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Advances in Assembly Planning for Multi-Variant Production Based on 3D PDF

Felix KAHL[a], Stefan RULHOFF[b], Josip STJEPANDIĆ[b,1] and Klaus THATENHORST[a]
[a] *KHS GmbH, Germany*
[b] *PROSTEP AG, Germany*

Abstract. Rapidly increasing, global competition has led many companies to pay more attention to each singular requirement of their customers and, therefore, caused the tendency to small batch sizes and a greater variety of products. Assembly workload and human labor is the prime expense factor during the assembly of products. Here the hours of work by workmen multiplied with a company-specific factor equal the occurring costs. Based on the frequent use of variant-oriented product modelling, the efficiency of preparation processes has been improved. However, the assembly planning of single productions or short runs is often based on experience or the method of compare and estimate. Most production planning systems used in practice have an essential weakness in that they do not support hierarchical planning based on assembly constraints and do not observe resource constraints at all production levels. Therefore, tight synchronisation between design and production structures is necessary in early stage of the preparation and planning process in parallel to the design process. In this paper a project is presented, in which the assembly planning is put into practice based on engineering 3D CAD models in 3D PDF and a preplanned library of work steps. Through connected time values multiplied by frequency and under consideration of assembly difficulties, transparent assembly basetimes can be calculated and expectable costs can be estimated. Though connected resources the needed tooluse per workstation can be determined. Furthermore a connection of product, assembly process and resource is implicitly created by the planning process itself, which machine-readable will provide a lot of potential for future automatisms.

Keywords. Assembly Planning, 3D PDF, Cost Estimation

Introduction

Although at most manufacturing companies production and assembly costs are primarily determined by the development department, harmonization between developers and production planners is in many cases hampered by the fact that they are separate from each other in terms of personnel, organization and work at different locations and sometimes even on different continents [1][2]. The design data is not passed to the production planners until the geometry and drawings have already been worked out to a great extent and this is usually still done on paper. This means that little information that would allow concurrent engineering between development and

[1] Corresponding Author, Mail: josip.stjepandic@opendesc.com.

production planning, and thus shorten development cycles, is exchanged during the early phase of the product development process [3].

The high level of automation exhibited by conventional manufacturing technologies (machining, forming, molding, etc.) means that assembly costs have risen proportionately measured against the total cost of production [4]. It is often the most expensive production process and is therefore subject to constant rationalization pressure [5]. A crucial corrective measure in this context is assembly-oriented product design (DfA) that facilitates efficient assembly planning [6][7][8].

1. Related work

Assembly refers to the act of putting or connecting together individual manufactured parts to create a functioning product with a high degree of complexity by means of joining, handling and control operations as well as adjustments [9]. Assembly planning comprises all of the activities that serve to create the framework conditions required for efficient assembly, precisely determine requirements in terms of human and operating resources, and deploy the resources in a targeted and efficient manner [10]. A distinction is made between operations (rough) and detailed planning (Table 1). The aim of operations planning is to develop an assembly system and to create a rough workflowchart [11]. During detailed planning, the assembly system and the workflowchart are defined in greater detail [12]. Using drawings, BOMs, the assembly structure and the rough layout, the assembly planners create the detailed layout, plan the work stations and means of moving workpieces between stations, and create the assembly plan including work instructions, calculations sheet, etc [4].

Table 1. Functions and planning phases of the assembly planning process [3].

	Task	Input Information	Output
Operations planning	Assembly System Development		
	• Work system design • Developing system structures • Capacity planning	• Assembly task • Production program • Square measures • Concatenation principle	• Assembly structure • Rough layout • Capacity requirements
	• Structuring product • Rough flow planning	• Parts list • Drawing	• Precedence graph • Rough flow structure
Detailed planning	Assembly System Refinement		
	• Principle solution planning • Workstations planning • Concentration resource planning	• Parts list • Drawing	• Detailed layout • Workstations • Concentration resources
	• Determining assembly content • Creating assembly plan and assembly documents	• Assembly structure • Rough layout	• Assembly plan • Work instructions • Spreadsheet

Generally speaking, the assembly sequence is derived from the product structure and the geometric relationships between the components in the structure during assembly planning [13]. This means that the product is broken down again into its individual parts. In some – but by no means all – cases, the assembly sequence is derived directly from the sequence in which the components were assembled [14]. Lotter and Wiendahl found that 40% of the time needed for planning is spent determining the optimum sequence for assembling the components [4]. The huge amount of time spent determining the assembly sequence has resulted in the research community focusing much of its attention on this aspect [15][16][17][18]. There are numerous approaches for determining the assembly sequence more efficiently, for example based on the sequence in which components are disassembled, an approach which however is stretched to the limit when it comes to products with a large number of variants such as large machines and systems [19]. Another major challenge is creating the assembly documents on time – documents without which the machine or systems cannot be delivered. A good overview of various planning approaches is presented by Renu.

The first result of the assembly planning is the assembly graph which represents the possible assembly sequences in a network structure as a tree structure. Herein, the individual parts are forming the leaves, inner branches are seen as sub-assemblies, which in turn are taken up by complex ramifications and, finally, end up in the root, the base element. Low-fidelity CAD models created in the early phase of product development can be used to roughly predict assembly times, thereby supporting earlier inclusion of design for assembly methods in the design process [21]. Expanding on previous work to predict assembly times from detailed assembly models, low fidelity part models are used in a series of predictive performance experiments. Results reveal that this tool can predict the assembly time of a product to within 40% of the target "as built" time using a high fidelity neural network and a low fidelity CAD model. The tool is based on structural complexity, representing the assembly graph as complexity vector of 29 metrics. A neural network is then used to build a relationship between the complexity vector (input) and the assembly time (output) [13].

Various computer-aided planning approaches are compared with an overweight of the knowledge-based and STEP-based approaches in recent years. Advanced planning approaches in the assembly planning can be subdivided in a number of categories, i.e. feature-based technologies, knowledge-based systems, artificial neural networks, genetic algorithms, fuzzy set theory and fuzzy logic, Petri nets, agent-based technology, internet-based technology, STEP-compliant CAPP and other emerging technologies [12]. It comprises a framework and organization of the conceptual assembly design system with the help of knowledge-based engineering, where it takes into integrated consideration the assembly sequence, joint configuration, and tolerance allocation in the auto-body assembly design process planning.

Heuristic knowledge and empirical knowledge play active roles in the generation of the assembly sequence and dimension chain, the configuration of joint types, and the allocation of tolerance limits [22]. Qualitative simulation is conducted by knowledge reasoning or rule reasoning with all kinds of rule, criterion, and principle [23]. In this way, the knowledge-based vehicle assembly design system can improve assembly concept quality by means of qualitative simulation to fulfil the concurrent integration between conceptual design and detail design stages. Further example of a military system is presented to demonstrate the feasibility of a three-stage integrated approach with heuristic working rules [14]. Similarly, a planning system comprises an assembled advisory module, a knowledge-based module and a user interface. It allows users to find the best solution for the assembly process during the commercial vehicle seat assembly process. Furthermore, the planning system is able to support the design engineer in selecting the best and fastest assembly method [24].

The procedure of generating assembly instructions of complex one-of-a-kind products takes a long time, since many trade-offs between various stakeholders are needed [8]. In addition, the process can still yield some disadvantages: If errors are found in the documentation, an updated version must be created, printed and distributed. For such reason a comprehensive support by appropriate, easy-to-use tools is necessary, in particular to facilitate tasks on the shopfloor-level. Large planning systems are powerful and complex, difficult to learn and use.

To make the assembly planning process and the usability of the planning documentation more efficient, providing an assistant tool for the automation of the process is necessary [25]. In our case, the use of 3D PDF contributes the optimization of the process of assembly planning [26].

2. Planning practice and need for improvement

Most machine and plant engineers still plan and document the assembly of their systems using the object in question, i.e. they assemble the system in its entirety or in parts prior to delivery so that they can properly document the process. New photos and illustrations are often created for the assembly instructions instead of using existing material from the engineering department. This approach is not only time-consuming and labor intensive but also requires an unnecessarily large amount of space for assembling the systems.

One of the main problems, however, is that the technicians cannot start planning assembly and creating documentation until the system components have been completed, and by then time is usually short. As a result, changes made while the system is in operation are not systematically incorporated into the documentation, thus making maintenance more difficult [8]. Furthermore, detailed assembly planning can often not be started until the start of production. If it could be performed in parallel with development, problems during assembly could be detected early and cost-intensive assembly steps could be simplified. This would not only make it possible to reliably calculate assembly costs earlier but also reduce these costs by optimizing the assembly steps [1].

Companies therefore have an urgent need to start assembly planning earlier and calculate the assembly costs more reliably. Other requirements include reducing the time and effort needed to create the assembly documentation through the intelligent reuse of the 3D models from the engineering department and improving the quality of the documentation so that the risk of errors during assembly can be minimized. Companies also want to be able to update the documentation faster and with less effort when changes are made to the system.

3. Solution approach

In principle, the sequence of the assembly operations can be specified step-by-step by using a computer and 3D models of the individual components to be assembled .

However, when it comes to larger and complex systems comprising thousands of components, performance problems can quickly arise. In addition, companies would also need additional CAD workstations for assembly planning, which are relatively expensive to buy and maintain. One recommended alternative is therefore to use a lightweight format, which ideally can be animated to make the assembly operations easier to understand.

In this contribution, a solution for assembly planning is presented which is based on the 3D PDF technology.By using 3D PDF technology 3D models can be converted from all common CAD systems into the tessellated U3D or PRC format, making it more than 90 percent "lighter" than the original models [26]. 3D PDF documents and the embedded models can be viewed using the normal Adobe Reader, which is free of charge and installed on nearly every computer. Another major advantage is that the 3D models can easily be combined within the document with 2D information such as detailed views and drawings, which means that the 3D PDF is very similar to conventional assembly documentation. The documentation can be compiled to a great extent automatically with the help of the server solution PDF Generator 3D and appropriate templates.

The proposed approach is shown in Figure 1 as context diagram.

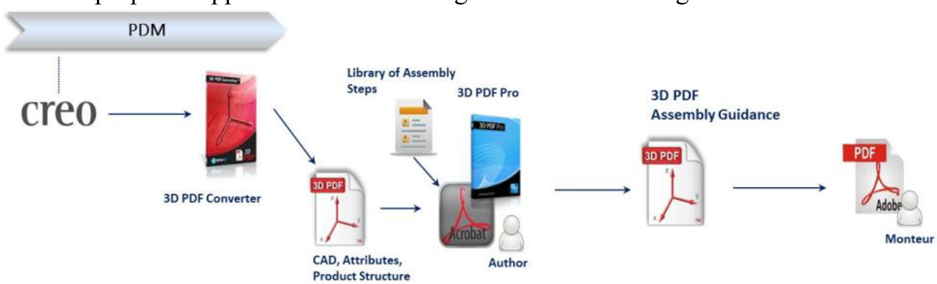

Figure 1. Context diagram of assembly planning tool based on 3D PDF

This procedure starts with either export from a PDM system or conversion of a CAD model from the archive of the product which is to be planned. This PDF data is put into a PDF pre-defined assembly template which cover all needed data for an assembly guidance.

Further work is conducted on this PDF template supported by a library of corresponding assembly steps. As the result of the assembly planning we get an assembly guidance based on 3D PDF which is used on shopfloor level as lead digital document for working instructions.

Basically, we distinguish two use cases: assembly planning (role: assembly planner) as well as assembly execution (role: assembly worker) which both must interact to achieve the optimal result. Main activities of this both roles are depicted in Figure 2.

According to this description, it is obvious that both involved business units (production planning / assembly planning, further the industrial engineering and the assembly station on the shopfloor-level) need to work interactively and collaboratively with the 3D assembly plan. The assembly worker needs the possibility to impact the planning process by his suggestions and final revision. It can be done at any time just by making a remark in the PDF document.

An important component of this solution is the assembly planning library. It comprises resources based of the Methods-Time-Measurement (MTM) recommendation as well as the company specific experience [4]. Assembly costs are also calculated on the basis of MTM, a method that is widely used to analyze workflows and determine planned and target times. It involves breaking down all the tasks performed by humans into certain basic motions (e.g. reach, grasp, move) that can then be combined to create more complex motion sequences. This allows the time required for complex assembly workflows to be determined relatively quickly and reliably.

The concrete planning work consists of subsequent set of basic 2D/3D work instructions in regard to authoring and viewing applications. The user takes the template and adds, inserts or selects the corresponding data from the assembly planning library into the specific steps in assembly sequence. The utilization of templates simplifies the derivation of variants in case of multi-variant products which dramatically reduces costs.

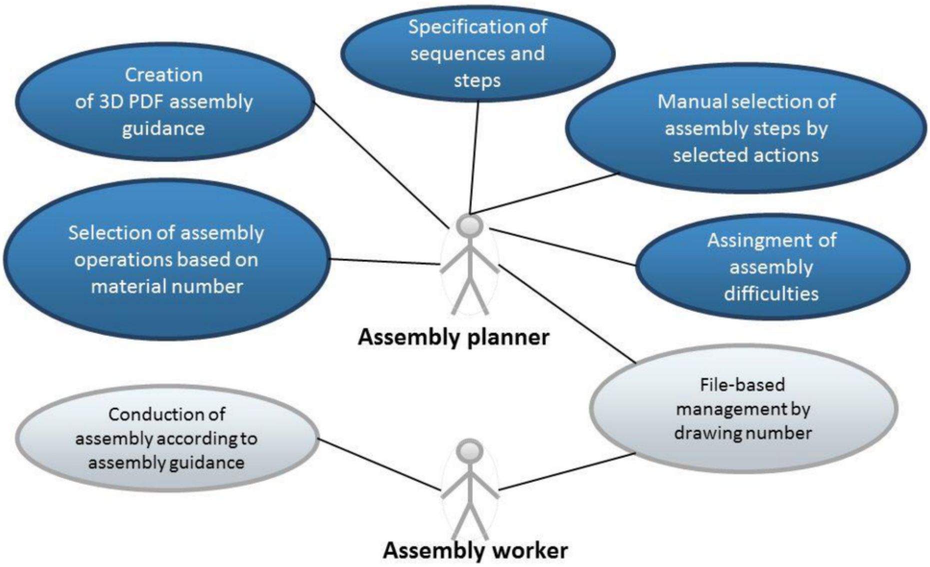

Figure 2. Activities of both roles Assembly planner and Assembly worker

The assembly guidance consists of an interactive 3D model of the related product assembly and related text description with attributes. An excerpt of the data model with main relationships between entities is given in Figure 3. This data model comprises singular assembly steps which are hierarchically structured by multiple assembly sequences. An assembly step comprises one or more assembly procedures which are linked to the related part, the needed resource and selected activity. At the definition of assembly steps, the assembly planner is supported by the assembly planning library which facilitates the selection of structured procedural objects (e.g. procedure, resource, time).

An assembly procedure gets along a text description in multiple languages, a reference to the used resource, specified activity and also reference to the parts resp. part classes by the material number as classification criterion. In particular, a reference to the product data facilitates an intelligent assistant for specific assembly functions. So in case of selection of screw joints, the assembly planner can select among several operations for join operations. Further linked variable is the time which must be considered for the assembly time calculation and, therefore, the total manufacturing time and total costs. Repeatable operations are also considered as well as surcharge for assembly difficulties.

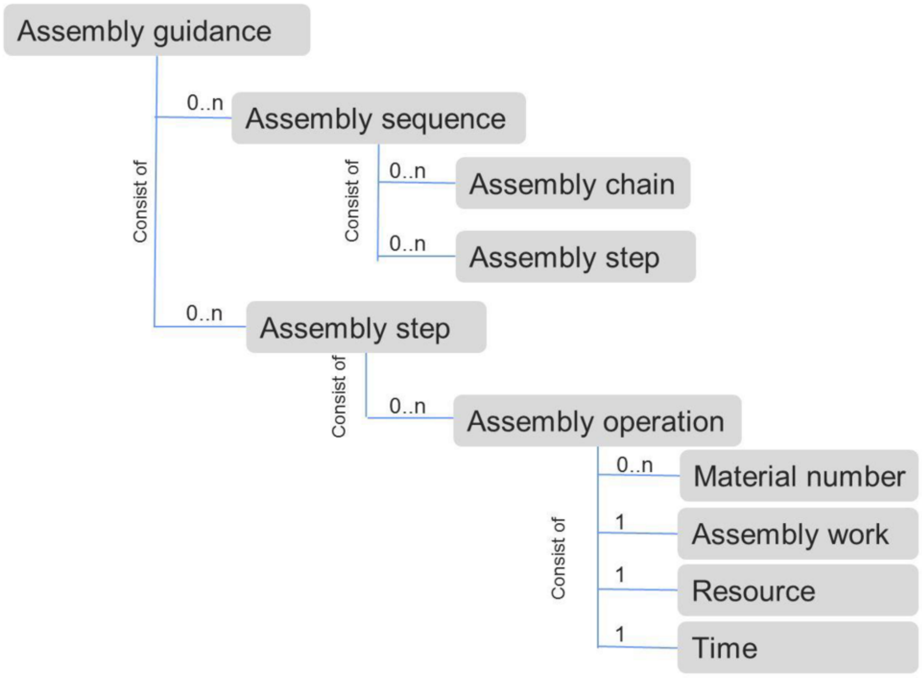

Figure 3. Entity relationships in data model.

A large library of typical assembly operations makes the planners' work easier and allows the assembly costs to be calculated reliably since company-specific cost rates can be stored for the usage. It comprises all common assembly operations, associated resources and times, and it is easy to adapt and expand to include customer-specific applications. Besides, it is easily possible to edit this data base and, for example, insert further items which describe new assembly procedures by new assembly technology in manufacturing. In Figure 4 an exemplary assembly planning process is illustrated which includes animation of singular assembly sequences and steps.

4. Interactive animation of the assembly steps

Our software for creating 3D PDFs is available in different configurations, from a desktop version to a fully-automated, server-based solution. All packages can be installed with a minimum of effort and can be used immediately. There is no need for adaptations on either the CAD or the PDM system.

Companies can use the 3D PDF-based solution to plan assembly operations digitally on the basis of the CAD models. All texts are stored in different languages, which means for example that the assembly operations can be planned in German, but the instructions can be used in English or Chinese without any need for an additional translation.

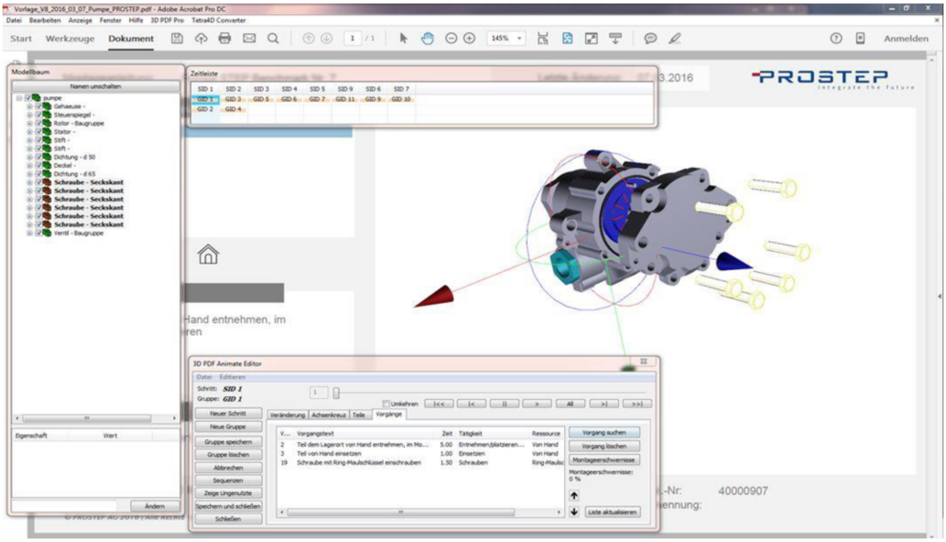

Figure 4. Authoring and assembly planning tool 3D PDF Pro.

A key strength of the our solution is the ability to animate the 3D models of specific assemblies and components irrespective of the CAD system used to create them, i.e. after they have been imported into the 3D PDF document, thus making certain assembly steps easier to understand. The 3D PDF Pro plug-in for Adobe® Acrobat® Pro provides the basis for creating the animations and allows the intuitive creation of animated documentation. The software now supports more accurate navigation in the structure tree and searches for specific component attributes. The search tool makes it easier to handle large assemblies in the 3D animations. 3D PDF Pro also makes the creation and updating of 3D PDF documents faster by automatically linking descriptive fields and buttons in the templates with the latest 3D contents. Like all the documentation, the animations created with 3D PDF Pro can also be visualized using Adobe Reader, which is available worldwide free of charge.

5. Optimal protection of intellectual property

When viewing the embedded 3D geometry, Adobe Reader, like any commercial 3D viewer, allows user to rotate and tilt the models, zoom in on them, and also take certain measurements. The functional scope of Adobe Reader can be limited when the 3D PDF documents are created in order, for example, to protect a company's intellectual property when the documentation is passed on to outside companies. It is even possible to use the optional PDF Generator 3D Rights Management module to restrict access to the documentation to certain people or impose a time limit, and also to revoke access rights previously granted.

This 3D PDF solution can very easily be integrated into an existing IT infrastructure in order, for example, to incorporate additional information from the PLM system or transfer information such as the assembly costs to the ERP system. This significantly reduces the amount of manual work required to create assembly documentation. Furthermore, the documentation can be updated pretty much at the touch of a button after changes have been made. The digitalization of assembly planning allows this activity to be performed at an earlier phase, which contributes to shortening delivery times.

Combined with the option of incorporating animated image sequences in the 3D PDF documents, 3D visualization makes it easier for the technicians and assembly workers to understand the assembly instructions and ensures that they make fewer errors. It also allows information about problems that arose during assembly and adaptations made to be included directly in the assembly documentation using the redlining and habitation functions provided by Adobe Reader, thus ensuring ensures that this information can be used to improve assembly planning for future machines and systems.

6. Summary and Outlook

Tackling the challenge of the agile assembly planning for multi-variant production, the use of 3D PDF technology allows closer links to be established between product development and assembly planning and an earlier exchange of information between developers and planners. This is a necessary precondition for a greater parallelization of the different tasks and activities in the product creation process. Concurrent engineering offers benefits both in terms of time and costs and also contributes to improving product quality [27]. In order to reap these benefits, the tools used in development and assembly planning must be harmonized so that a seamless workflow evolves. 3D PDF documents provide an ideal means of exchanging information between both working and system environments as they contain data from different source systems and can be visualized using the normal Adobe Reader which is available almost everywhere.

The use of digital models for assembly planning makes it easier to validate the assembly of large and complex machines and systems involving a large number of variants. At the same time, 3D assembly planning is an important step towards the model-based enterprise (MBE), i.e. towards establishing end-to-end, drawingless processes and systematic utilization of existing 3D information. Thanks to its versatility, 3D PDF technology can be used to digitalize any business process in which paper documents are still used. Like assembly documentation, it can also be used to create customer-specific spare parts catalogs, maintenance and repair documents or to provide non-PLM users with 3D CAD and BOM information, for example. It also can be used as a baseline.

The presented approach contributes an important added value to production design and planning through usage of knowledge in the existing systems. The exploitation of this approach under productive conditions has recently been started and already achieved the expected results. Further development of tool sets and methods could help to reduce the high initial effort for adjustment of the data even more. Besides the evaluation of the results based on product data, it is important to investigate the behaviour and results of the methodology for new assembly and joining technologies in production [28].

This initial solution provides a basis for future enhancements using 3D PDF template technology. In order to implement future developments efficiently, the assembly planning template was designed as flexible as possible. The objective of this further development is the implementation of further derived requirements such as additional optimization algorithms [8] [18].

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