general, sequencing rules can be applied to various production environments [13]. Sequencing rules assign priorities to production orders according to specific principles. They usually improve the performance for a particular target value, but they do not ensure global improvement in performance [14].

Optimization methods, in contrast to sequencing rules, are based on the generation of a production plan that optimally fulfills a predefined target function. Due to the complexity of the optimization problem, nowadays mainly heuristics can be applied efficiently to larger problems [15]. Thereby, most heuristics are designed for specific problem scenarios. They use problem specific knowledge about circumstances and restrictions to reduce the possible solution space. According to the multiplicity of planning problems, there is a vast number of problem specific heuristics [16]. Metaheuristics such as Tabu Seach, Simulated Annealing or Genetic Algorithms, in contrast to problem specific heuristics, are based on the idea to use existing heuristics or sequencing rules to create an initial solution, respectively an initial population [16-17]. Rule-based nearest neighbor methods modify the initial solution and evaluate the solution by a chosen target function. The procedure ends after a defined number of iterations and gives the best solution as a result [18]. An overview of existing approaches, clustered by single-machine problems, problems with parallel machines, Flexible-flow-shop, Job-shop and Open-shop is given in [16].

Dynamic disturbances in the operative execution of production plans such as rush orders or machine breakdowns can lead to a high deviation from the original production plan. This causes rising cycle times and/ or an unsatisfying adherence to delivery dates. Therefore, approaches of reactive and robust planning are increasingly in the focus of scientific consideration [19]. While approaches of robust planning aim at the consideration of dynamic perturbations already during the production planning, reactive approaches aim at the adaption of production plans to changing conditions during the run-time. Reactive approaches adapt the plan partially or induce a full rescheduling. Generally, these approaches can be differentiated into predicative, reactive, predicative/ reactive and proactive ones [20].

These approaches deal with production systems from a central perspective. As an alternative, the concept of autonomous control focuses on coping with perturbations by means of autonomous decision-making authority.

C. Autonomous production control

Autonomous control methods enable coping with undesirable dynamics in the production process. In contrast to reactive, predicative/reactive or proactive approaches they are not based on central planning, but on decentralized decision-making authority [21]. In order to increase the robustness and to ensure the logistic performance under dynamic conditions, logistic objects interact with each other, exchange information and decide for themselves on this basis [1]. The concurrence of these autonomous decisions directly influences the system status, which is in turn the decision basis for future decisions of autonomous logistic objects. According to this behavior, the chaining of multiple autonomous decisions causes self-supporting dynamic system behavior. From the perspective of self-organizing systems, this behavior can be described as emergent [22]. Appropriate information and communication technology ensures the interaction of logistic objects in this context. Examples for these technical enablers are component-integrated sensors and communication interfaces. Especially the permanent data availability enables the implementation of real-time production control operations [23].

Prevailing autonomous control approaches focus on the usage of existing flexibility potentials in the production system for generating decision alternatives [24]. For that matter, parts or production orders can be enabled to decide autonomously on available alternative routes through the production system [25]. Applying appropriate autonomous control strategies can have a positive influence both on the logistic performance and on the internal system dynamics. Autonomous control methods increase the logistic performance, especially under the condition of growing external dynamics [26].

In literature there are autonomous control methods comprising several different possible applications depending on the desired logistic command variable, such as cycle time or adherence to delivery dates, or on the machine configuration, like set-up time or machine arrangement [25]. A possible classification pattern contains the criteria time reference, number of planning steps, type of communication, data usage, actuator and data source [26]. This classification can be expanded by differentiating the criterion data usage, respectively its information horizon, into local information based methods and information discovery methods [26]. Parts using local information based methods rely on decision relevant information about the system status, which is acquired from objects in their adjacencies, such as machines or buffers.

These methods can furthermore be differentiated according to the decision logic into rational methods and bounded rational methods. Rational methods take solely rational information like estimated waiting time or expected finish date into account [25]. Bounded rational methods comprise for example bio-analogue methods, which adapt the self-organizing behavior of real biological systems. There are bio-analogue methods adapting the foraging behavior of ants [21, 28], adapting the communication pattern of bee colonies [29] or adapting the kinetic behavior of flagellated bacteria [30]. Such autonomous control methods have already been developed within the Collaborative Research Centre 637 at the University of Bremen [31]-[33] as well as concepts of the infrastructure [34], [35] and concepts for simulation [36], [37]. Information discovery methods, in contrast, additionally enable local decisions of logistic objects such as machines or semi-finished products. However, these methods use data exceeding the local information horizon. Existing information discovery concepts use methods of data communication, which specifically request information from a network. This enables the anticipation of future system states and the consideration of these anticipations in the local decision making process [18].

D. Modeling logistic systems

There are several approaches for modeling and simulation of logistic systems, which can be divided by the type of state transition [38]. Within the simulation, this criterion describes the relationship between state variables and the progression of time. Generally, simulations can be divided into continuous, time-discrete and hybrid types. Continuous simulations treat model time as a continuous variable. The system variables change continuously depending on the model time. In time-discrete simulations system variables change stepwise in countable time intervals. If the progress in time is implemented not by equidistant time steps, but by the incidence of events, then these are event-discrete models. Hybrid simulations comprise both continuous elements (such as material flows) and discrete elements (such as control elements of the material flow) [39]. Continuous simulations are especially appropriate to evaluate aggregated tasks for basic cause-effect-mechanisms. Discrete simulations fulfill high requirements on the modeling granularity [40]-[41]. This modeling granularity is required in logistic systems to analyze the mutual interdependencies between single logistic objects including their causes [42].

E. Research Gap

Nowadays, mainly predicative planning approaches are used for the detailed schedule

ng in production systems. However, the resulting a priori plans entail high plan variations and a reduced logistic performance under dynamic conditions. Existing central approaches try to cope with this dynamics by creating robust production plans or reacting quickly to disturbances of the production schedule. Main disadvantage of approaches for creating robust production plans is the dependency on the forecasting quality concerning dynamic influences. The weakness of reactive approaches is the effect of so-called planning nervousness. It describes the phenomenon, that already minor deviations of production parameters can cause strong deviations of the production schedule [43].

In this context, autonomous control methods mark a paradigm shift from a central to an autonomous perspective. These autonomous approaches enable coping with undesired dynamics in production systems. Nevertheless, it is essential to maintain the benefit of planning security of central planning methods. Therefore, there is a need for new methods of interlinking central planning methods with autonomous control methods in the context of production systems.

III. APPROACH AND METHODOLOGY

A. General Approach

Successfully interlinking central production planning with autonomous control influences both the production system's behavior and its performance regarding logistic target values. Fig. 1 illustrates the approach for the interlinking of autonomous control with production planning and the basic relationship between methods of central production planning and autonomous control.

The approach focuses particularly on the interdependencies between central planning and autonomous control in the context of in-house PPC. Applying autonomous control methods in the production control process enables efficient reactions towards dynamic influences and disturbances. However, these methods potentially cause variations from the original production schedule. Consequently, adjustments of planned parameters are necessary to improve the logistic performance. This relationship between the degree of plan fulfillment on the one hand, and the logistic performance referring to operative logistic command variables on the other hand is also shown in Fig. 1 in the context of dynamic production systems.

B. Methodology

Central research task is the development of efficient methods for interlinking central production planning with autonomous control to improve both the logistic performance and the degree of plan fulfillment in production systems. The methodology of managing this task comprises seven fields of action, referred to as tasks in the following.

The first task consists of developing specific categories of production problems to describe different production systems. Using the portfolio technique it is particularly possible to represent complex structures of material flows, such as job-shop, flexible-flow-shop or open-shop problems. The planning process causes different initial dynamic influences for each problem type, which can also be depicted in the portfolio. Additional portfolios for applicable planning heuristics and appropriate autonomous control methods are required to guarantee an integrated modeling approach. These three compatibility portfolios serve as basis for a recommendation, which planning heuristic in combination with which autonomous control approach can be used for specific categories of production problems.

The second task enables an evaluation of the effects when applying autonomous control methods concerning the degree of plan fulfillment. This is necessary in order to provide a substantiated recommendation. Therefore, an appropriate evaluation scheme is developed, that can be applied to all identified categories of production problems. It comprises the definition of representative production scenarios and evaluation criteria as basis for the later simulation model. As mentioned above, an extensive evaluation explores the effects of interlinked central planning and autonomous control both on the logistic performance and on the degree of plan fulfillment. Therefore, it is insufficient to carry out an

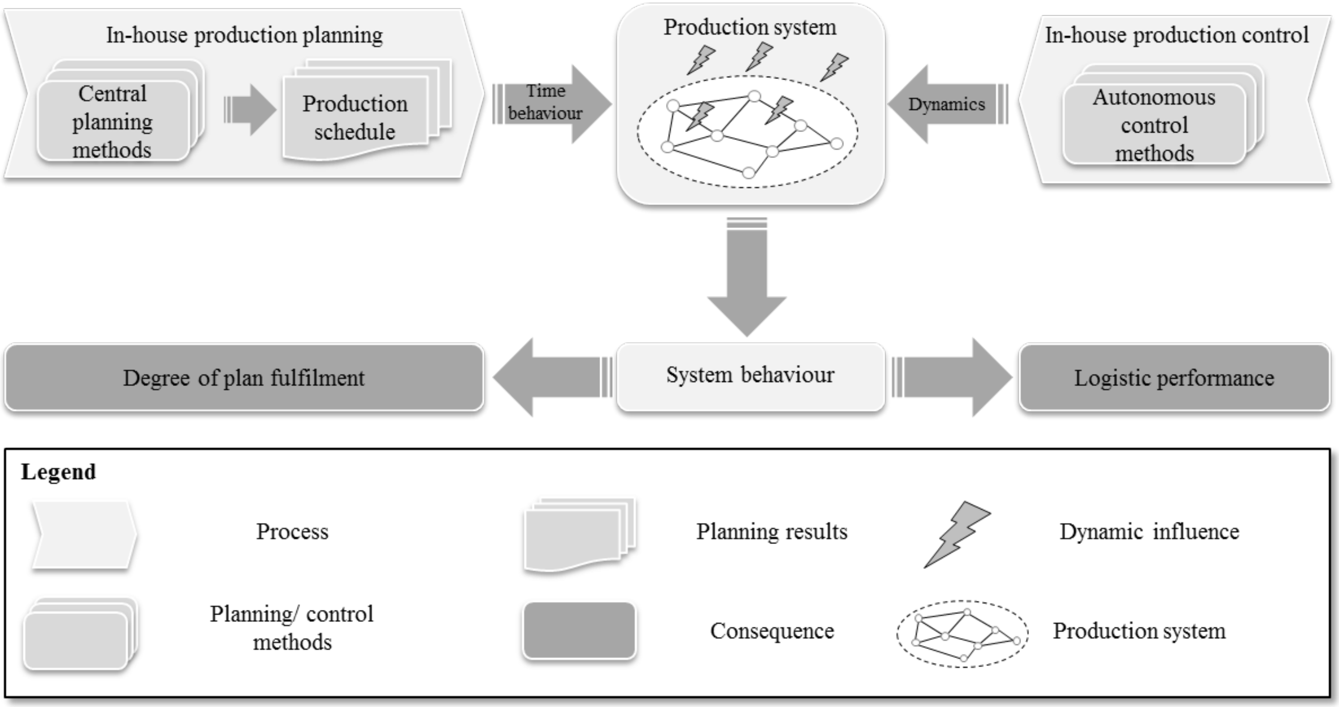

Figure 1: Relationships of interlinking central production planning and autonomous production control

evaluation solely on the basis of statistical performance indicators such as cycle time, stock and adherence to delivery dates or utilized capacity. The evaluation rather has to consider the robustness of production schedules, respectively possible plan variations. In literature there are various problem-specific approaches to accomplish this evaluation. These are based on different key performance indicators such as the variation of due dates like start or end of production, make-span variations or variations in the production sequence. Therefore, they are restrictedly comparable.

Setting up an executable simulation model in Tecnomatix Plant Simulation represents the third task. This software contains several interfaces (e.g. to C, SQL), offers functions for structured experiment administration and is therefore particularly suitable for our approach. The simulation model represents the identified production problems, central planning methods and autonomous control methods. It enables extensive analysis and evaluations of possible combinations.

The fourth task lies in the processing of the evaluation results. The systematic preparation of the findings is done by means of an evaluation matrix. The results serve as decision basis for identifying critical combinations of central planning methods and autonomous control methods for the various production scenarios in form of production problem categories. Critically in this context means, that the logistic performance or the degree of plan fulfillment is insufficiently. In these cases, further detailed time series analyses investigate the dynamics in the production system to identify the underlying reasons for the insufficient target achievement.

Designing appropriate and problem specific measures for interlinking central production planning with autonomous control represents the fifth task. This work also includes the identification of inappropriate combinations. A variable degree of autonomy serves as guideline for the design of interlinking methods. It can for instance be achieved by changing the parameterization or the mathematical decision logic of autonomous methods. The interlinking itself can for instance be achieved by changing the parameterization of autonomous control methods, by expanding the relevant control variables of autonomous decision making or by designing a new control method.

The sixth task comprises the evaluation of the designed methods including the adjustments with real production data from a commercial PPC-system. The combination of central planning and autonomous control methods for this use case will be validated by means of a representative and realistic production scenario from industrial application. So the result of this task is die validation of previous results under real production conditions and an extension of the evaluation matrix.

The seventh task provides the findings in a generally applicable framework. This framework is created by clustering the results of the evaluation matrix according to the properties of the several evaluated production scenarios. This framework of central production planning methods and autonomous control methods serves as a decision tool for both academic and industrial application. It enables the selection of appropriate combinations of central production planning and autonomous control methods for design, parameterization and operation of efficient production systems. Therefore, it contains guidelines, rules and constellations of parameters for the conception and the operation of combined central planning and autonomous control methods.

C. *Modeling dependencies using the DSM-Method*

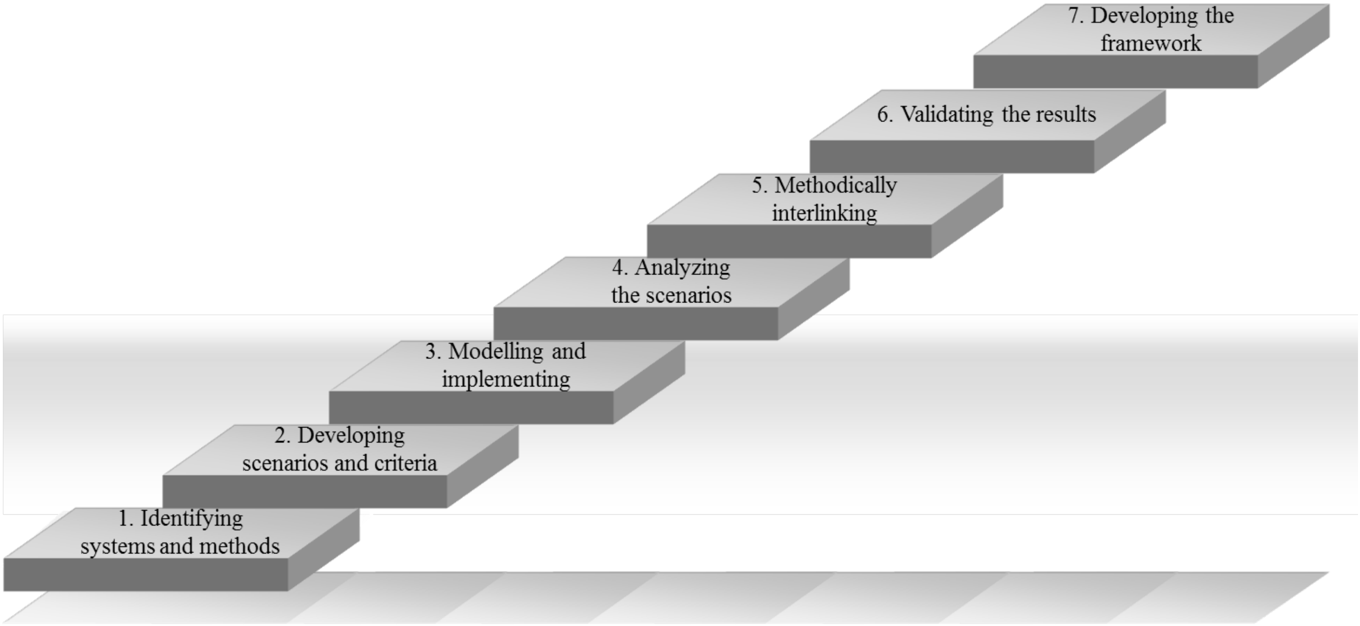

Figure 2: Fields of action interlinking central production planning with autonomous control

While Fig. 2 illustrates the fields of action in the basic logical order, it is necessary to investigate the dependencies of the single elements for planning further activities. The Design Structure Matrix (DSM) is considered as an appropriate method for analyzing the relationships of elements in highly networked systems [44]. Generally, Design Structure Matrices can be divided into static and time-based matrices [45]. While static DSMs represent functional relations between system elements, time-based DSMs indicate the flow of time by the ordering of rows and columns [44], [45]. Approaches using DMS for detailed scheduling of project activities can be found in [46], [47]. We apply a time-based DSM for analyzing the dependencies between the (intermediary) results as explained in the methodology using the notation given in [48] to describe possible relationships. Thereby, we differentiate between Finish-Start-relationships (FS), Start-Start-relationships (SS) and Finish-Finish-relationships (FF). A FS-relationship means that result A is required to start working based on result B. A SS relationship indicates that for result B an early intermediary result from A is necessary. And a FF relationship analogously states that result B requires a late intermediary result from A. An application of this method on the (intermediary) results described in the methodology is shown in Fig. 3. It is to be read according to the principle “line influences column”.

The application of the DSM for the introduced approach allows the identification and specification of dependencies. Thus, on the one hand it supports the project management process and ensures that (intermediary) results will be prepared adequately to support subsequent activities. On the

SS: Start-Start FS: Finish-Start FF: Finish-Finish	Categories of production problems	Overview of central planning methods	Overview of autonomous control methods	Compatibility portfolio: production problems - planning methods	Compatibility portfolio: production problems - autonomous control methods	Compatibility portfolio: planning methods - autonomous control methods	Representative production scenarios	Multicriteria evaluation scheme	Simulation models	Evaluation matrix	Interlinking method(s)	Extended evaluation matrix with interlinking method(s) and real data	Framework
Categories of production problems	■			FS	FS		FS	FS					
Overview of central planning methods		■		FS		FS		FS	FF				
Overview of autonomous control methods			■		FS	FS		FS	FF				
Compatibility portfolio: production problems - planning methods				■									
Compatibility portfolio: production problems - autonomous control methods					■								
Compatibility portfolio: planning methods - autonomous control methods						■							
Representative production scenarios							■		FF				
Multicriteria evaluation scheme								■	FF				
Simulation models									■	SS			
Evaluation matrix										■	FS		
Interlinking method(s)											■	FS	
Extended evaluation matrix with interlinking method(s) and real data												■	FS
Framework													■

Figure 3: Applying the DSM to approach elements

other hand, the analysis of these dependencies gives an overview over content based correlations and thereby supports the development process of interlinking methods between central planning and autonomous control methods.

IV. CONCLUSION

Today, production planning and control faces increasing market dynamics and growing complexity caused by on-going integration into global value chain networks. Autonomous control methods are considered a promising approach for coping with these challenges. However, it is important for industrial application to maintain the planning security of central planning approaches. Therefore, the interlinking of autonomous control methods with central planning methods promises the combination of the advantages of both methods. This paper presents the basic approach to enable this interlinking. Expected future results are going to provide the scientific basis for the practical application.

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