Knowledge-based planning and evaluation of production systems

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Abstract

Uncertainties as well as a variety of company internal and external factors influence the development of production systems. Adequate methods and tools are necessary for the planning processes. This paper presents a new concept for complete planning and multi-criteria evaluating of production systems inclusive a first software based realization and an exemplary planning application. Identified enablers are used to reduce planning time, to diminish planning costs and to increase the planning securing. The concept can be seen as a complementary tool for planning production systems. The concept is characterized by following points: application of a knowledge storage including their assessment, bottom-up planning of variants, planning securing via employing an integrated stochastic simulation model for the consideration of uncertainties, ramp-up and series-specific effects and automating routine tasks.

1. Introduction

1.1. Problem

Producing companies are always exposed to new challenges. Nowadays, a central challenge is the globalization [1] which leads to an increased competition and cost pressure [2]. The current business environment can be described as dynamic, discontinuous, turbulent, complex and uncertain [3, 4]. Characteristics therefore are for example shorter product life cycles [5], turbulent and volatile markets [6], higher individualization of customer requirements with the consequences of smaller volumes [7] and higher product complexity [8] as well as a volume fluctuation in short times [9]. These numerous challenges complicate accurate forecasts of future trends. However, they must be taken into account for the development of production systems. The planning difficulty is the trade-off between necessary flexibility, cost and time. The consequences of the numerous challenges are:

- increasing planning frequency [10],
- shorter planning times [11],
- higher planning flexibility,
- increasing planning complexity [8] and
- increasing uncertainties [4].

In order to manage these circumstances successfully for a long-term, new methods and tools for the planning process are required. On the one hand, they can be used for decision support, on the other hand, they can help to save planning costs and time.

1.2. Current situation

For the planning of production systems, there are already a number of different methods and tools. Mainly standardized design and simulation programs such as material flow simulation and visualization of concepts based on the principle of the digital factory are used. These standard tools do not have always the desired functionalities. Hence, individual, specially designed programs or calculation tables which are tailored to the specific requirements are often used. During the planning process, a number of

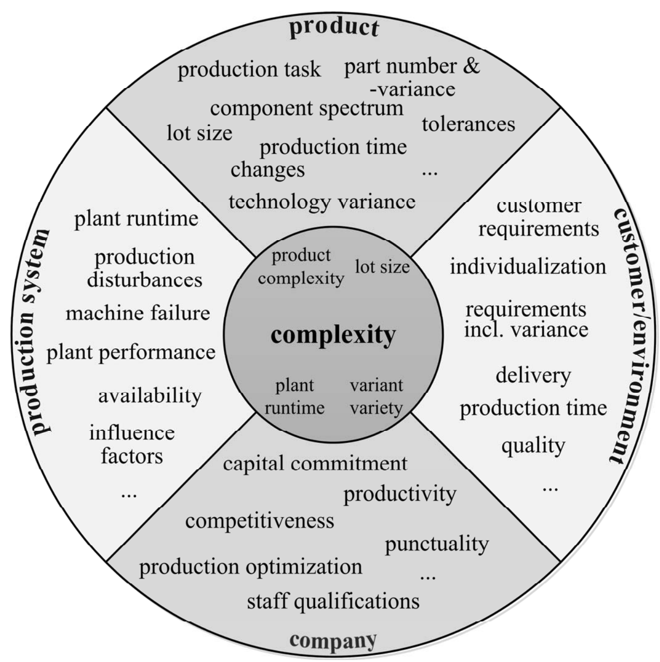

Figure 1: Parameters for the planning process [12]

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		TIME REFERENCE			
		static consideration of a specific point in time: model abstracts from the time		**dynamic** consideration of a period: model describes the system changes in time	
UNAMBIGUITY	**deterministic** all incoming data known/determined	value - from theory - from measurement - from estimation	value - from analysis	function of time - from theory - from measurement - from estimation	time function values - from analysis
		example: investigation, for example optimal cycle time of a production system		example: study of dynamic contexts in production systems with for example learning effects and demand	
	stochastic specification of probabilities, because procedure depends on random influences	distribution - from theory - from measurement - from estimation	set of values (sample) - realization from analysis	stochastic process - from theory - from measurement - from estimation	time function values (sample quantity) - time series of realizations from analysis
		example: planning of investments for one point of time under uncertainty		example: planning of production processes over time with uncertainties (e.g. fluctuating operating times) with inclusion of e.g. learning effects	
		exogenous data	endogenous data	exogenous data	endogenous data

Figure 2: Classification of the data requirements and the results depending on the model type [12]

requirements have to be considered which are results from the product, the customer or the business environment, the company and the production systems (see extract in figure 1). The number and complexity of factors and their interaction significantly influence the justified planning effort.

Stochastic and dynamic aspects can take a special importance in planning. Figure 2 illustrates the time reference and the uniqueness of exogenous and endogenous data. Static methods are based on a one period analysis. In contrast, dynamic methods allow a multi-period analysis. In this way i.a. learning effects and time-dependent variables (e.g. failure probabilities, production rates and demands) are taken into account. On the side of the data, the uniqueness can differentiate. In the case of deterministic assumptions, these are clearly specified. If data depends on random influences, probabilities can be specified.

The choice of the necessary time reference and data quality for planning depends on the particular issue. For example, specific time points with deterministic data would satisfy for a study of the optimal cycle time of a production system. In contrast, the consideration of a period and the specification of probabilities for data allow an analysis taking into account the time with uncertainties (e.g. failure probability) including for example learning effects.

1.3. Objective

This paper presents a new developed approach to support the planning process of production systems by using a bottom-up procedure. The aim of these approach is to increase the planning quality, to shorten the planning time and to reduce the planning costs. In addition to the concept which is called PEAS-concept (primarily developed for Planning and Evaluating Assembly Systems), a first software-based implementation and an application example is introduced.

2. Theoretical background

For supporting the planning process, different methods can be used. These include for example the VDI guidelines 2221 [13] and 2222 [14], method of Bullinger [15] and 6-step method of REFA [16]. All methods subdivide the planning in different phases. The sequence, iteration and content of the steps depend on the methods. In general, the procedure can be divided into problem analysis, problem formulation, development and design as well as system implementation and operation. [17, 18] The planning of systems are done in two levels: rough and detailed planning (see e.g. [15]). The assessment of system variants constitute an important aspect in the planning process. Key performance indicators can be used for the assessment. Classical characteristic values measure technical, economical, ecological and social aspects. Identified deficits of common planning methods are:

- consideration of variants in early development phases (usually in the rough planning),
- evaluation of variants with deterministic assumptions (all incoming data are specified exactly) and considering of only one period (static),
- inconsistent planning and assessment basis,
- consideration of a small number of uncertainties as well as ramp-up and series specific aspects,
- low degree of automation in planning and evaluation system variants and
- restriction on the top-down approach for the development of systems.

The following requirements and approaches can be derived from the deficits for planning and evaluating production systems:

- use of consistent and established data as planning input by using a knowledge storage,
- supplement the conventional planning systematic in terms of a procedure for configuration of systems with pre-developed modules by using a bottom-up planning algorithm for the calculation of all possible variants,
- consideration of uncertainties as well as random generated scenarios by implementation of a stochastic simulation model,
- capability analysis of the ramp-up and series production by implementation of an algorithm for calculation characteristic values for periods of the system runtime (dynamic) and
- simplification of routine activities by designing a computer-based environment.

3. PEAS-concept

The PEAS-concept (Planning and Evaluating Assembly Systems) was especially developed for the bottom-up planning and evaluation assembly systems, but it can be applied also to the planning of production systems.

3.1. Enablers and potentials

The concept uses new identified enablers to shorten planning time, to reduce planning costs and to increase planning quality (see figure 3). The modularization of production systems and standardization of modules are the first two enablers. This makes possible to build up a construction kit system which can be used for the system configuration (bottom-up planning). The construction kit contains real and fictional modules for production systems. The constitution of the kit is initially

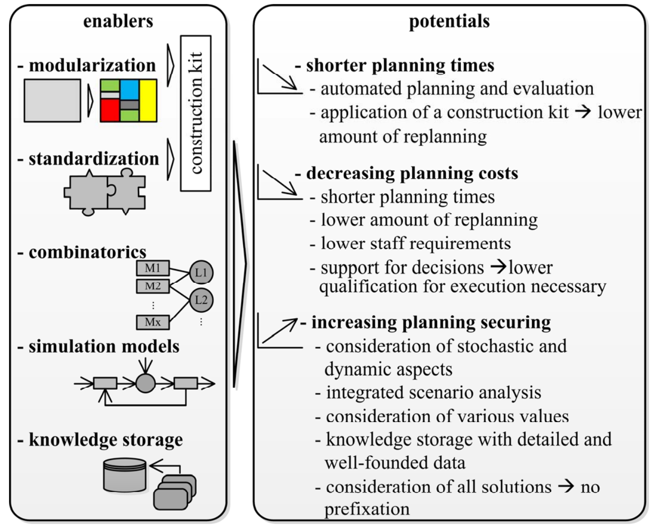

Figure 3: Enablers and potentials of the new approach [12]

associated with additional work, but later on, the planning process is thereby simplified and objective information is available. The use of a construction kit leads to the enabler combinatorics. Due to the pre-developed modules in a detailed planning, it is possible to consider all system solutions for the variant analysis (referred as complete planning). This procedure and the assessment of the variants are supported by simulation models which are considered i.g. stochastic and dynamic aspects. The necessary information about the modules, processes and components that are required for planning and evaluation are provided by a knowledge storage.

The described enablers should lead to shorten planning times, diminished planning costs and increase planning quality. The shorter planning time can be achieved by the automation of routine steps. Therefore, simulation models which must be parameterize for each planning task by the scheduler are used. In addition, the configuration of production systems are realized on pre-developed modules.

The reduced planning costs are mainly ascribed to the shorter planning time, the use of pre-developed modules and the automation. By using the construction kit as planning basis, costs for replanning can be saved. This aspect as well as the automation of recurring steps leads to less staff. Furthermore, the needed staff qualification is not so important due to a automated decision.

The planning quality can increased due to different aspects. Simulation models for configuration and calculation several characteristic values consider i.a. stochastic and dynamic aspects. This allows for example a scenario analysis inclusive a detailed and meaningful assessment. In addition, the approach of combinatory allows the consideration of all solutions for production systems (which are possible with the modules of the construction kit) in the context of a detailed evaluation. Furthermore, the use of the knowledge storage leads to a higher planning quality due to established data, a finer modeling and due to the feedback of the module specific information.

3.2. Classification of the approach

The new approach does not represent a fundamentally new method, but it should be supporting the phase of the system development (see figure 4). The new approach does not apply the classical procedure with the rough and detailed planning, but there are used pre-developed modules for production systems. These modules must be developed in a previous and separate step. Consequently, the production systems are developed bottom-up on the basis of the construction kit.

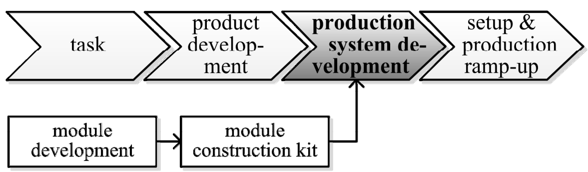

Figure 4: Classification of the new approach in the planning cycle [12]

The planning steps of the new approach are different to common planning methods (see figure 5). Due to the construction kit and the bottom-up planning, the detailed planning of the modules is carried out in advance. The necessary data for all planning steps are stored in a knowledge storage. Knowledge includes facts, information and data of modules, processes and components. As with conventional approaches, the definition of the planning problem is the first step. Based on this, the system processing which involves the calculation of the production systems as well as the characteristic values are performed. After the simulation, the results are rehashed and are used for the evaluation. After selecting a favorite variant, the system must be build up and be activated.

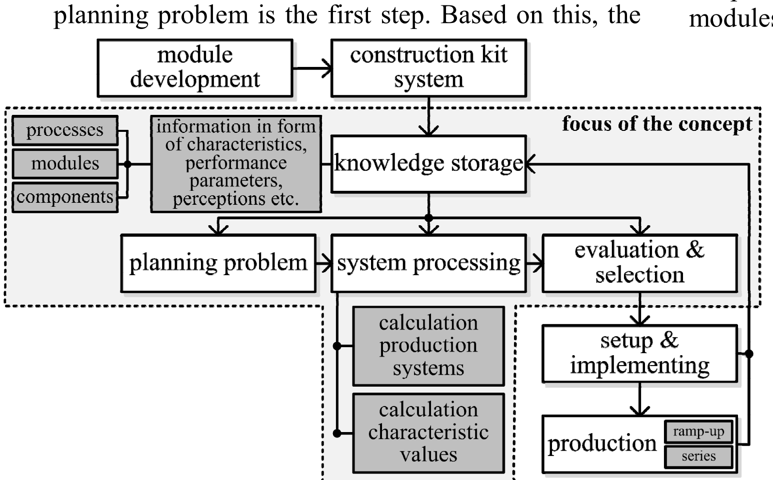

Figure 5: Phases with the new approach for planning and evaluation of production systems [12]

3.3. Concept design

The developed PEAS-concept consists of several major steps. Starting from a specific problem – a specific production task with given components and boundary conditions – all possible variants for production systems are calculated on the basis of a construction kit. The optimal variant (each variant represents one possible configuration for a production system) can be determined in the subsequent evaluation. The characteristic values for the assessment are calculated by using a stochastic simulation model which are also considered dynamic aspects.

The basic structure of the approach is shown in figure 6. The concept consists of three components: the simulation construction kit, the system processing with the algorithm for the calculation of system variants and characteristic values for different scenarios and periods as well as the evaluation with final visualization of the results.

3.3.1. Simulation construction kit

The block simulation kit serves as a knowledge storage and includes most of the necessary information about the modules for production systems, components for the products and production processes. These includes for example information of processing times including potential variances, suitability degree of modules, precedence affiliations of processes as well as compatibilities between modules and components. In addition, further user specific information will be requested for incremental planning steps.

The stored information will be used in the further planning procedure. These data provides the interface between the planning and the product, processes and resources. Thus, it forms the basis of the other two concept devices.

The information is stored in different classes. Classes are “component and product”, “production process” and “module”. Moreover, the relation between the classes and the amounts of the respective classes are saved. Objects of each class are described by attributes, e.g. time, cost, weight and compatibility. An overview of

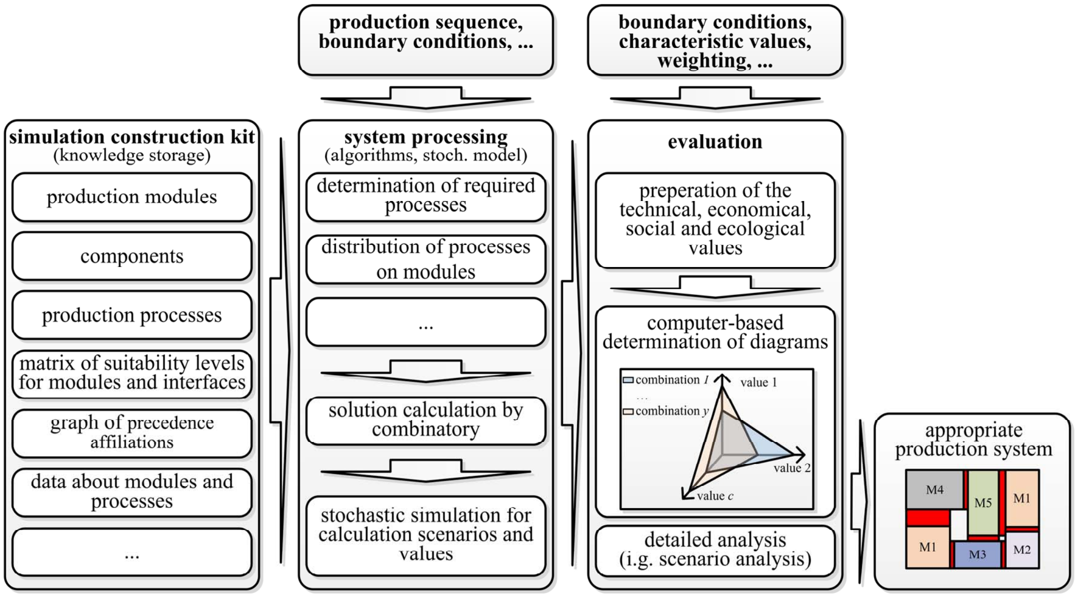

Figure 6: Basic structure of the PEAS-concept [19, 20, 12]

the construction kit model is illustrated in figure 7. This model was specially designed for the system processing and evaluation of the new concept.

3.3.2. System processing

The second block contains the algorithms and models for the system processing. These are

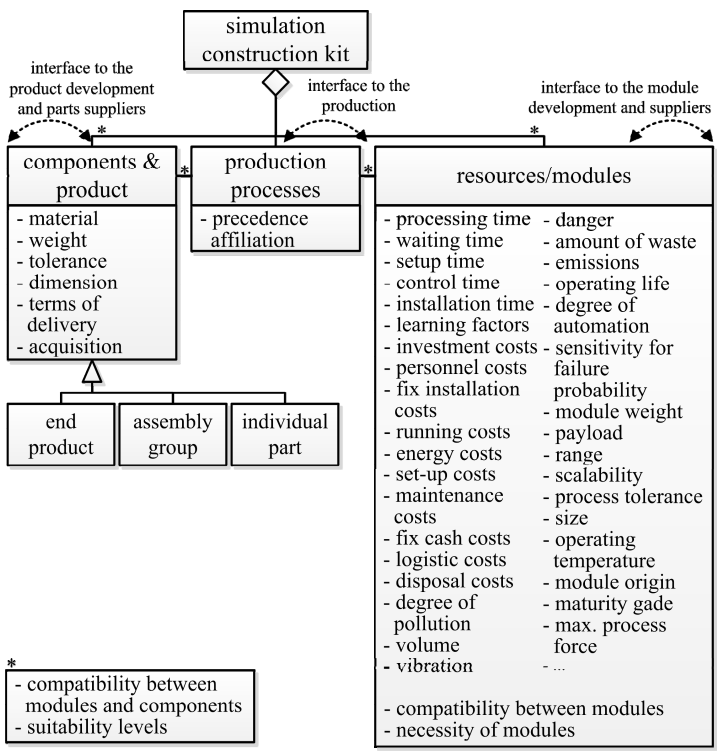

Figure 7: Overview of the construction kit module [12]

necessary for calculation all possible production systems as well as characteristic values for the evaluation on the basis of the construction kit. For calculation all variants of production systems, the principle of combinatory is used. In this step, additionally the feasibility of the implemented scheduling problem will be verified. For this purpose, further information for the production sequence, consisting of processes and components as well as other boundary conditions which are retrieved from the knowledge storage are needed.

The different variants for production systems are calculated with the procedure shown in figure 8. Hereby, the data from the simulation construction kit and the user specific planning problem which describe the production sequence and boundary conditions are used. In a first step, the entire production sequence ($\vec{M}_{ges}$) will be determined. Eventually, additional processes are necessary for executing other processes. Additional processes can be identified by using the matrix of precedence affiliations **P**. Following, realization possibilities ($\tilde{\mathbf{R}}$) which describe possible modules for each process step are calculated by the use of the suitability levels (**E**). Then, the identified modules of the realization matrix $\tilde{\mathbf{R}}$ are checked iteratively in terms of the defined boundary conditions (iteration cycle 1). For this purpose, different, user-specific criteria are used (e.g. accuracy and payload). The necessary information for

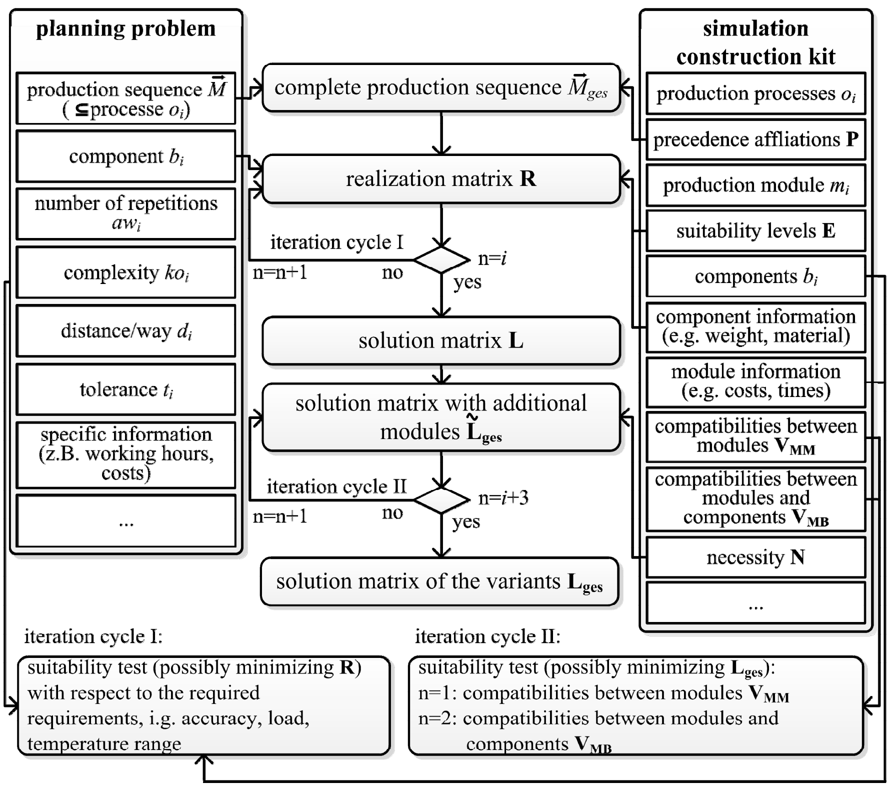

Figure 8: Overview of the algorithm for calculation of variants for production systems [20, 12]

the control are taken from the simulation kit. The result is possibly a reduced realization matrix **R**. On the basis of this matrix, the different production systems can be finally calculated automatically. The complete solution determination is made using the laws of combinatory (stored in **L**). In the next step, the solutions should be analyzed whether additional modules are necessary for the use of individual modules (e.g. an industrial robot is essential for the use of a drilling endeffector). The required information are stored in the necessity matrix **N**. Finally, the compatibility between modules as well as between modules and components are proved (iteration cycle 2). Eventually, solutions must be eliminate. Appropriate variants for production systems are saved in the matrix $\mathbf{L}_{\mathbf{ges}}$.

After generating variants for production systems, characteristic values for evaluating these variants are necessary. The values are calculated by using a stochastic simulation model for different random scenarios. Thereby, dynamic aspects are also considered. The use of the stochastic approach offers several advantages compared to deterministic approaches (see e.g. [12]). The model estimates i.a. future events and reduces events to result values. This allows statements about risks and uncertainties. The structure of the simulation model is shown in figure 9. Based on the calculated variants and the simulation construction kit, events such as disturbances or temporal fluctuations are generated and resultant characteristic values are calculated. If (part of) events are assumed to be determined (neglected of uncertainties etc.) then the calculation of values are possible on the basis of expected values.

The scenarios are generated by a stochastic scenario generator. For every stochastic parameter, a realization of the random variable is generated per period. This procedure is repeated n times (n depends to the earnings distribution which must be stabilized) to realize the analyzing of different assumptions for each parameter. Every simulation run represent one scenario. The generated assumptions for each input parameter which can be divided in internal and external assumptions, are used for the projection calculation. After the calculation, it is important to evaluate the stochastic parameters. Characteristics can be described by distribution functions. The projection calculation gives the result variables of the model. The simulation results are a probability distribution of random events in form of characteristic values. Conclusions about the quality of the assumptions can be done by a regular monitoring of the simulation results (target/actual comparison).

3.3.3. Evaluation

Following to the system processing, the simulation results have to be prepared and evaluated (assessment block). For the evaluation of all calculated production systems and generated scenarios, technical, economical, social and ecological characteristic values are used. The valuation model takes into account more than 20 key performance indicators from the state of the art as well as specially defined metrics (e.g. life cycle cost, lead time, installation time, overall equipment effectiveness, degree of automation, output and efficiency). These calculated values can be displayed in user specific characteristic fields. Based on these

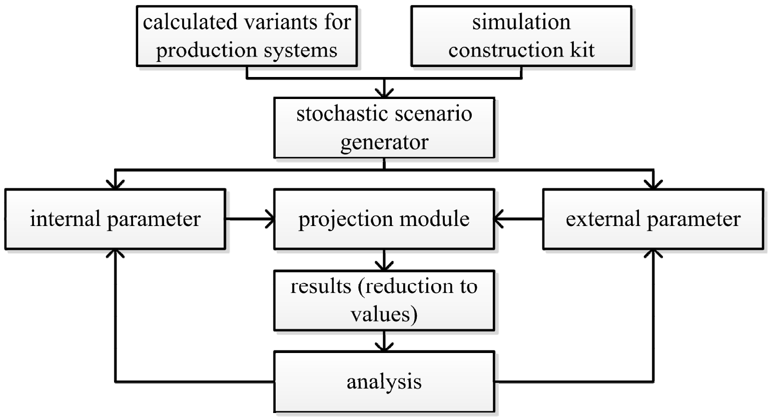

Figure 9: Basic structure of the stochastic simulation model [20, 21, 12]

fields, the most appropriate solution can be determined by the user or suggest through the system by specifying a value weighting. In addition, a detailed analysis of the simulation results can be performed. This includes i.a. a scenario and risk analysis as well as a analysis of the complete system runtime.

Moreover, different forms of organization, material flows and linkage types of the stations can be analyzed in the evaluation.

4. Software technical realization

For verifying the functionalities and for further implementation of the new concept, a software tool is build-up. The base of this tool are the core functions of the three concept blocks which is implemented as software modules. The complete planning and evaluation environment was build in MATLAB. For the knowledge storage, a object-oriented memory structure is used. Necessary data are dynamically loaded. Graphical user interfaces are realized for a simple and intuitive operation in all planning and evaluation phases.

5. Exemplary application

As an example of the new approach, the structure assembly of an aircraft is considered. For this purpose, information from documentation and expert knowledge, the developed software tool as well as real and fictitious modules for production systems are used. The information about processes, modules and components such as assembly times and costs based in particular on estimations, empirical data from the state of the art and reverse determined information.

5.1. Assembly task

The assembly of the barrel element is considered as an example. The barrel consists of a floor grid and different shell parts [22, 23]. For this example, a two shell vertical division with seven main assembly steps is considered. The process chain can be simplified divided into the following seven steps:

- clock in the components,
- positioning the components,
- drilling the rivet holes,
- applying the sealant,
- setting and removing the rivets,
- checking the form and
- clock out the finished section.

5.2. Knowledge storage

The simulation construction kit which is considered as data base, includes the necessary information such as real and fictitious modules. These modules have individual characteristics, for example different ranges and payloads for industrial robots. A selection of modules is shown in figure 10.

5.3. System processing

Based on the defined planning problem, the variants for production systems are calculated. Therefore, all possible combinations which can be realized by the construction kit are determined. Subsequently, these variants are proofed in respect of their suitability (e.g. required payload and compatibility, see procedure in figure 8).

More than 100 variants for production systems are possible. An excerpt for individual variants and process steps is shown in figure 10. The variants differ mainly in the choice of the handling equipment and the measuring device.

5.4. Planning and evaluation results

In order to assess the variants, a multi-criteria system with characteristic values is used. The calculation of the values is performed by using the stochastic simulation model. Therefore, 10.000 different random, but realistic scenarios are considered.

The variants analysis is done in more steps. In the first step, the most appropriate variant must be determined. In this example, the weighting of the values has a big impact. When using a uniform weighting, the solution which is shown in figure 11 represents the best variant. Shown are the major components inclusive the assignment to the processes and the assembling. The handling will be done by standardized industrial robots. As interface between the robots and the parts, separate endeffectors are

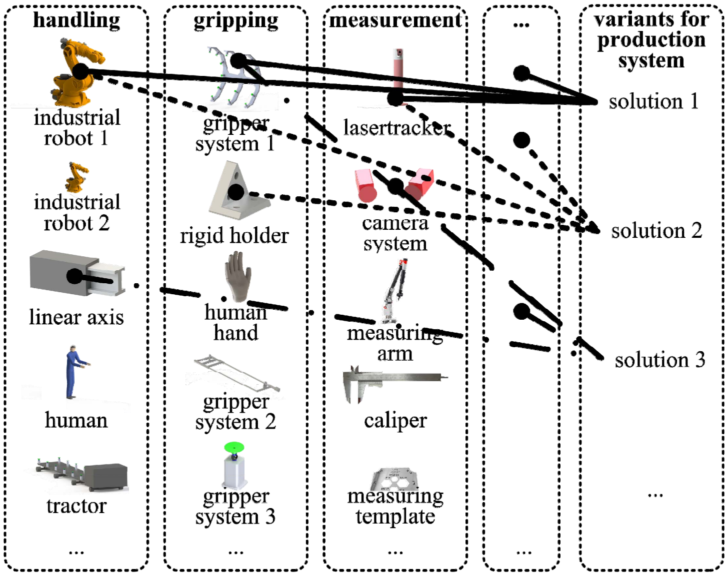

Figure 10: Extract of the implementation options and variants

used. In order to use the robots for the handling of the floor grid, an auxiliary structure in form of a portal is necessary. The measurement of the component attributes is performed by a lasertracker. The processes drilling, riveting and sealant application are taken by machines. The clock in and clock out of the components are carried out by special tractors with mounted devices.

Following to the selection of a variant, a detailed scenario and risk analysis is possible to obtain statements about stochastic and dynamic effects. For example the estimate time cycle cost, time behaviour (e.g. ramp up) and risk to compliance delivery times.

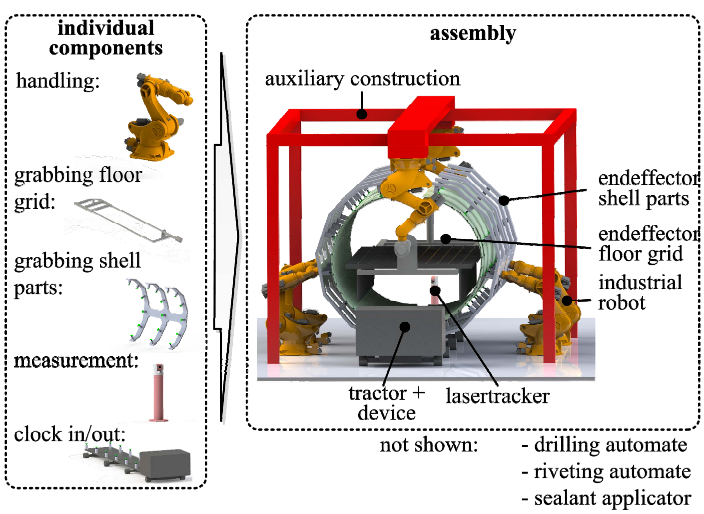

Figure 11: Partial solution and overall design [12]

5.5. Comparison between new approach and conventional planning approaches

In order to assess the results of the new approach, these results are also compared with the results of conventional procedures. Conventional procedures consist of four essential steps: definition of the task, derivation of the elementary process steps, identifying of solution principles and determination of system variants. The solution principles are identified by using a benchmark. The solution variants are determined with a creativity technique (morphological box). The variants are investigated by using a dependency checking which is done by experts. The three best variants are used for the comparison. The assessment of partial and complete solutions with the conventional approach requires a comprehensive expertise. In the manual assessment, dependencies cannot be estimated accurately or they are even ignored. Furthermore, the result securing is lower due to a limited possibility of consideration dynamic (e.g. learning effects) and stochastic (e.g. contingencies) aspects.

Especially the solution principles and the solution composition are analyzed in the comparison. The main principles of the favorite variant with the new approach are also used by the best three variants of the conventional planning approach. Consequently, the proposed variant of the new simulation model represents a combination of principles which is used in the variants from conventional approaches. The reason therefore can have different causes. The main three aspects are:

- Variety of solutions: The new approach leads to a greater variety of solutions in the evaluation without excluding individual variants in early planning phases.
- Planning procedure: The PEAS-concept enables a fully automated calculation of proposed solutions and characteristic values based on a knowledge storage (objective results). In comparison, the manual procedure of common approaches lead frequently to subjective planning results, because the decision depends highly to the involved peoples, previous knowledge and constitution.
- Value calculation: The new approach consider stochastic and dynamic aspects for the calculation of characteristic values. The observation of a period and consideration of

stochastic variables lead to a better planning confirmation which usually is not considered manually due to the complex connections. Finally, the procedure of the new approach and of conventional approaches are illustrated in figure 12.

6. Discussion of results

The utilization of the new concept and the first software technical tool have shown, that it can be used to support the planning and evaluating of variants for production systems. The routine-like planning and evaluation steps are illustrated largely automated. The planning is based on a systematic and comprehensive structured knowledge storage, including stochastic and dynamic aspects. This allows a detailed perspective on the production task. For the evaluation which is carried out using a mulit-criteria value system and different scenarios, the calculated variants for production systems are compared with each other. An integrated scenario and impact analysis allows i.a. the identification of vulnerabilities and appropriate operating parameters.

A knowledge storage is required for the new concept. Information for the modules, processes and components have to be converted into objective and appropriate data. The first application of a knowledge storage is expensive. An extension of the storage is subsequently possible. For the creation, data of the components, processes and module including the performance data are necessary. A requisite standardization and modularization of production systems as well as the disclosure of module performance data are not yet widely used in the industry. The integration of technical, cognitive capabilities in the factories systems [24] may represent a future approach for data sampling.

Due to the extensive data quantities (e.g. costs and time) a methodology for data collection is advisable. Ideally, the module developers and producers are directly involved. Performance parameters can be determined directly by the developer or by experience gained from the operation.

It remains that planning quality largely depends on the data quality and quantity. More accurate data leads to better planning results. Moreover, a greater variety of solutions for production systems can be achieved by a more extensive construction kit.

The effort for data collection for the planning process, as required by the new concept, is justified especially for planning complex and expensive production systems.

7. Summary

Companies are constantly exposed to new challenges. Production systems must be tailored to the specific requirements. The development of such systems represents a complex task which is influenced by a variety of company internal and external factors. For this reason, the planning process must be supported by adequate methods and tools.

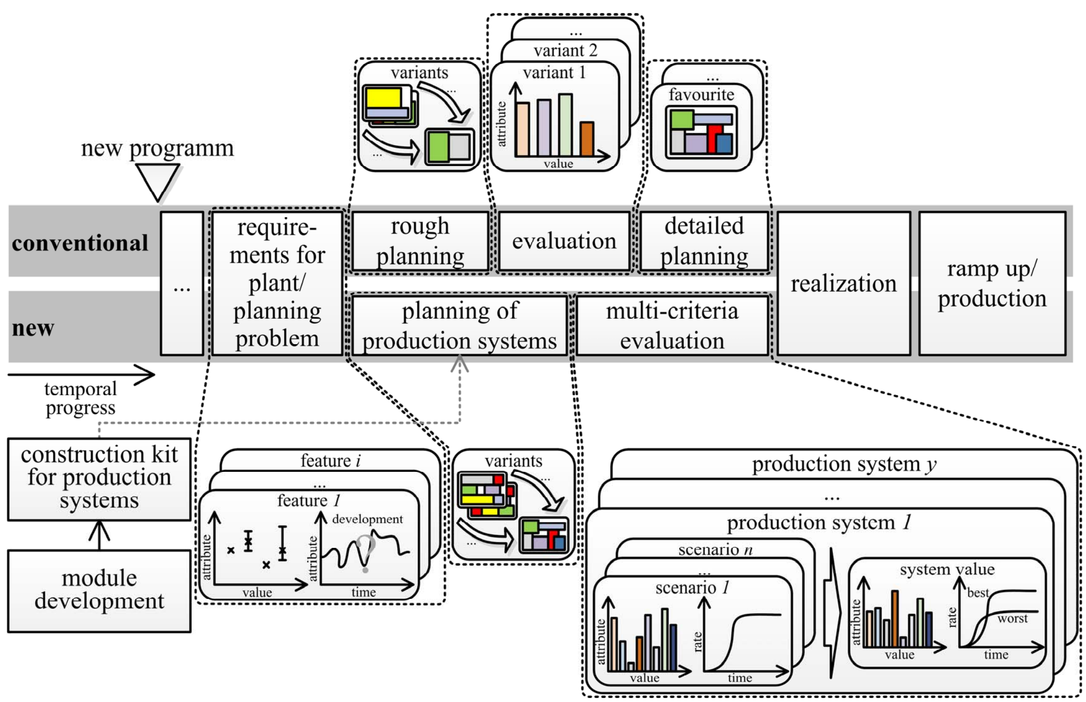

Figure 12: Comparison between conventional approaches and the new approach [12]

Different approaches can be found in the state of the art which appear insufficient for many planning tasks nowadays.

Based on the derived need for actions, the PEAS-concept (Planning and Evaluating Assembly Systems concept) for the knowledge based planning and evaluation is developed. The utilization of identified enablers yield to shorter planning time, reduced planning costs and higher planning securing. The concept is not intended a fundamentally new method, but rather serves as an additional tool which consists of a block for the knowledge storage, system processing and evaluation.

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