Multi-Dimensional Production Planning using a Vertical Data Integration Approach

A contribution to modular factory design

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***Abstract*—Due to the continuously and fast increasing complexity of products and production processes, manufacturing companies have to face more and more challenges in order to survive on a competitive market. Thus, in modern planning scenarios of the manufacturing process, the goal is not only to achieve the most efficient low-cost production, but also to take into account the interests of the customer. Especially the increasing impact of the customer on the market leads to rapidly changing boundary conditions and thus different requirements concerning the production process. As a consequence, the production has to be designed more flexible and adaptive to changing circumstances. In order to reach the desired flexibility, the production as well as the communication management within the factory has to be designed on the basis of a modular planning approach.**

This requires vertical exchange of information through all levels of the company, from the management layers and the Enterprise Resource Planning (ERP) to the automation and shop floor layers, where the aggregated information is needed to optimize the production. The interconnection of these corporate layers can only be achieved through the use of an information model that serves interoperability between these mostly heterogeneous systems. The processing and visualization of ERP data using an integrative information model enables a continuous optimization of the production systematics. Through the information model, cross-linked data structures of the production monitoring and automation can be connected and thus be integrated and consolidated into a consistent data basis.

In the current work, such an information model will be introduced and validated by making use of an optimization algorithm that is carried out through the layout planning phase of a factory. The use-case scenario presented aims for serving a flexible and dynamic optimization of the production structure of a manufacturing enterprise. During the optimization, the algorithm takes into account historical data taken from the ERP level of the company as well as time constraints to design multi-dimensional process chains for multiple manufacturing scenarios.

Data Mining; Big Data; Virtual Production Intelligence; Operations Research; Operations Management; Factory Planning

I. INTRODUCTION

In the context of modern factory planning scenarios, some key competencies are of primary importance. Hereby, we are concentrating on leading positions in cost minimization, quality management and the individual care for consumer interests [1]. The education and the application of those key competencies during the planning of a factory make a decisive contribution to the “competitive strategy” of modern companies [2]. This strategy constitutes how the different players of the market will determine their strategic product-market-combinations in order to reach a competitive advantage against their concurrence [2].

In connection with rapidly rising challenges due to the globalization of the markets, the manufacturer’s impact on the market decreases. However, the expectations and requirements defined by the consumers concerning the quality and flexibility of the products increases. This leads to a higher dominance of the customer on the market [3] and causes higher expectations concerning the design and the variety of the products as well. As a consequence, the customer expects products to be as cheap as mass products, but also as flexible and modular as being produced in low volume production. This requires novel concepts in production design and planning, because products need to become more complex and flexible, whereas the technology dynamics increase and innovation cycles shorten.

However, current manufacturing environments, especially within highly automated industrial segments, are still focused on mass production [4]. This creates high planning certainties as well as an efficient production and high working cycles. At the same time, individual products are not easily realizable.

Due to the rising interests of consumers in an increasing variety of the products, the modularity of the production gains in importance. Thus, necessary modifications of the production structure and their impact to technical and economic aspects have to be taken into consideration already during the planning process. As the consideration of all such dependencies in the factory and production structure planning process is highly complex and often imponderable, the planning has to be divided into distinctive planning steps, thus a modular planning procedure is needed. One approach to the modularization of the planning was introduced by Schuh et al. [5]. The presented “Condition Based Factory Planning” approach splits the factory planning into distinctive planning steps in order to create a more structured and systematic way of dealing with multiple degrees of freedom in production planning. The advantages of such a planning approach consist of the determined procedure

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of factory planning projects and the possibility to split the process into working packages, which can be performed by the according experts. The next step of this approach consists in the consideration of interdependencies between the different planning modules. The establishment of interconnections between these modules is hereby complicated due to the use of different optimization methodologies and tools in the different planning domains. The structure and embedding of different planning modules is depicted in Figure 1.

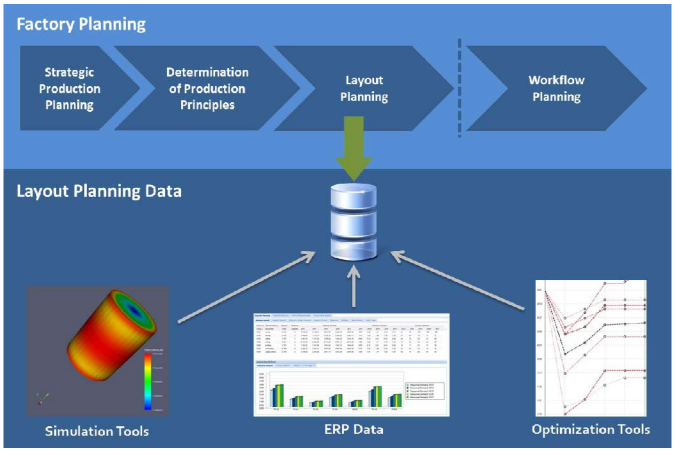

Figure 1. The Layout Planning of a Modular Factory Planning Approach

The top of the picture shows a section of the factory planning working chain. It consists of the planning modules described earlier. Within the current work, especially the layout planning module is examined. With regard to the layout planning, different relevant sources of data can be identified as shown in the lower area of Figure 1. Besides the information from the ERP level, data taken from already existing production sites, which are referred to as "historical data", as well as data taken from simulation and optimization tools are used to perform the layout planning. In order to combine these different information into one holistic view, an embedded platform has to be carried out that is capable of managing all information provided. Such shared IT-environment requires an integrative information model as well as a common data basis that supports communicative and administrative support of concurrent simultaneous engineering processes [6].

In order to reach a consistent factory design as described above, the different planning modules have to be linked in terms of such holistic model. Hence, a common information management system is needed, which is capable of integrating the different planning modules into one integrative information model. Thus, the goal of a holistic factory planning consists in the definition of an information model that contains not only the capabilities to integrate the different modules of the factory planning process, but also to manage the information generated and provided by various sources. In order to practically use an information platform that is capable of these functionalities, a software framework will be utilized to integrate the layout planning module into the overall factory planning context. The framework in use, which is referred to as "Adaptive Data Integration using Services (ADIUS)", is based on the concept of "Virtual Production Intelligence (VPI)" and serves as an information platform and thus enables operations beyond all planning modules and tools concerning factory planning.

In the present work, the state of the art in layout planning and data integration with the focus on vertical data exchange will be examined in section 2. In order to reach an adaptive optimization approach, the planning process of a factory needs to be structured in a more flexible way. Thus, a layout planning approach, which takes into account multiple scenarios, will be described in section 3. Accordingly, in section 4, the added value of such an approach is demonstrated by making use of a complex planning problem, before first practical results will be demonstrated in section 5. In the use-case, the traditional layout planning process will be extended by taking into account time constraints by applying a flexible planning algorithm.

II. STATE OF THE ART

A. *Layout Planning*

Layout planning represents a central part of the factory planning and has advanced to a core element of production planning in the context of functional and production-oriented allocation of resources. The optimal allocation of resources can be understood as the material flow-fair assignment. Thus, the flow of material serves as a defining criterion for the optimization of the production flow. This is mainly due to the high economic relevance of the material flow costs compared to the overall costs of the operating factory [7].

Layout planning of a factory is carried out in several steps and is based on planning modules. According to the VDI [8], layout planning is part of the conceptual planning of a factory and is carried out by determining the ideal layout first and the real layout afterwards. The derivation of the ideal layout is hereby comprised of structure planning and the dimensioning of resources. Afterwards, the production control, the logistics and the information and communication flow are determined in terms of the real factory layout. The relevant literature shows a wide range of approaches to layout planning [7] [9].

According to the current state of the art, the ideal layout is initially designed using existing production data before it is adapted to other requirements of the production facilities. Thus, the first step in designing a production structure is to derive basic structures of the production from existing factories or planning projects. Existing data or manufacturing information can for instance consist of product lists, processes, quantities and other variables of the Enterprise Resource Planning. Based upon these "historical data", several possible scenarios of the production configuration are selected and compared.

The planning of the ideal layout is hereby independent of the variables associated with the design constraints of the real layout planning, which takes into account all relevant boundary conditions, e.g. architectural or legal restrictions. Thus, the ideal layout planning determines the production configuration only in terms of an optimized material flow. Numerous analytical, heuristic and graphical methods have been carried out in order to support a structured determination of the ideal layout [10]. The considerations of all boundary conditions happens in later steps of the planning through the application of further planning modules in order to determine the real layout of the plant [7]. A well-structured summary of the different approaches and factors influencing the layout planning process is provided by Kampker et al. [11].

Nevertheless, especially the step from the ideal to the real layout is usually influenced by the knowledge of experts and is therefore principally shaped through experience values. Accordingly, the main challenge in layout planning is the quantitative measurability of various scenarios with the aim to determine an optimal solution – not at least due to the fact that the approaches to determine the real layout are only documented in a qualitative and abstract form. Hence, there is a lack of explicit instructions in the literature regarding the compliance of conditions such as ensuring the flow of communication as well as the flexibility and modularity of the production. Similarly, there are only few quantitative approaches for estimating the costs arising from the consideration of all according boundary conditions [11].

At present, an individual evaluation system has to be developed for each production planning project. This system is not only based on the conditions of the current project, it also takes into consideration historical planning data. On the basis of this rating system, different scenarios are evaluated and compared with each other in order to determine the "optimal" factory layout. The evaluation is either based on qualitative or on semi-quantitative methods using point evaluation systems, whereas the "ratings" are based on the comparison with planning successes of previous projects. The disadvantages of this approach are the low reproducibility of planning successes as well as the low degree of systematization of the planning process. Due to the uncertainties, which are accompanied using this way of optimizing the layout of the factory, the results have to be adaptable and flexible for later modifications. In order to evaluate the planning success in each later step of the factory planning and from each level of the manufacturing enterprise, a holistic and pervasive vertical data integration needs to be established within the planning processes.

B. *Vertical Data Integration*

One of the most important approaches concerning the cross-linking of different scopes in enterprises has arisen from the Business Intelligence (BI) movement [12]. Initially, BI was introduced to interconnect the different departments of a company from the economic point of view [13]. However, due to their data-oriented, enterprise-wide character, BI can also serve interconnection functionalities as well as decision support within a connected environment of production facilities. The basic idea of Business Intelligence is to collect and to process information in order to gain a deeper understanding of processes in companies. These intelligence functionalities can be applied either on the economical part of an organization or within the production environment of the company.

In terms of production planning, intelligence tools can be used for both analyzing historical manufacturing data as well as processing real-time data taken from the production process. An establishment of cross-sectional data treatment processes in the production environment is necessary to guarantee a propagation of information to all people who are involved in planning processes in an appropriate form [13].

With regard to the factory planning domain, intelligence tools like BI can support the integration of different tools into one optimization framework through a consistent information model. In this context, numerous software solutions exist providing an IT support in the planning phase. However, most of the existing systems are stand-alone solutions that focus on one aspect of the planning task and are therefore insufficient with regard to the evaluation of the overall planning process. These tools do not build a monolithic system, so that a homogeneous connection of the IT environment will probably not be possible [6]. In order to apply the BI idea on the different tools of a manufacturing enterprise, the BI term has to be extended on different fields on the management and on the production level at the same time.

In order to spread this Business Intelligence approach to the field of production, other terms have been introduced such as the operational Business Intelligence (OpBI), Corporate Performance Management (CPM), Process Intelligence or Business Performance Management, which continue the idea of BI on new fields of application [14]. Accordingly, approaches have been discussed in the current literature that could lead to a merge of intelligence systems from the different levels of a manufacturing enterprise. In this context, a first differentiation is made especially between Operational Business Intelligence (OpBI) and Manufacturing Execution Systems (MES).

Both concepts have in common that they analyze and coordinate entrepreneurial processes. However, they operate in different sections of the value chain. OpBI systems provide real-time data analysis through BI technologies like Real-Time Data Warehousing and Online Analytical Processing (OLAP), but they are focusing on data models and on functions of sales and marketing [15]. MES, however, provide data consolidation and monitoring capabilities within the production environment. This is primarily performed through engineering-oriented concepts, which are capable of organizing the manufacturing processes [16]. A flexible planning, which is able to manage changing and unexpected circumstances within production can only be realized through the interoperability of OpBI and MES. Hereby, the data collection and analysis from different levels of the company has to be guaranteed as well as the integration of the according information into a database system [17].

An integrative solution to serve the desired interoperability between these heterogeneous, distributed systems was shown with the adaptive information integration according to Meisen et al. [18]. A framework based on this approach allows the creation of an integrative information model in connection with the propagation of data into a common data basis, which contains both input and output data from various applications in a structured form [19]. This framework and the according information model enable an establishment of Business Intelligence approaches into the domain of virtual production and are referred to as “Virtual Production Intelligence (VPI)”.

III. VERTICAL DATA INTEGRATION USING THE VIRTUAL PRODUCTION INTELLIGENCE PLATFORM

The Virtual Production Intelligence allows a merge of heterogeneous planning, simulation and optimization tools. Based on the information model, a platform has been carried out that is capable of integrating information from different corporate processes, production processes and simulations into one common data basis [19]. This multi-dimensional data basis enables – through the integrative methodology of the common information model – a vertical data flow of information from all levels of the production management and operations.

This vertical information flow is necessary to enable a full mapping of the processes in a manufacturing company. In order to guarantee a holistic optimization of production processes, the flow of information has to be designed especially for simultaneous data propagation and data treatment. These functionalities are only realizable through methodologies, which enable an integration of data from different sources into central data storages. These data can, for instance, consist of data taken from the ERP level or of sensor values taken from the field levels. The merge and the common analysis of these data sets are essential for a sound and well-founded analysis of the processes that can be understood by the experts involved in the planning of the production. The needed interface for the interaction between the user and this system can be realized through database views that are based on the described information model. Thus, through a full integration of all relevant information, the optimization system is capable of providing all needed information to the user by visualizing the data within diagrams or by showing reports of aggregated data sets. According to Vogel-Heuser [20], the goal of connecting the production systems with a distributed IT environment can be reached by integrating an information layer between the production site and the IT systems (Figure 2). This intermediate layer replaces the interfaces between applications from the manufacturing layer and the information management layers.

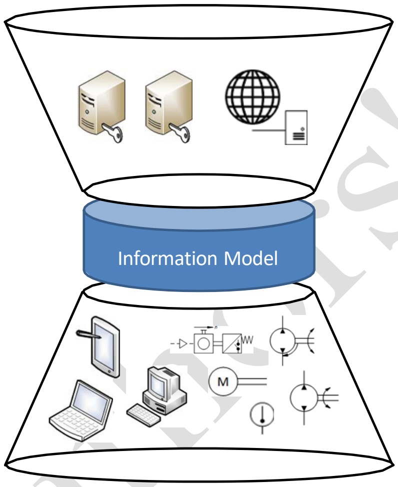

Figure 2. The Information Model Layer for a conected IT environment

Through the information model' capability to interpret data from the field level of the production, single connections between the machinery and hardware (bottom in Figure 2) and the IT environment (top in Figure 2) are obsolete.

In order to enable the interpretation of data, the information model has to contain semantic knowledge about the production process as well as the different actuators, sensors and IT systems used within production. Using this information in connection with domain-specific knowledge, the information model is able to transform the information in order to enable a consolidation of the information in the data structures of the IT environment within the enterprise administration level.

The idea of inserting a semantic information model as an intermediate layer can also be utilized in the interconnection of significantly heterogeneous software systems or planning tools. Hence, the information model, which was introduced together with the VPI platform, is capable of serving an intermediate information layer between distributed applications and simulation or optimization tools. By using the domain-specific knowledge about different optimization and software tools, the VPI integrates multiple planning and optimization steps into one holistic planning model. As a consequence, modifications in single planning steps will have an impact on the overall planning results, because changes in the project configuration are immediately integrated into the overall planning context.

In the next section, the advantages of integrating a formerly distinctive optimization tool into the overall idea of the factory planning project is demonstrated by means of a layout planning use-case. Through the integration of different results for determined process chains into an integrative data basis, modifications and parameter variations can be dynamically performed at any stage of the planning progress.

IV. MULTI-DIMENSIONAL AND MULTI-VARIANT PROCESS CHAIN OPTIMIZATION IN LAYOUT PLANNING

As mentioned in the state of the art section, layout planning is intrinsically characterized by the knowledge as well as by the experience values of experts. Hence, decisions made during the planning and determined results are commonly not evaluable in an entirely quantitative way. As a consequence, modifications and corrections during the planning are inevitable. In order to integrate these changes into further factory planning steps, an information model can serve features to identify cross-module connections within the planning to integrate the according changes in all affected planning modules.

In order to store the information as well as domain-specific knowledge about the identified cross-module references into a database by making use of a suitable information model, multi-dimensional databases are one well-established solution. For instance, so-called Data Warehouses are filled by performing Extraction-Transform-Load (ETL) processes. In the extraction phase, comparatively sparsely structured data is extracted from a common relational database. In the transformation step, these data are treated to take into account different information views and to facilitate reporting functionalities. In the last step, the data is loaded into a Data Warehouse.

The layout planning use-case that is carried out in order to demonstrate the advantages of applying multi-dimensional databases in the planning is initiated by data taken from the ERP level of a producing enterprise. The according data sets provide basic information about the manufacturing process of products, for example resource group numbers, machinery usage, production segment assignment as well as dates and manufacturing durations. The resource group number, which represents the machine in use, is of special interest here, because it can be used to carry out a formal description for the manufacturing process of each product. Thus, the production process of each single product can be expressed by process chains, a row of determined manufacturing steps (Figure 3).

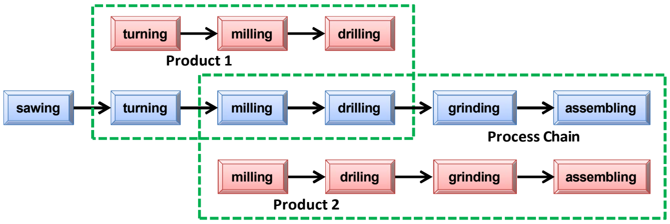

Figure 3. A Process Chain designed by the manufacturing steps of products

The goal of the layout planning primarily consists in the determination of the most common process chains. If the manufacturing entities within a factory are placed according to this optimal configuration, the respective products will be manufactured using a minimum of logistical efforts. The optimization process to perform this ideal allocation of manufacturing resources is carried out in several steps:

1. Identification of repetitive process chain patterns,
2. Determination of an a-priori solution for the optimized process chain configuration,
3. Validation and improvement of these process chains by an iterative optimization algorithm,
4. Application of time constraints in order to perform a multi-dimensional machinery allocation optimization.

At first, the given product list, which consists of more than 30k products, is quantitatively analyzed in order to determine the most frequent products of the historical ERP data. This step is performed using counting methods and similarity patterns within the process chains. Due to the huge amount of possible solutions for this logistical optimization, the determination of the optimal solution is connected to an NP-hard problem.

Consequently, the described quantitative methods can only lead to a semi-optimal solution. This solution is then defined as the a-priori solution to the problem and further developed using iterative optimization steps. This iterative approach is carried out by the following procedure. Firstly, preliminary determined chains are checked concerning redundancies and similarities that could be caused by a high dominance of repeating products. In the next steps, these overlapping process chains are systematically replaced by process chains, which represent product configurations that have been undermined within the first optimization step, but are also of primary importance.

In the following step of the process chain formation, time constraints are applied to dynamically further optimize the identified process chains. During the dynamical optimization phase, the previously one-dimensional process chain term is enhanced to multi-dimensional chains in order to be capable of taking into account different manufacturing times of various machines within the production process. Hence, this multi-dimensional approach allows a parallel arrangement of the production entities within one manufacturing chain. As a consequence, waiting times of rather quick or slow machines can be rearranged in order to reach a continuous flow of the products, which have to be manufactured.

The algorithm (point 4) that provides these functionalities is comprised of several steps that are performed as follows:

4a. Determination of the maximum number of parallel machines for each process chain due to general considerations like space requirements et cetera:

$$n_i \;\square\; n_{i,\max} \qquad \square\square\square$$

4b. Identification of the machine i within each process chain that has got the maximal manufacturing time t_i,

$$t_i \;\square\; t_{i,\max}\left(n_i\right) \qquad \square\square\square$$

4c. Calculation of the ideal number for each other process chain machine j by using the process times t_i and t_j,

$$\square n_j\,,\; j \;\square\; i\!: \quad n_j \;\square\; n_i \;\square\; \frac{t_j}{t_i} \qquad \square\square\square$$

The result is rounded down to the next integer number.

4d. Logical determination of the real number for each machine considering the maximal number of parallel machines and the ideal number for each machine

$$\text{if} \quad \left|\frac{t_j}{n_j} \;\square\; \frac{t_{j-1}}{n_{j-1}}\right| \;\square\; \left|\frac{t_j}{n_{j+1}} \;\square\; \frac{t_{j+1}}{n_{j+1}}\right| \qquad (4)$$

$$\text{then} \quad n_j :\square\; n_j \;\square\; 1 \qquad (5)$$

This last step of the algorithm is performed in order to assess the buffer time of slow machines that are fully occupied to the waiting times of faster machines that are not working on its capacity limit. Hence, this optimization procedure creates a setup of process chains with multiple degrees of freedom and thus compromises between inevitable waiting and buffer times.

V. PRELIMINARY RESULTS

In preliminary test scenarios, the full algorithm as described was performed multiple times for several parameter variations. The hereby determined process chains were continuously validated by matching the manufacturing configurations of the products from the ERP systems. After several iterative steps, the results were approaching to a certain boundary value that cannot be further improved using static optimization methods.

For this specific test case, the parameter variation was performed for the total number of machine chains in a factory, thus the range of this particular parameter was varied between e.g. 3 and 6. Hence, each run of the algorithm determines a fixed number of so-called main process chains, which represent the ideal machine configuration for this specific use-case.

The results of each run were then integrated through the integrative information model served by the VPI Platform. Thus, the different parameter configurations can be selected modularly for different use-cases or optimization scenarios. The results of each optimization run can consequently be visualized continuously within a Web application, which was developed for information management purposes. The use of the web interface allows a user defined parameterization of the different scenarios as shown in Figure 4.

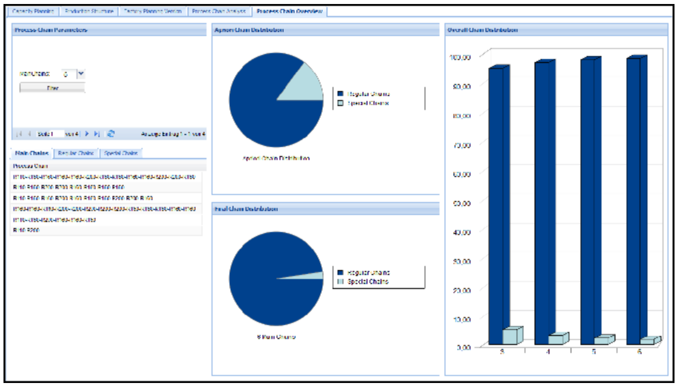

Figure 4. Web-App for the parametrized vizualisation of optimization results

In the figure a screenshot of the user interface for the layout planning module of the factory planning application is shown. The results for the process chain optimization algorithm that are visualized in the UI can be modified at each step of the planning progress. The dependencies of these variations to other planning modules are consequently integrated in the overall planning process. The results for each specific parameter configuration can thus be utilized in all following planning steps without further efforts.

VI. CONCLUSION AND OUTLOOK

Based on a use case it was demonstrated that the use the Virtual Production Intelligence result in far reaching benefits in production planning. Due to the application of the VPI platform various constraints and parameters can be considered in the planning. This enables an integrated, holistic view of various scenarios of the factory planning so that individual modules of the production planning can be evaluated in the overall context of the planning process. Quantitatively reliable statements over the planning success can thus be made at any time.

In the context of optimized production planning, the next steps will consist especially in expanding the concepts presented in terms of a holistic interconnection of all levels involved in the production planning as well as in the manufacturing process.

On the methodological side, the presented concepts of the vertical integration of production data have to be realized by extending the Virtual Production Intelligence Platform in terms of data flows from MES and the field level. These information need to be processed and aggregated automatically so that they are available within the ERP systems and production planning. Only through the interoperability between these systems an integrated digital mapping of the production is possible. This provides the basis for intelligent tools for the planning and decision support in order to ensure a continuous improvement and further development of the production planning process.

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