Identification of alternative assembly sequences for large-scale products

Philip Rochow[a], Peter Burggraef[b], Christina Reuter[b], Henrik Prinzhorn[a],
Johannes Wagner[b], Torben Schmitz[b]
[a]Institut für Integrierte Produktion Hannover gGmbH (IPH)
Hollerithallee 6, 30419 Hannover, Germany
[b]Laboratory for Machine Tools and Production Engineering (WZL)
RWTH Aachen University, Steinbachstrasse 19, 52074 Aachen, Germany
t.schmitz@wzl.rwth-aachen.de

Abstract
Assembling large-scale products involves frequent process interruptions induced by e.g. delayed material deliveries or missing availability of resources. Our approach for identifying alternative assembly sequences by analyzing the product structure and process dependencies allows for continuing with the assembly process in case of interruptions and therefore increases the process efficiency.

Keywords: large-scale products, adaptive assembly, alternative assembly process

Introduction

Large-scale products, which are produced in job order and low volume manufacturing, are characterized by high technological and structural complexity, large dimensions and heavy weight (Potthast and Baumgarten 2011, Lang et al. 2008a, Lotter and Wiendahl 2012, Behrens et al. 2009). Another important attribute are high production costs (Meers et al. 2010, Lang et al. 2008b). According to the definition of IPH Hannover, the production costs of large-scale products increase over-proportionally relative to the further increase of a particular characteristic product feature, such as the size or the range of functions (Behrens et al. 2013). Examples for this kind of product are ships, airplanes or wind energy plants (Swyt 1992, Goudarzi and Behrens 2010).

The assembly of large-scale products provides a variety of challenges (Reuter et al. 2014). The characteristic production of small quantities with a limited number of repetitions results in few potentials for standardization (Petersen 2005). Due to the high level of customization of large-scale products, frequent product modifications occur during the assembly. These alterations lead to an ongoing rescheduling of new assembly sequences (Qi at al. 2006) that also affects tier one suppliers in the supply chain (Harrison 1997). Furthermore, the assembly process itself demands for flexibility. Producers of large-scale products face a high number of unanticipated interruptions as a continuous challenge (Cauvin et al. 2009). Common reasons for such interruptions are a lack of material (Esser 1996) as well as a limited availability of resources and tools (Mason 1986).

Production planners often use their experience and intuition to reschedule an assembly process in case of interruptions, but the challenging environment complicates the adherence to delivery dates and might lead to financial consequences due to penalties (Tatsushi et al. 2005). To limit the negative impact of interruptions under these circumstances, producers of large-scale products need to identify and analyze the alternative assembly sequences when an interruption occurs. That way, production planners are able to reschedule the assembly sequences based on all technologically feasible alternative assembly steps. In this paper, the feasibility of an assembly sequence is determined by precedence constraints between assembly steps. As a simple example, the dashboard of a train's driver's cab must be assembled before the doors are fit, because otherwise, the dashboard cannot be fed into the cabin anymore.

Within the research project "Adaptive assembly for large-scale products", WZL of RWTH Aachen and IPH Hannover develop a methodology, which determines, evaluates and visualizes all possible assembly sequence alternatives in case of an interruption (Reuter et al. 2014). The goal of this research project is to create a decision making tool that provides a visualization of evaluated options for assembly sequences so an optimized sequence can be picked and effects of interruptions are minimized. In this paper, we focus on a methodology for the identification of technologically feasible assembly sequence alternatives. First, we present the state of the art including existing approaches to represent assembly processes as well as to identify alternative assembly sequences. Second, a methodology is introduced that captures the structure of an assembly process, converts it into a standardized format and then determines all technologically feasible assembly sequences using a specifically designed algorithm. Finally, the algorithm is exemplarily applied and described.

State of the art

Representation methods

Various methods for the representation of assembly processes exist in literature that have been successfully applied. Precedence graphs are commonly used to illustrate priority relations. In such a graph, each individual assembly step is represented as a node (Niu et al. 2003). The relationship of the nodes to each other is realized by edges (Henlich et al. 2011). These edges connect the activities and show the dependencies by connecting at least one predecessor node with the direct successor node (Weigert et al. 2011). Precedence graphs have a simple structure and are easily readable for the user. Therefore, this method is still a commonly used application and practically orientated. However, the simple structure also leads to disadvantages in the representation of alternatives (Henlich et al. 2011).

Another method to represent assembly sequences is the AND/OR graph (De Mello and Sanderson 1990). AND/OR graphs can be characterized as bipartite graphs and contain two disjoint sets of nodes (Weigert et al. 2011). With this method, it is possible to illustrate both AND relationships as well as OR connections. Therefore, all assembly sequence alternatives can be shown in only one graph (Henlich et al. 2011). Additionally, this graph needs less nodes compared to the precedence graph (Weigert and Henlich 2009).

Another option for a visualization to plan the sequence of process steps is a Petri net (Weigert et al. 2008). Petri nets are bipartite graphs as well and are created with places, transitions and arcs. Additionally, tokens are used to represent a configuration of the Petri net. A transition symbolizes an active component which can create or change these tokens under given circumstances, i.e. time or number of tokens in the precedent place (Reisig 2010). It is connected

with directed arcs to places which represent a passive component that can store a discrete number of tokens. Petri nets have all the prerequisites to illustrate assembly sequence alternatives (Henlich et al. 2011). They do not only include data on the sequence of assembly, but can reflect information about the current progress of the assembly (Weigert and Henlich 2009).
For this paper, the precedence graph is used for the visualization of the process step structure of large-scale products. The simple structure allows for an easy overview while all necessary information for the identification of alternative assembly sequences are included or can be derived.

Identification of feasible assembly sequences

Besides representing the precedence relations of an assembly process, another important aspect for this paper is the identification of alternative assembly sequences. A number of approaches for this purpose have been developed that focus on certain constraints within the assembly process for the generation of alternative sequences.

Moradi et al. (1997) develop an approach for assembly planning based on grouping parts according to their geometry using Directional Blocking Graphs (DBG) and Non-Directional Blocking Graphs (NDBG). By grouping assembly steps based on their geometry, the number of possible assembly sequences is limited to possible combinations of groups. A group is defined as a set of parts that can be assembled only in one direction. The authors distinguish between serial groups (only one order of assembly orders is possible) and parallel groups (several assembly orders are possible). For both, they develop an algorithm and apply them to products from the electronics industry. Even though the approach is able to reduce the effort for determining assembly sequences significantly, taking into account only the geometry of a product leaves out important aspects of the assembly of large scale-products such as further process dependencies between assembly steps (Moradi et al. 1997).

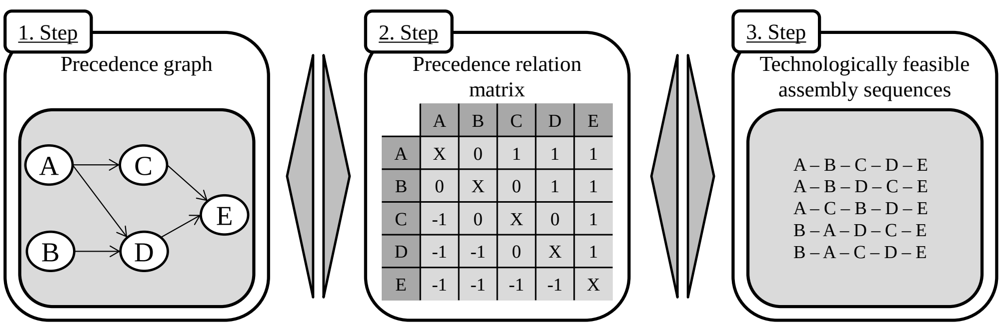
Another method is the connector-based hierarchical assembly planner (CBHAP) by Yin et al. (2003). In this approach, the generation of assembly sequences is based on connectors that consist of mating features or mechanical elements for joining parts. The resulting constraints are described by assembly precedence diagrams (APDs). For the creation of APDs, the following elements have to be elaborated beforehand: an assembly solid model, the connector-based relational model (CBRM) graph, special constraint graphs (SCGs) and the selected base part. Afterwards, a connector-based structure (CBS) hierarchy is computationally derived that is used to derive feasible APDs. Although some technological constraints are considered in this method, it can only be used for a small range of connector types such as screws (Yin et al. 2003).

Niu et al. (2003) present a hierarchical approach for the generation of assembly sequences. The information for this approach is taken from mating relation graphs (MRG) as well as hierarchical relation graphs (HRG). The assembly sequences are calculated using two algorithms that determine the geometric precedence relations within and between hierarchical levels. The approach derives feasible assembly sequences as well as an optimized sequence based on geometric constraints. Nevertheless, it is not taken into account that for an optimized assembly sequence, information about the capacities of resources and staff needs to be considered (Niu et al. 2003).

The reflected approaches for identifying feasible alternative assembly sequences demonstrate that often geometric constraints are regarded. In the case of large-scale products that often combine mechanical, electrical and hydraulic parts, it is important to include further constraints such as process dependencies that cannot be derived from the geometry of the product. Furthermore, the determination of optimized assembly sequences depends on scheduling information that is based on the available capacity of resources and staff. In this paper, we develop an approach in which different kinds of precedence information can be integrated. Also, the approach can be modularly integrated into a methodology for determining optimized assembly sequences using extended input such as capacity information. However, the latter is only part of the research project “Adaptive assembly for large-scale products” and will not be discussed in this paper.

Approach

The new method developed in this paper identifies all technologically feasible assembly sequences of a large-scale product. The precedence graph, which describes the technology-related sequence constraints, is a fundamental prerequisite for the definition of alternative assembly sequences. Therefore, the first step within this method is to determine all precedence relations for the regarded assembly process. Based on that, the precedence relation matrix is created, formally describing the structure of the precedence graph. The precedence relation matrix is the central element of the newly-developed algorithm in the third step that allows for finding all technologically feasible assembly sequences. Figure 1 illustrates the three key elements of the methodology presented in this paper.



	A	B	C	D	E
A	X	0	1	1	1
B	0	X	0	1	1
C	-1	0	X	0	1
D	-1	-1	0	X	1
E	-1	-1	-1	-1	X

Figure 1 - Key elements of the methodology for identifying technologically feasible assembly sequences

1. Step: Creating the precedence graph

In order to create the precedence graph, all technological constraints must be identified. For this paper, two approaches have been assessed to define the precedence graph. The first approach is based on the derivation of precedence information from data stored in ERP or MRP systems, specifically from the production scheduling modules. The cascade of scheduling process steps in a certain order contains information about possible assembly sequences. The integration of information from such systems would simplify the planning process immensely, but not all manufacturers of large-scale products use ERP or MRP software. Furthermore, the derived data, e.g. the identified assembly sequences from the production scheduling module, is often inaccurate and incomplete. Therefore, not all dependencies between process steps and possible assembly sequences can be identified. For the research project “Adaptive assembly for large-scale products”, data from SAP of a company cooperating in the project has been analyzed and technologically feasible assembly sequences have been identified which could only partly be verified by the production manager. Therefore, the applicability of the first approach is limited.

While data from ERP or MRP systems typically offers little information about possible assembly sequences, the second approach is a workshop with experts of the assembly process. Within such a workshop, hidden degrees of freedom consisting of technologically feasible alternatives can be elaborated. All possible precedence relations are manually written down after being discussed. The team for such workshops consists of assembly and production managers, assembly planners, foremen and operative staff. Due to the high degree of complexity, only one specific product and its technologically-related sequence constraints should be discussed in one workshop. The technological constraints for the analyzed product can be derived from work plans and design drawings. Figure 2 illustrates the result of such a workshop for the assembly process of a streetcar on the level of basic modules. In this example, the drive train/bogie and the bogie frame have to be joined before it can be assembled to the streetcar frame.

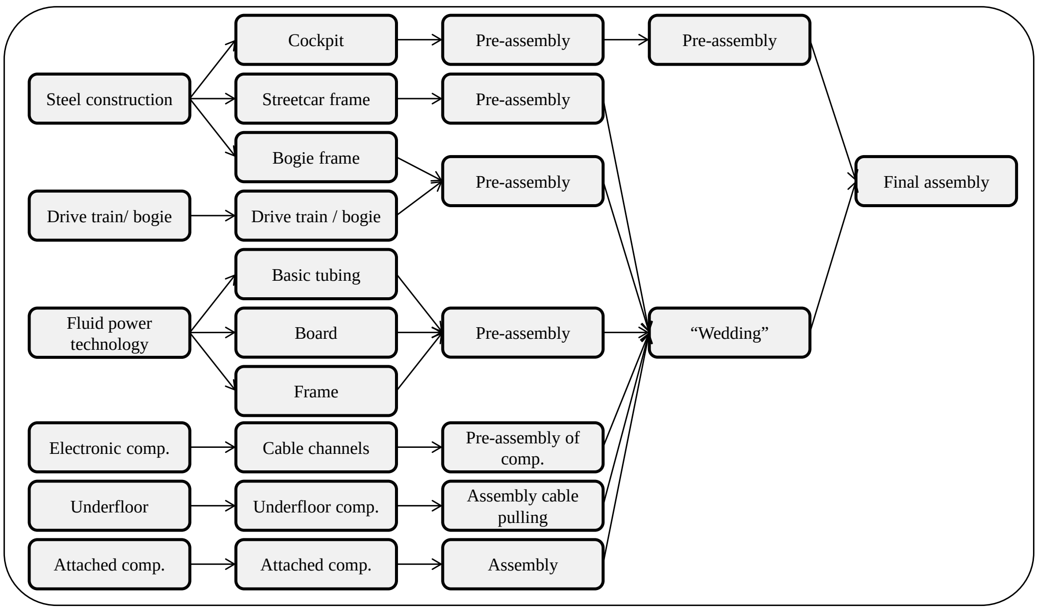


Figure 2 - Example of a large-scale product assembly process (streetcar)

For the purpose of this approach, it is important to define a suitable aggregation level of the product structure and its manufacturing process when creating the precedence graph. Commonly, this is the assembly of sub-modules. To unveil the required degree of freedom of the assembly sequences, a finer level of detail is necessary. Therefore, the process steps of each sub-module have to be described to enable a suitable intervention in the processes procedure in case of interruptions. Additionally, product groups should be given particular attention. The differences between individual products within a certain group often only become visible at a level of detail that is not shown in the module-based assembly precedence graph. Therefore, a single representation portrays the assembly steps for an entire product group. Only the processing times, which can be found in the varying work plans for each product, allow for differentiation and therefore need to be included in the final evaluation of the preferred assembly sequence. However, this evaluation is not a subject within this paper.

2.Step: Defining the precedence relation matrix

The second step after developing the precedence graph is to convert the corresponding information into a format that can easily be processed. For that reason, a precedence relation matrix is set up in the form of an adjacency matrix (see Figure 1). All process steps are listed in the first column and the first row of the matrix. The matrix contains information about any restrictions between two different process steps. To create the matrix, information about constraints are necessary. One constraint could be that a given process step must be carried out before or after another process step. It is also possible to have no constraints between two process steps, and the assembly sequence of these steps is interchangeable. Therefore, a third characterization is required. For a pair of process steps, these technological constraints are represented by "1", "-1" and "0". Describing a constraint in the precedence relation matrix with a "1" determines that the process step represented in the row must be performed prior to the process step of the column. Equivalently, the precedence relation is reversed if the evaluation matches a “-1”. Hence, a “0” describes a pair of process steps with no constraints. Using this logic to describe the precedence relations of process step pairs, additionally it is possible to computerize and illustrate the assembly sequence in the form of a precedence graph.

3. Step: Determination of technologically feasible assembly sequences

The last step of the methodology presented in this paper is an algorithm for automatically calculating all technologically feasible assembly sequences of a large-scale product. By identifying all possible combinations without technological constraints and eliminating those sequences that are technologically infeasible, the computational effort would be prohibitively high. The number of calculated assembly sequences for a number of n process steps is $n!$. In case of an assembly sequence that contains 15 process steps, 1,307,674,368,000 alternative assembly sequences would have to be calculated and assessed before rejecting the technologically infeasible assembly sequences. The method at hand lowers the number of necessary calculation significantly and systematically by identifying technologically infeasible conditions. The general procedure of the method is described in this section.

A product, which requires n process steps, consequently must have just as many process steps in the assembly sequence. The basic idea of the approach is to establish an assembly sequence successively and interrupt the creation of an assembly sequence or use other assembly steps (reconfiguration range) when adding a process step in the incomplete assembly sequence creates an infeasibility. The reconfiguration range within an assembly sequence represents the area between the last position and the first position that can be assigned to an assembly step. An assembly sequence is referred to as incomplete if there is at least one position of the new assembly sequence that has not assigned a process step yet.

Technologically infeasible conditions are identified within this method based on the precedence relation matrix. While positioning each process step, the relationship to its predecessors and to the process steps which have not yet been positioned is checked. In case of feasibility, the process step which is examined can be positioned and the procedure continues with the next position of this particular assembly sequence. Infeasibility would interfere with the construction of the current assembly sequence and the algorithm would skip to the next possible alternative. Following the example shown in Figure 1, every assembly sequence is technologically infeasible if process step E is not set to the fifth position of the assembly sequence. This results from the negative relationship to all other process steps, characterized by “-1” in the precedence relation matrix. Furthermore, it is essential that each process step must be exclusive in the resulting assembly sequence to determine a technologically infeasible assembly sequence. Each process step can be assigned to a specific position, which means the number of considered process steps equals the number of potential positions.

In a method table, the possible positions and the process steps are set in relation to one another (see Figure 3). It serves as a guide for positioning each process step and helps to identify those that are already positioned in the assembly sequence. In the table, an "o" represents the position of a process step in the corresponding assembly sequence. That implies that no further process step can be set to this position. An "x" indicates a particular process step as "locked" because it is already set on a different position in the assembly sequence. In case a process step is marked with neither an “o” nor an “x”, the process step is not included in the assembly sequence yet. Therefore, a technologically feasible assembly sequence must have one process step marked with an “o” on each position. When all process steps have been set at position 1 for an assembly sequence and the other process steps were tested for feasibility, the scanning process is completed and all possible assembly sequences have been identified. A termination of the search happens when no valid permutation from a certain position can be carried out with the remaining process steps.

Exemplary application of the alternative assembly sequence identification algorithm

The schematic procedure of the algorithm for identifying technologically feasible assembly sequences is shown in Figure 4 and will be described below for the example given in Figure 1. Starting point of the method is the first process step of a product - in this case, process step A.

As seen in the precedence relation matrix, process step A has no negative correlation with any of the process steps in the first permutation, which still need to be integrated in the assembly sequence (B, C, D, E). Hence, A is set to position 1 of the assembly sequence and labeled in the method table with an “o”. The successful scheduling of process step A is indicated by locking all the following positions and marking them with an “x”. The second position is now filled with the first succeeding process step that has not yet been positioned successfully. In the example at hand, this is process step B. The same procedure is being repeated for positions 3, 4 and 5 while the precedence relations between the process steps are considered. Ultimately, the first technologically feasible assembly sequence equals A-B-C-D-E. In addition to the method table, both the relation path and the final assembly sequence for the first permutation are illustrated in Figure 4.

Based on the last feasible assembly sequence A-B-C-D-E, the algorithm attempts to generate other technologically feasible assembly sequences. During this procedure, the method table assists to avoid redundant permutations. The reconfiguration process starts between the last position of the assembly sequence, position 5, and a previous position in the method table which contains the first empty spot. The search for an empty spot starts from position 5 and descends to position 1. The first empty spot can be found for process step E at position 4. As a result, the reconfiguration range for permutation 2 includes position 4 and position 5. The resulting incomplete assembly sequence A-B-C-E now needs to be rearranged starting from position 4. Since only process step D is left to be positioned, it is set to position 5. However, process step E cannot be carried out before step D is done. Therefore the second permutation A-B-C-E-D is technologically infeasible and the reconfiguration attempt of the assembly sequence A-B-C-E is stopped. The precedence graph illustrates this problem by plotting two edges pointing in opposite directions (see Figure 4).

For the next permutation, a view on the method table reveals that all process steps that can be set to position 4 have been tried out (process steps D and E). As before, the process step which contains the first empty spot is identified. At this point, the first empty spot for process step D is position 3 and the reconfiguration range is defined as [position 3, position 5]. All process steps that have not been positioned have a non-negative entry in the row of process step D in the precedence relation matrix. Therefore, process step D is set to position 3 in the assembly sequence. Process steps C and E are set according to the procedure described in the first permutation leading to the second technologically feasible assembly sequence: A-B-D-C-E.

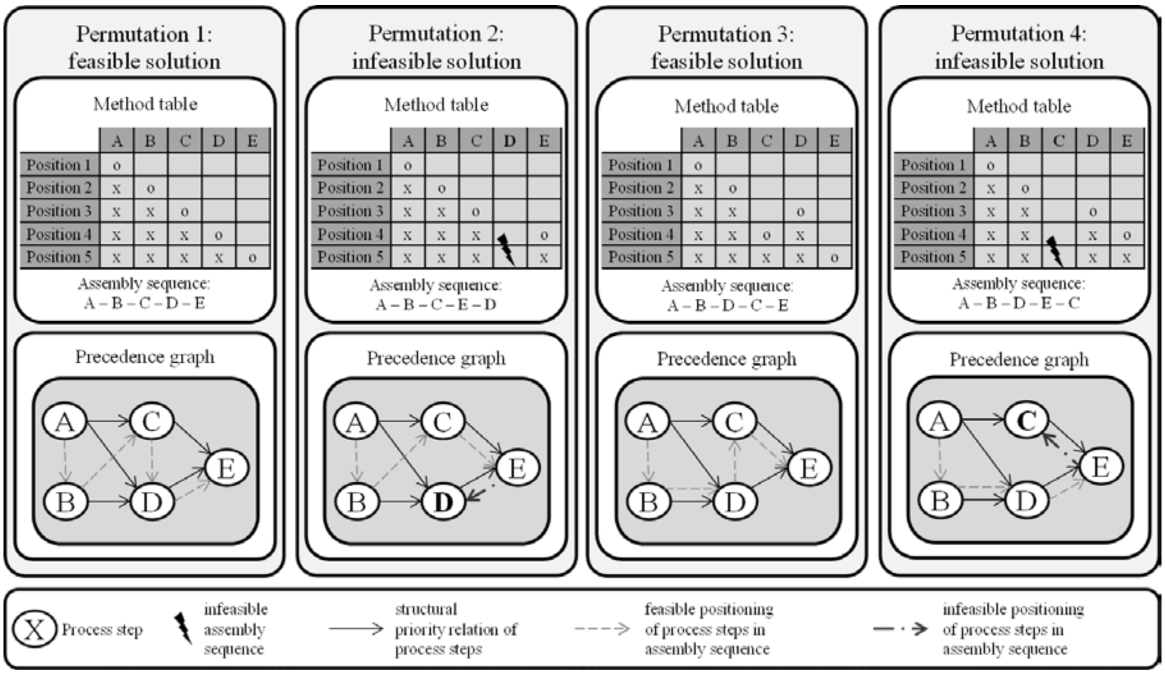


Figure 3 - Permutations of the alternative assembly sequence identification algorithm

The following permutation starts with the newly found technologically feasible assembly sequence A-B-D-C-E. As seen in permutation 2, the first empty spot that can be found at position 4 leading to the reconfiguration range [position 4, position 5]. Positioning process step E on position 4 is not possible and therefore leads to a technologically infeasible permutation because, process step E cannot be carried out before process step C. Based on that, this attempt of rearranging the defined positions is interrupted.

To determine all further technologically feasible alternative assembly sequences, the described procedure is repeated until every process step was set to position 1 and the remaining process steps were tested for feasibility. The described method is able to identify alternative assembly sequences while considering those process steps facing interruptions and those that have already been carried out. Besides searching for a technologically feasible alternative after the interruption occurs, all alternative assembly sequences can be computed and stored in a data base beforehand. With the continuous procedure of updating the current assembly status after each finished process step, the determination of assembly sequences that are not affected by any interruption is possible without any delay. An implementation of this new method in Java was successfully realized and is able to calculate the number of technologically feasible assembly sequences following the described algorithm.

Conclusions and future research

Planning the assembly process for large-scale products involves a number of challenges. The high complexity of products, changing customer specifications and unexpected interruptions within the assembly process steps are a few major challenges to mention. Especially interruptions in the operative process steps due to missing materials or resources are a common problem. Companies try to react to these interruptions by rescheduling the process. However, caused by a lack of information and transparency, production planners have to rely on their experience and intuitive knowledge for this task. In order to find a suitable assembly sequence that does not rely on intuition, which is prone to errors, we present a new methodology. This approach analyzes the structure of process steps for products and identifies the full range of technologically feasible alternative assembly sequences. The methodology consists of three steps: first, a precedence graph has to be created based on all technological constraints for the assembly process of a large-scale product. Second, the precedence graph is converted into a precedence relation matrix that formalizes all dependencies within the assembly. Third, an algorithm determines all technologically feasible assembly sequences for the complete assembly process of a large-scale product.

The next step for future research is to integrate the possibility to conduct process steps in parallel. Therefore, the algorithm needs to be developed to feature a function for synchronizing or combining steps that can be carried out simultaneously. Another important research topic is to convert the determined assembly sequences into an assembly plan. This assembly plan provides the basis for further evaluation. Doing this, the optimal assembly sequence will be computed using the logistic performance objectives as evaluation criteria (Nyhuis and Wiendahl 2009). For that purpose, the logistic performance objectives need to be weighted and converted into costs. The most important performance objective for the companies is the adherence to delivery dates (Schuh et al. 2013).

The approach at hand is a key element for the methodology to illustrate, assess and evaluate assembly sequences in order to find the most suitable sequence in case of interruptions within the assembly process of large-scale products. The methodology will be integrated in a software demonstrator that both visualizes the actual state of an assembly process and indicates an evaluated, optimized assembly sequence based on the steps that have already been conducted and the interruptions the assembly process is facing.

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