TYPES AND USAGE OF ASSEMBLY PRIORITY CHARTS
IN A MODULAR ASSEMBLY SYSTEM

W. Kern 1, 2, T. Bauernhansl 1, 3
1 GSaME Graduate School of Excellence advanced Manufacturing Engineering, University of Stuttgart, Stuttgart, Germany
2 Audi AG, Ingolstadt, Germany
3 Fraunhofer Institute for Manufacturing Engineering and Automation IPA, Stuttgart, Germany

Abstract
The increasing diversity and dynamics in the automotive market require more flexible and changeable automotive assembly configurations. However, when dealing with alternative assembly concepts, the methods for planning and operating an automotive assembly as well as the used information have to be adapted. A modular assembly system with uncoupled workstations and a flexible flow of products through the system, e.g. requires an assembly priority chart to plan and control the cyber-physical assembly system. In this paper, the different types and characteristics of the required assembly priority charts and their usage for planning and controlling a modular assembly system are described as well as the methods to generate them. Moreover, the assembly priority charts from a case study of a German automotive subassembly are shown and discussed. By this, the required level of flexibility and changeability of future automotive assembly systems can be enabled.

Keywords: Assembly, automotive assembly, cyber-physical production systems, modular assembly, modularity.

1 INTRODUCTION
The diversity and dynamics in the automotive industry have been increasing in recent years due to a turbulent global market environment, shorter lifecycles of products and technologies as well as the related and ongoing differentiation and individualization of products [1, 2]. This trend is expected to continue in the future because alternative drive concepts, additional types of usage, or new materials and technologies emerge [3]. As a consequence, the level of flexibility and changeability in automotive manufacturing has to be increased correspondingly, especially in automotive assembly systems where the largest part of product variety is created [4, 5]. Two basic enablers to reach this higher flexibility and changeability are modularization on the one side [6, 7, 8] and inter-connected, self-controlling systems on the other side [9, 10]. By this, the potentials of smart factories and the anticipated fourth industrial revolution can be utilized [3, 11]. In this context, flexible and changeable assembly configuration concepts with uncoupled, modular workstations and an individual flow of products through the assembly system are being developed [12, 13]. They are based on interconnected objects in a cyber-physical production system [3, 10], i.e. products being aware of their required assembly processes, their precedence constraints and their current status of assembly as well as workstations being aware of their capabilities, their current workload and their upcoming production program [12, 13].

However, such modular assembly configurations also require an adapted production planning and controlling in contrast to current automotive assembly systems [10, 14]. Today, nearly all existing large-scale automotive assembly systems follow assembly line production principles. In this context, assembly line balancing is applied to assign assembly tasks to workstations along an assembly line, and customer orders are sequenced to avoid excessive workload variations at the single workstations [15, 16]. As the flow of products is predefined by the conveyor belt and thus one identical order of assembly is implemented for all products in an assembly line production, the requirements towards product data and production data for planning, scheduling and operating an assembly system are different. The precedence constraints of assembly processes, for example, are required for assembly line balancing. Such assembly priority charts (APCs) are needed on a very detailed level of single process steps and are thus very complex. Moreover, for assembly line balancing they are used in a complex interaction with other constraints regarding logistics, equipment or infrastructure. As a consequence, assembly priority charts are in general not explicitly documented in the industrial environment but are rather known implicitly [4].

However, to enable an individual flow of products in a modular, self-controlling assembly system, the assembly priority chart of a product is definitely required. By this, an interaction with the other elements of the cyber-physical production system can be established to control and optimize the assembly system and to react to variations, disturbances and changes in the system. Hence, to plan and control a modular cyber-physical assembly system, current product and production data have to be transferred into an assembly priority chart in a structured and efficient way and in the required level of detail. By this, alternative assembly configurations can be realized and enable the required flexibility and changeability in future automotive assembly systems can be enabled.

The paper is organized as follows. In Section 2, the situation in current automotive assembly systems, especially mixed-model assembly lines, is described as well as the basics of graph theory to document and visualize an assembly priority chart. The characteristics of a modular automotive assembly system are outlined in Section 3, and its requirements towards an assembly priority chart are described as well in this section. In Section 4, the two methods to gain and record this required information are explained and the two required types of assembly priority charts as well as their usage in a modular cyber-physical assembly system are described. These two types of assembly priority charts from a case study of a German automotive subassembly are shown and discussed in Section 5. Following this, Section 6 summarizes and concludes the paper.
2 BACKGROUND

2.1 Assembly line production in the automotive industry

Assembly line production is the dominant assembly system configuration in large-scale automotive assembly. It is characterized by the synchronized movement of products along an assembly line while they are sequentially assembled [5, 15]. The method to assign assembly tasks to workstations along an assembly line and to define one sequential order of assembly is called assembly line balancing [15]. Therefore, the smallest possible assembly process steps are defined and balanced on the workstations of an assembly line production. By this, a high and balanced utilization of all workers along the assembly line should be reached. For this assignment, not only the cycle time or worker utilization, but also accessibility, ergonomics, material supply areas, working height, required equipment and predecessor-successor-relations of the respective assembly processes have to be considered [4, 15]. Moreover, usually two subsequent product generations have to be assembled in one assembly line production in parallel for a certain period of time, limiting the changes and improvements regarding product concepts in general and precedence constraints in particular.

2.2 Mixed-model lines and product mix variations

However, in current automotive assembly systems, not only two product generations have to be assembled for a certain period of time in parallel, but mixed-model assembly lines are established with several models, each having numerous variants and features and thus a variant-dependent assembly time at the single workstations of the assembly line production [15]. For this reason, assembly line balancing becomes very complex and has to be accomplished by the sequencing of the product mix of the production program on an assembly line in a suitable sequence in order to level workloads along the assembly line [16]. However, based on customer orders, this product mix is also volatile over time.

In addition to that, several other efforts have to be made to either decrease or control the effects of assembly time variety caused by the different models, product variants and features of the production program in a mixed-model assembly line [17]. Design for manufacturing and assembly, the building of subassemblies or specific workstation designs are exemplary measures to decrease assembly time variety. Worker drifting, feature-specific workplaces or additional supporting workers, for example, help to handle the varying assembly times and changing product mix in a mixed-model assembly line [17].

2.3 Assembly priority charts based on graph theory

The assembly tasks to be performed in such an automotive assembly system are defined by the components of the resulting product and the assembly processes to assemble these components [15]. Graph theory is often used for the description and visualization of such product structures and production processes [4, 15]. Within product development, for example, a liaison graph describes the components of a product (as nodes) and their physical connections (as edges) [4], see Fig. 1.

Based on product data like the liaison graph, production planning is transforming these physical relations between components into production processes. To establish a process and to generate an assembly sequence, one main component on a workpiece carrier or even an empty workpiece carrier is the initial starting point for the subsequent assembly processes [4], e.g. a body-in-white on a skid in an automotive assembly system.

In this context, a precedence graph or assembly priority chart is the graph-theoretical description of such an assembly process. The nodes of the graph are the assembly processes and the edges between the nodes describe the technical constraints of these processes for a product to be assembled [15]. Assembly priority charts are directed graphs – visualized by having arrows as edges – as these edges represent a technical order of assembly, i.e. a direct predecessor-successor-relation between two assembly processes [15]. As one assembly process cannot be a (direct or indirect) predecessor and successor of another assembly process at the same time, such graphs are non-cyclic ones and have at least one initial node to start the assembly process [15], see Fig. 2.

Moreover, a weight is assigned to the nodes of the graph in terms of the predefined assembly time for the respective assembly process [15]. By having the precedence graph or assembly priority chart of a product to be assembled, all feasible assembly sequences can be deduced from the graph [4].

Depending on the level of detail of the described assembly processes, assembly priority charts can be very complex [4]. However, due to the low abstraction level which is needed for assembly line balancing, assembly priority charts are generally not documented in automotive industry on the level of assembly steps [4]. Therefore, the knowledge about predecessor-successor-relations is often implicit and not transparent.

Moreover, when having more than one product in a production system – as in mixed-model assembly lines – different assembly priority charts have to be merged to a mixed graph [15]. Here, average assembly times are used according to the production rates of an assembly task in a certain product mix in an existing or estimated production program.
3 A MODULAR AUTOMOTIVE ASSEMBLY SYSTEM AND ITS REQUIREMENTS TOWARDS AN APC

In a cyber-physical production system – like the modular assembly system developed by the authors – all main objects like products, workstations or workers are represented by virtual entities. Hence, their status is transparent and they are interconnected to the other objects of the cyber-physical production system. By this, their interaction to schedule, control and optimize the processes in the assembly system is enabled in order to reach a high utilization of resources as well as a flexible reaction to variations, disturbances and changes.

3.1 Characteristics of the modular assembly system

The three main characteristics of this modular automotive assembly system are [12]:

- uncoupled workstations without a defined cycle time,
- flexible product flows by automated guided vehicles,
- integrated production logistics processes [18].

According to these main characteristics, this alternative to assembly line production in the automotive industry has a variable order of assembly instead of a sequential and standardized one along an assembly line [12]. The variable order of assembly is only determined by the technical constraints recorded in a product variant's assembly priority chart, see Section 2.3. The possible workstations in a specific situation are defined by these constraints. The assignment to one subsequent workstation is dependent on the current status of the product, the current workload of the possible workstations as well as on the current distance between them [12]. Hence, the operation and control of the modular assembly system is based on a decentralized decision-making and interconnected objects in the cyber-physical production system. By this, a self-controlled and self-optimized flow of products can be reached which is reacting to the individual situation inside the assembly system [9, 10].

With this new approach to configure a large-scale, highly flexible and changeable mixed-model assembly system, the methods to plan and control an assembly system are different to assembly line production configurations [12, 14]. In an assembly system with uncoupled workstations both the assignment of assembly processes to workstations as well as the controlling of the flexible flow of products and materials is changed. As a result, the assembly priority chart describing all feasible orders of assembly in an explicit and comprehensible way becomes a key information for the planning and the (self-)controlling of such a cyber-physical production system [4, 10]. By this, the assembly system's degree of freedom in planning and controlling is increased and enables the system's potential regarding the level of flexibility and changeability in comparison to assembly line production [12]. In the following, the specific requirements towards an assembly priority chart for a modular assembly system are outlined.

3.2 Requirements towards an assembly priority chart

The assignment of assembly processes to the uncoupled workstations in a modular automotive assembly system is performed on the level of assembly tasks, e.g. the assembly process of a whole component, as there is no defined and common cycle time for all workstations in the assembly system [12, 14].

Hence, the required level of detail regarding an assembly priority chart in a modular automotive assembly system is on the level of assembly tasks as well. Thus, it is more abstract than the very detailed level of every differentiable assembly step as it would be required for the assembly line balancing of an assembly line production system [4, 12], see Section 2.3.

Moreover, as the variable order of assembly allows different product flows for different product variants, there is no need for building one standardized order of assembly for all product variants in a modular assembly system [12]. As a consequence, varying predecessor-successor-relations of different product variants, which cause additional efforts in an assembly line production, can be easily handled by the flexible flow of products in the modular automotive assembly system.

For each assembly task of the respective products to be assembled in the system, the following information is required:

- direct predecessor task(s)
- production rate of each (variant of an) assembly task
- assembly time of each (variant of an) assembly task

With having this information an assembly priority chart can be documented, visualized and used according to the descriptions in Section 4.2 and Section 4.3.

4 TYPES AND USAGE OF ASSEMBLY PRIORITY CHARTS IN A MODULAR ASSEMBLY SYSTEM

In this section, the two different types of assembly priority charts and their usage in a modular, cyber-physical assembly system are described. Prior to this, the two sources to generate this required data are outlined.

4.1 Generation of APCs from existing data

In general, there are two possible sources to generate the required assembly priority chart on the level of assembly tasks from existing production data or product data:

- aggregation from assembly process data
- derivation from product-structure data

Aggregation from assembly process data

In case of an already established production process – e.g. of an existing assembly line – the single assembly steps, their predefined process times and production rates can be used for the generation of the required assembly priority chart on the level of assembly tasks.

Therefore, a two-step approach is applied:

1. Group assembly steps to assembly tasks.
2. Define predecessor-successor-relations of assembly tasks.

In this approach, the grouping of assembly steps to assembly tasks is mainly based on the product structure and thus the individual components of the product. Subsequently, the definition of predecessor-successor-relations between the individual assembly tasks is practicable due to the more abstract level of detail, see Section 2.3.

Derivation from product-structure data

In case of a new product without existing production process data, the required assembly priority charts on the level of assembly tasks has to be derived from product-structure data, e.g. the bill-of-material, liaison graphs or other construction data.

Therefore, an iterative, two-step approach is applied:

1. Define predecessor-successor-relations of product components
2. Transform construction data to process data.

413
In this case, the definition of predecessor-successor-relations is performed on existing data of main components of the product before the physical relations of components are transformed into production processes containing not only construction-related assembly times for the joining of parts (i.e., engineering hours per vehicle/product), but also process-related assembly times regarding the preparation of processes, the handling of materials and equipment, the walking in the workstation or quality checks. Moreover, a production rate for different process variants has to be estimated.

4.2 Usage in planning a modular assembly system

The assembly priority chart on the level of assembly tasks generated from production or product data is used as input data for the assignment of assembly tasks to workstations in a modular assembly system. By doing this, reasonable workstations of a modular assembly system according to product-related and process-related principles are defined, for details see [14].

After this assignment of assembly tasks to workstations, the APC on task level can be transferred into an assembly priority chart of the assembly system’s workstations, see Fig. 3.

![Figure 3. APC on workstation level (schematic).](image)

This type of assembly priority chart is still containing the respective information described in Section 3.2, aggregated for each workstation of the assembly system:
- direct predecessor workstation(s)
- production rate (percentage of production program requiring a specific workstation)
- assembly times (per product variant and as sum of each workstation)

4.3 Usage in controlling a modular assembly system

This assembly priority chart on workstation level is then used for production control of a modular assembly system to realize the flexible flow of production through the system, as it contains all technical constrains regarding the order of assembly of the products [12], see Fig. 3. Therefore, each product variant entering the assembly system gets its initial data set containing all required workstations and assembly times to realize a situation-based decision of the next workstation to approach, see Table 1.

<table>
<thead>
<tr>
<th>Workstation</th>
<th>Assembly time (sec)</th>
<th>Predecessor (total)</th>
<th>Predecessors (stations)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>68</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>B</td>
<td>84</td>
<td>1</td>
<td>A</td>
</tr>
<tr>
<td>C</td>
<td>76</td>
<td>1</td>
<td>A</td>
</tr>
<tr>
<td>D</td>
<td>90</td>
<td>1</td>
<td>C</td>
</tr>
<tr>
<td>E</td>
<td>86</td>
<td>2</td>
<td>B, D</td>
</tr>
</tbody>
</table>

This initial data set for each product variant is then dynamically updated during the assembly process inside the modular assembly system. By this, the current status of assembly for each product as well as its possible workstation in a specific situation and thus all further possible orders of assembly are recorded and continuously updated in a dynamic assembly priority chart, e.g., see Table 2. In this dynamic list of the assembly priority chart on the level of workstations, the performed (or not needed) workstations are marked with an assembly time of zero (e.g., Workstations A and C), all other workstations having no predecessor to be done at this specific situation are possible (Workstations B and D) and all workstations having still one or more workstations to be done as predecessor are not yet possible for assembly (e.g., Workstation E).

<table>
<thead>
<tr>
<th>Workstation</th>
<th>Assembly time (sec)</th>
<th>Predecessor (to be done)</th>
<th>Predecessors (stations)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>B</td>
<td>84</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>C</td>
<td>0</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>D</td>
<td>90</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>E</td>
<td>86</td>
<td>2</td>
<td>B, D</td>
</tr>
</tbody>
</table>

In accordance to this, the individual flow of each product through the assembly system is based on both the required assembly processes and the status of assembly of a product as well as on the capable assembly processes and status of workload of each possible workstation in a specific situation [4]. Therefore, all products and workstations of the modular assembly system have to be interconnected and represented by virtual representatives in the production control system. As a consequence, the modular assembly concept is based on a cyber-physical production system. Following this, an efficient product flow, high utilization of workstations and a flexible reaction of the assembly system to variations and disturbances can be realized.
Table 3. Four types of graphs, their characteristics and usage.

<table>
<thead>
<tr>
<th>Type</th>
<th>Liaison graph</th>
<th>APC (step level)</th>
<th>APC (task level)</th>
<th>APC (station level)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Nodes</strong></td>
<td>Product components</td>
<td>Process steps</td>
<td>Assembly tasks</td>
<td>Workstations</td>
</tr>
<tr>
<td><strong>Edges</strong></td>
<td>Physical contact (undirected)</td>
<td>Precedence relations (directed, non-cyclic)</td>
<td>Precedence relations (directed, non-cyclic)</td>
<td>Precedence relations (directed, non-cyclic)</td>
</tr>
<tr>
<td><strong>Weight</strong></td>
<td>-</td>
<td>Assembly time of process step</td>
<td>Assembly time of task variants</td>
<td>Assembly time of variants in station</td>
</tr>
<tr>
<td><strong>Usage</strong></td>
<td>Product development</td>
<td>Assembly line balancing (often implicit knowledge due to complexity)</td>
<td>Production planning of a modular assembly system (static usage)</td>
<td>Production control of a modular assembly system (dynamic usage)</td>
</tr>
</tbody>
</table>

5 APPLICATION AND EVALUATION IN A CASE STUDY OF THE GERMAN AUTOMOTIVE INDUSTRY

5.1 Case study of an automotive subassembly

The methods to generate and use the two different types of assembly priority charts described in Section 4 are applied to a case study of a subassembly of the German automotive industry. This subassembly is organized as a large-scale mixed-model assembly line production, differentiated into 242 single assembly steps.

5.2 Application and results

In this approach, the required assembly priority chart on the level of assembly tasks was generated from existing production process data of the current assembly system, see Section 4.1. In doing so, the 242 single assembly steps are grouped to 29 assembly tasks, see Fig. 4 [14]. For each assembly task, a production rate and an average assembly time of a given production program is attached, with six assembly tasks (No. 1, 2, 12, 18 and 26) being variant-dependent in terms of having a production rate of less than 100%. In this context, it is shown that the required assembly priority chart on assembly task level for the assignment of assembly processes to workstations is less complex than the assembly priority chart needed for assembly line balancing with 242 nodes.

![Figure 4. Assembly priority chart with 29 assembly tasks [14].]

This assembly priority chart on the level of assembly tasks is then transformed into the assembly priority chart on the level of workstations during the production planning process of a modular assembly system [14], see Section 4.2. The resulting assembly system has eleven workstations, see Fig. 5 [14], – with two of them being variant-dependent (Workstations A and B).

![Figure 5. Assembly priority chart with 11 workstations [14].]

<table>
<thead>
<tr>
<th>Workstation</th>
<th>Assembly time (sec)</th>
<th>Predecessor (to be done)</th>
<th>Predecessors (stations)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>68</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>B</td>
<td>84</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>C</td>
<td>76</td>
<td>1</td>
<td>A</td>
</tr>
<tr>
<td>D</td>
<td>90</td>
<td>2</td>
<td>B, C</td>
</tr>
<tr>
<td>E</td>
<td>86</td>
<td>1</td>
<td>D</td>
</tr>
<tr>
<td>F</td>
<td>70</td>
<td>1</td>
<td>D</td>
</tr>
<tr>
<td>G</td>
<td>58</td>
<td>1</td>
<td>F</td>
</tr>
<tr>
<td>H</td>
<td>92</td>
<td>1</td>
<td>F</td>
</tr>
<tr>
<td>I</td>
<td>82</td>
<td>3</td>
<td>F, G, H</td>
</tr>
<tr>
<td>K</td>
<td>74</td>
<td>1</td>
<td>H</td>
</tr>
<tr>
<td>L</td>
<td>82</td>
<td>2</td>
<td>I, K</td>
</tr>
</tbody>
</table>

5.3 Implications for science and practice

After explaining the types, characteristics and usage of assembly priority charts in a modular assembly system, some implications for science and practice have to be noticed. Despite the explicit description of all feasible orders of assembly in an assembly priority chart, the contained information are modifiable in several perspectives. First, the structure of a product can be influenced, and thus the possibilities for subassemblies, modular products or required production processes. Second, the technical constraints between assembly tasks can be influenced by changes of production equipment or the accessibility of the product. And finally, there is no definite assignment of assembly tasks to workstations, i.e. depending on the process to assign assembly tasks to workstations, different assembly priority charts on the level of workstations can be derived.

Moreover, in terms of the dynamic usage of an assembly priority chart on the level of workstations to control the flow...
of products through the assembly system, additional research has to be conducted. In this context, the optimization of the situation-specific decision making in the cyber-physical production system, or more detailed and sophisticated measures and reactions to variations and disturbances within the modular assembly system are just two examples.

6 SUMMARY AND CONCLUSION

In this paper, the required types and characteristics of assembly priority charts for a modular assembly system and the generation of this information either from existing assembly process data or from product structure data are described.

Further, the usage of these assembly priority charts is explained. First, an assembly priority chart on the level of assembly tasks as input to plan the modular workstations of such an assembly system and the derived assembly priority chart on the level of workstations is characterized. Second, the usage of this type of an assembly priority chart to control the flow of products through this cyber-physical assembly system is described. As an assembly priority chart represents all feasible orders of assembly, it is used for the decentralized decision making to define the possible workstations in a specific situation of a product being assembled. In this context, the assembly priority chart is dynamically updated during the assembly process of a product and includes variations and disturbances regarding the respective product or the workstations of the assembly system.

The described methods are applied to a case study of a subassembly of the German automotive industry and the resulting assembly priority charts are shown as graph and dynamic list.

Based on the required information regarding the two types of assembly priority charts, the adapted methods to plan and control a modular assembly system as alternative to assembly line production in the automotive industry are enabled. By this, the advantages from this flexible and changeable assembly system can be gained, and thus help to handle the further increasing diversity and dynamics in the turbulent market environment of the automotive industry.

7 REFERENCES