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PRODUCT AND PROCESS EVALUATION IN THE CONTEXT OF MODULARIZATION FOR ASSEMBLY

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ABSTRACT

Modular product structure determination requires continuous evaluation of the processes involved. Modularization is an appropriate method for product structuring. It takes into account the requirements from product life phases, such as development, production and after-sales. Assembly, as an essential part of production for the company, requires easily mountable products. Short lead-times and flexible processes are some other main requirements. The methodical procedure presented in this paper proposes a single diagram to represent the product structure and its resulting assembly sequence in an integrative manner. The tool developed performs structuring on the product and demonstrates the impact on the assembly process. The use of key figures is proposed for the evaluation. Data required for the calculation of these key figures is extracted from the diagram. The procedure is applied to the development of a model aircraft interior.

Keywords: Design for Assembly, Modularization, Product Structuring, Process Evaluation, Key Figures

1 INTRODUCTION

A wide range of companies sustain their position in global markets through customised products. Market success, however, is only achieved when the product can be offered at a price that is based on internationally competitive cost structures [1]. Analysis of the distribution of costs along the product emergence process shows that the assembly department is a major contributor; however, the product development department is responsible for these costs. For this reason, planning of the assembly of complex products requires a systematic procedure that identifies and implements economical product and assembly. The question of which approaches and methods for product design and assembly should be applied is an essential challenge to companies. To preserve competitiveness it is necessary in product development to take the fulfilment of technical requirements into account and to focus on reducing production costs. Further aspects in the lifecycle, such as maintainability and recyclability, need to be included in the design of a product [2].

A way to meet the partially conflicting requirements is the modular structuring of products. Different product concepts are developed in the course of modularization. Based on an evaluation using key figures, concepts are evaluated and selected for further elaboration, as designated in common engineering design procedure [3]. The use of a key figure system is advisable for the evaluation. In the early stages of product development, where modularization is performed, the calculation of key figures turns out to be insufficient. Using the example of the product life phase “assembly”, a systematic procedure is presented. By integrating two aspects of product structures, determination and evaluation, support is provided to modularization. First, a holistic procedure model for Life Phases Modularization is presented. Subsequently, an overview of the current state of methods in product structuring during assembly is given. The focus is also on the specific requirements of assembly. For the evaluation, key assembly and figure systems are assessed. Based on the findings, a generic procedure for modularization of assembly is developed. In this context, the application possibilities for an integrative product and assembly representation of structuring and evaluation capabilities are investigated. Finally, the approach is applied to the development of an aircraft cabin lining architecture.

2 BACKGROUND

The theoretical basis for the method consists of the following aspects. First, procedures for product modularization and their production objectives are presented. An analysis of approaches for the structuring of products that concentrate on assembly is performed. A list of assembly key figures for the evaluation of modular structures is then collated.

2.1 Life Phases Modularization in assembly

Defining modular structures provides the opportunity of taking into account requirements from different perspectives in the product life cycle. The range of perspectives runs from technical-functional requirements to product strategic aspects, such as purchase, production or after-sales. Specific modular structures are set up for each perspective. Different methodical approaches were developed to merge the perspectives into a common modularization. In the Modular Function Deployment by Erixon, the product components are linked with module drivers using a Module Indication Matrix [4]. Pimmler and Eppinger propose the application of a Design Structure Matrix to support the clustering of product components based on their mutual relations [5]. According to Stone, modular product architectures are developed by Module Heuristics, based on function structures [6]. In any case, the consideration of different views next to each other entails the risk to develop conflicting modular structures. For example, while it is in the interest of the purchasing department to receive large modules, the formation of smaller modules is preferred by maintenance. An example of the modular product structures and the relation of the components is shown in a Module Process Chart (MPC) [7] in Figure 1.

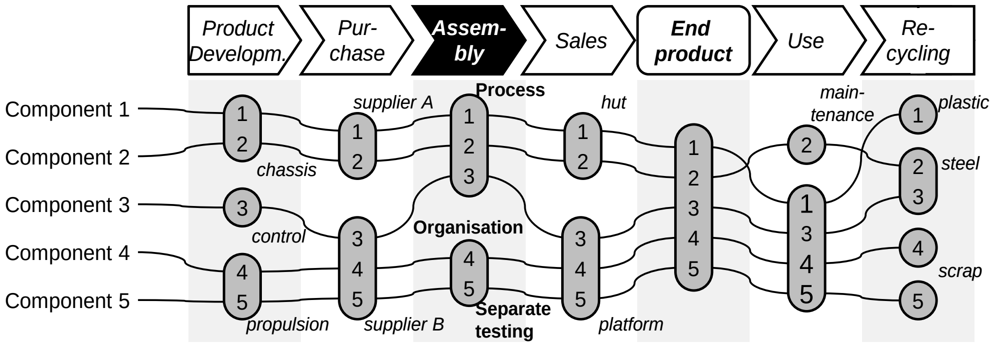

Figure 1. Life Phase based clustering of components into modules

A holistic approach for modularization was developed by [7]. The procedures for modularization are integrated into one methodology. Systematic support for resolving possible contradictions between views is proposed. Because of the decisive significance of production to the company, the focus of further investigation is on assembly.

In assembly, there are four major objectives in product modularization. By decoupling modules, a parallel production is possible, which leads to the *reduction of lead times*. The use of standardised modules lowers production costs and enables the achievement of *economies of scale*. Process quality is enhanced with the use of standardised parts, which entails the *reduction of the amount of defective goods*. Modular product structures enable pre-testing of complete entities prior to final assembly. Errors and malfunctions can be detected at an early stage. As a result, the quality and reliability of the production process can be improved. The costs of expensive rework can thus be omitted. The use of standardised modules enables product *customisation at a late stage of production*. Product design remains flexible and delivery times decrease.

To facilitate inclusion of these objectives in the method, the following module drivers were used to determine product structure. The module is subject to specific assembly *processes*. The module accumulates an appropriate scope of work for one *organisational* unit. The module will be *tested separately* prior to its final assembly.

Processing of the module drivers within the method to determine product structure is not systematically supported and is heavily dependent on the subjectivity of the user. In particular, the relationship between product design and the resulting production process regarding time and effort is essential to determine and evaluate modular structures. In the following section, approaches for product structuring for assembly are investigated for their ability to support modularisation.

2.2 Product structuring from an assembly point of view

Design for assembly (DFA) is widely established in engineering design research. The measures proposed in design guideline catalogues can be divided into the main categories *Reduce*, *Standardise*, *Simplify* and *Structuring* [3]. The corresponding DFA activities focus on the product aspects *structure*, *parts* and *interfaces*. According to Andreasen, the use of DFA measures concentrates on a product structural approach, since the expected effects are estimated to be higher than from a product part approach. However, the measures need to be applied with caution. The guidelines are only conditionally valid and can have negative effects [8]. Therefore, product structuring measures need to be applied, whose impacts on the specific benefit are directly assessed. In production, this benefit might be the ease of assembly and short lead times. In the following, two methodical tools for integrating production process aspects and the product structure are presented.

In the *Datum Flow Chain* (DFC) approach proposed by Whitney, the product structure is illustrated in an enhanced liaison diagram. Nodes represent the parts and arcs and arrows represent the physical relationships. The specific enhancement resides in the separation of the relationships into mates and contacts. The mates represent constraint and dimensional relations, while contacts solely support and fasten the part. An exemplary application of the approach is shown on the left side of the figure. For the example, an aircraft wing part is notionally demounted. The components and their relationships are displayed on the left side below the sketch. This abstract representation of the product enables further analysis of the assembly prior to the design of detailed geometry. For the assembly process analysis, algorithms support the translation of the hierarchical structure into assembly precedence constraints. An example illustration of an assembly sequence family is shown on the right side below the sketch. Traditional methods are used to evaluate assembly sequences [9].

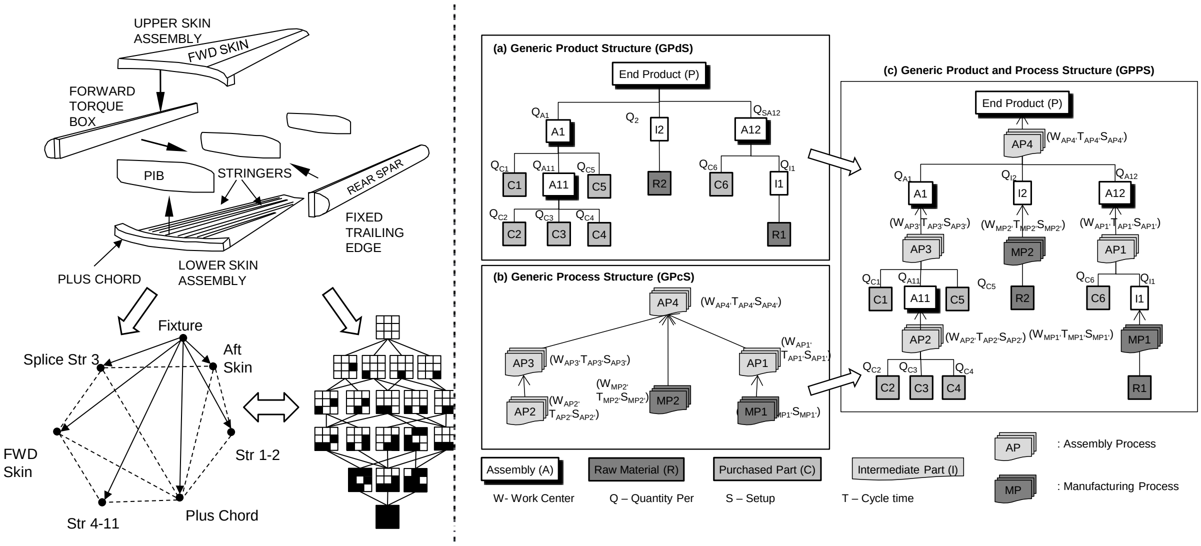

Figure 2. Datum Flow Chain [9], Generic Product and Process Structure [10]

Jiao proposes an approach for *Generic Product and Process Structure* for variety management [10]. The product data can be represented by a bill of material, breaking down the product structure into assemblies, sub-assemblies, parts and raw material. In the case of a product platform consisting of multiple product variants, a generic product structure is derived, as shown on the right side of Figure 2. The related production process is displayed in the form of generic process structures. Both product models are merged into one representation. As well as hierarchical relations, product elements and production steps, further information, such as quantities and times, is added to the diagram. Both approaches support the structuring of products. However, a systematic procedure for assessing the structures developed and for analysing the impact of restructuring measures taken is not included.

2.3 Modularity evaluation based on assembly key figures

The Life Phases Modularization method, as presented in Section 2.1, requires a compromise between the conflicting modular structures. A systematic evaluation procedure is applied to find an estimation that is as objective as possible. The use of key figure systems is common in this context since they

quickly provide concise information about a specific field of investigation. In this section, existing approaches for evaluating modular product families are investigated. The list of key figures is presented in Table 1 and is referenced to the literature for detailed information due to the large range [4, 11, 12, 13, and 14]. The list concentrates on the elements relevant to assembly.
The essential requirements for the key figures, i.e. effort, transparency and significance, are taken into account. The effort required for the key figures investigation and the resulting benefit should be in reasonable accordance with one another. Frequently, information needed for calculating the key figures is not available, especially in early phases of product development. The transparency of key figures describes their comprehensibility and traceability. Particularly in the evaluation of product concepts, barely interpretable key figures tend to negatively affect the decision. The significance of a key figure must also be considered. Although the effort required for the enquiry proves to be low and the transparency is high, the key figure may still be inappropriate if there is no benefit to the evaluation. The characterisation of the key figures for these factors is presented as per [15].

Table 1. Characterisation of Key figures

Author	Key Figure	Effort	Transparency	Significance
Erixon [4]	Interface Complexity	◐	◐	◐
	Ideal Interface Complexity	●	◐	○
	Optimal Number of Modules	●	○	○
	Lead Time	●	●	●
	Faultless Assembly	◐	◐	●
Hölttä [11]	Testability	◐	○	◐
	Make or Buy	●	○	◐
	Ease of Assembly	◐	◐	●
Blackenfelt [12]	Modul Interdependence	●	◐	◐
Martin/Ishii [13]	Commonality Index	◐	◐	◐
Lotter [14]	Primary Secondary Analysis	◐	●	●

Degree of compliance: ● High ◐ Medium ○ Low

The characterisation shows that the majority of key figures are calculated with high effort. The main reason therefore is the frequent lack of availability of the necessary factors. Either the information is not yet available at the relevant phase, or it is difficult to extract from the product data. For that reason, a solution must be found for the systematic support of relevant factor determination. The list of key figures is not intended to be exhaustive. As well as application of the existing key figures, the formulation of further figures can be considered.

3 GENERIC APPROACH FOR DETERMINING AND EVALUATING PRODUCT STRUCTURES MODULARIZED FOR ASSEMBLY

The proposed approach is developed for the Life Phases Modularization described in Section 2.1. The objective is to arrange a modular product structure for assembly. The procedure is based on the application of module drivers that show a sheer advisory character comparable to the DFA guidelines presented in Section 2.2. Systematic evaluation of the measures taken and modifications is not supported. Modularization for assembly is conducted in the context of the approach proposed and presented in Figure 3. The product information represents the input for the Modularization for Assembly. The output is an assembly-optimised product structure.
As in the overall modularization approach, it is based on the data of the existing product. The product structure is represented in the form of a module interface graph (MIG). The MIG depicts the rough shape of the components and outlines their interfaces. This graphical tool provides a brief but concise overview of the geometrical characteristics of the product. The second part of the product information

is given in the assembly sequence. The sequence is the decisive characteristic of a product and forms the basis for the assessment of the assembly effort. For example, the assembly procedure determines the formation of sub-assemblies, which have an impact on the resulting assembly system characteristics, such as layout and required tools. A procedure graph is suitable for graphical representation. Further information about both tools is provided in [7].

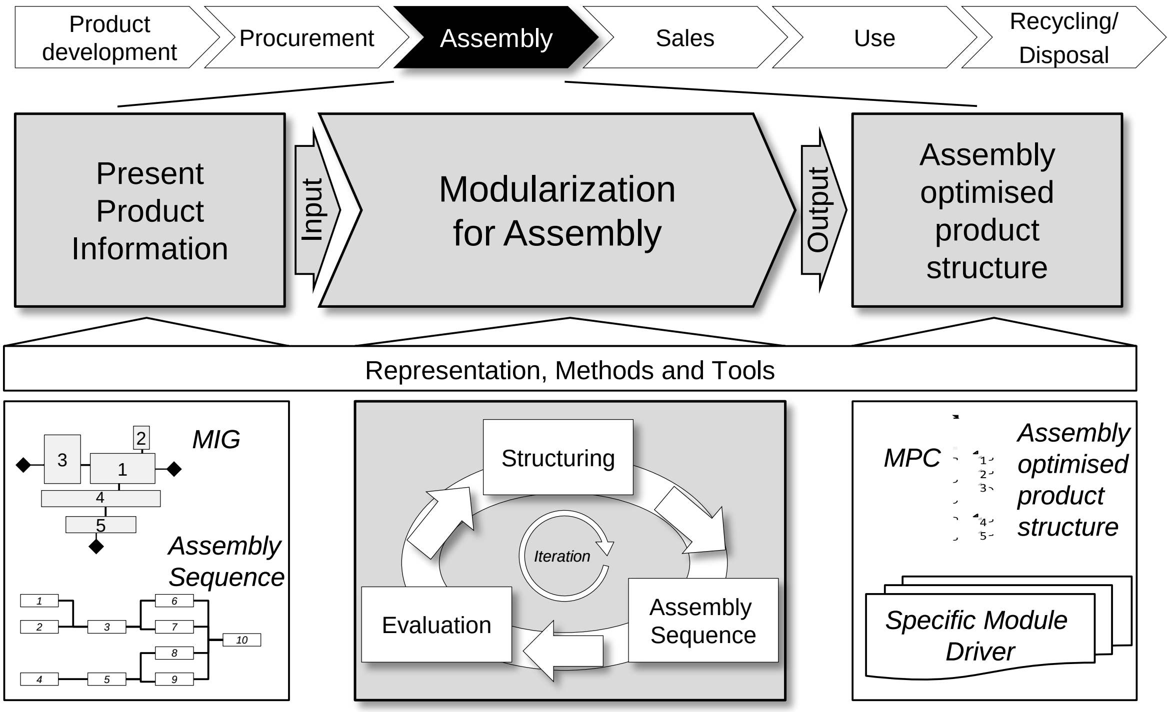

Figure 3. Modularization for Assembly – procedure and tools

An iterative process is applied for the actual modularization for assembly. It consists of the sequential activities structuring, assembly sequence derivation and evaluation. The resulting assembly sequence is derived from the initial product structure. In combination with methods from the field of labour time management, such as DFMA by Boothroyd [16] or MTM analysis [17], quantification of time aspects, such as lead time calculation, can be performed. Therefore, the necessary time for each activity is calculated and accumulated in the overall sequence. The evaluation identifies the weaknesses and provides an indication of which parts of the structure should be focussed on. The process is repeated with the modified structure. The initial and the modified structures are compared. The iteration is repeated until a satisfactory result is achieved.

The result is an assembly-optimised modular structure that is further processed in the Life Phases Modularization. A systematic way to support the restructuring and evaluation is presented in the following section.

4 THE IPAS METHOD FOR ASSEMBLY MODULARIZATION

One way of efficiently implementing the procedure for Modularization for Assembly is to take an integrative view of the product and the process. The intention is to integrate the two essential aspects determination and evaluation for product structuring into one tool. The approach presented here is predominantly based on the generic product process structure by Jiao, as presented in Section 2.2 and [18]. A substantial enhancement is the integration of assembly process times. The time related assembly effort for the product and the impacts of modifications are shown. The body of the integrative product and assembly structure (iPAS) is shown in the following figure.

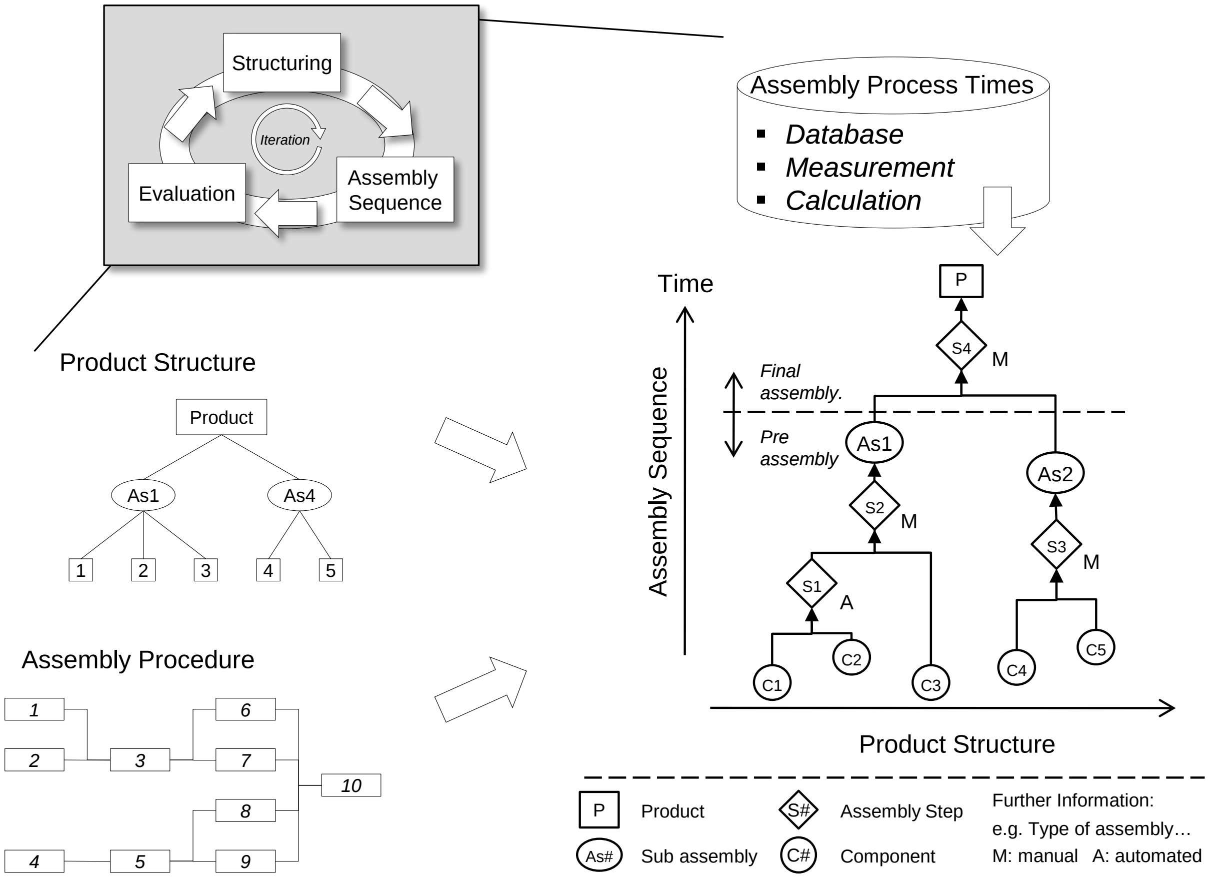

Figure 4. Integrative Product and Assembly Structure (iPAS) in the context of modularization for assembly

The product information of the conventional representations for product structure and the assembly procedure is merged into one illustration. Within the hierarchical product structure the final product is divided into assemblies, sub-assemblies and parts. The assembly precedence graph shows the possible sequences to compose this final product out of elements of lower order. The graph displayed on the lower left side of Figure 4 corresponds to the combination of both forms of representation. By means of the integration of time quantification tools, the resulting duration can be read off in the height of the graph. To calculate these times company-specific databases can be applied with the labour time management methods mentioned. Additional information, such as the specific assembly type description, is appended. The possible ways to use the resulting tool in determining and evaluating product structures are described in the following sections.

4.1 Determination of product structures

The intention is to support the structuring of the product into modules by using the integrative product and process structure. Possibilities reside in the graphical identification of assembly-relevant characteristics in the illustration. The graphical character of a sequential assembly process is shown on the left side of Figure 5. The product described in this example consists of five random components that are joined together sequentially. The procedure for identifying modules within the diagram has to be defined in order to use the tool as support in product structuring. In assembly, modules result from the aggregation of components that are situated in direct relation to each other along the process chain. As per the example in Figure 4, the components are grouped into two modules. The first module consists of the components one to three, while the components four and five constitute the second module. Based on this initial modularization, restructuring measures are made. Two further modular structures can then be proposed. The first proposal is to define component three as an independent module. In this case, the product consists of three modules. Alternatively, component three is detached from module one and grouped with module two. The resulting impact on the process can directly by visualised in the diagram.

Based on this way of identifying modules and the procedure for restructuring the module configuration, corresponding aims for determination are formulated. These aims direct the user to which measures should be taken. The procedure is distinguished by its bold and simple character due to its direct correlation to the graphical illustration. For the general DFA measures, the example heuristics result, as displayed in the following figure. The aim of the heuristic *Structure* is the parallelisation of processes. As shown on the left side of Figure 5, a sequentially assembled product structure is investigated. Partial parallelisation of the process is achieved by combining several components into modules. The modules can then be assembled separately; lead-time of the final product is considerably reduced.

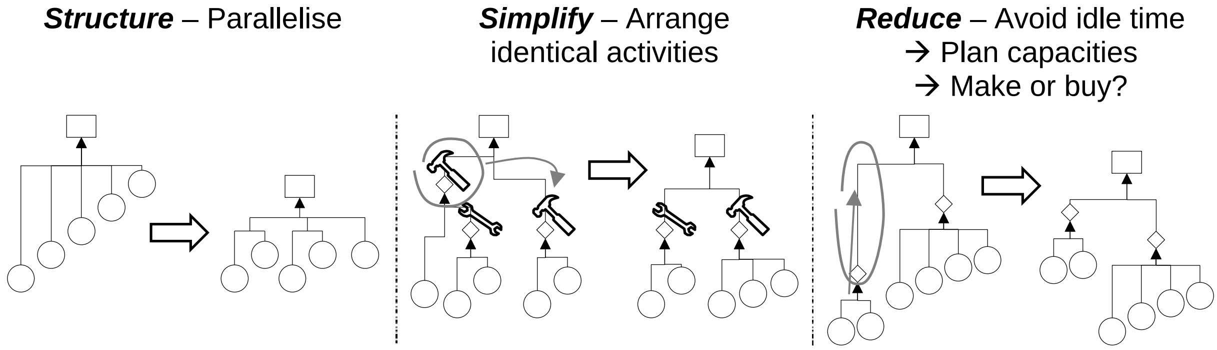

Figure 5. Graphical aims for product structuring

In the case of the general measure *Simplify*, the aim is to group the components that entail similar assembly operations into a module. An example is shown in the centre of Figure 5. The intention is to optimise the assembly system by concentrating the various activities on certain modules. The example aim for the measure *Reduce* is to avoid idle time between process steps of a module. They can be a result of a forced sequence induced by the product design. Next to lead-time reduction, the intention is to optimise the capacity of the related assembly system. Additionally, the module is a candidate for outsourcing.

4.2 Evaluation of product structures

Next to the assessment of lead-times and sub-process durations, further aspects for evaluation are provided with the help of the integrative illustration. In particular, it is possible to provide the necessary data to calculate the key figures. The following figure shows the correlation between the graphical illustration and the factors for the key figures. For the explanation, two key figures are calculated. In the case of the Primary Secondary Analysis [14], the assembly task proportions of the entire process are investigated. While primary tasks, such as joining, contribute to the creation of value, secondary tasks, such as rework or adjustment, do not contribute. The key figure is calculated by rationing the number of primary tasks in the entire process. The degree of efficiency of the assembly system is described. The resulting value is between 0 and 1. The upper boundary value means that there are only primary tasks. The lower boundary value is practically impossible. The classification into primary and secondary tasks is read directly from the description of the process steps. For the example presented in Figure 6, a distinction between the assembly tasks is presented in the appendices PT and ST. The proportions result from the duration of each corresponding process phase in relation to the total time.

In addition to the possible way of calculating the key figures presented in Section 2.3, the formulation of further evaluating factors for the integrative structure diagram can be considered. The proposed key figure is called the degree of possible parallelisation. It describes the proportion of tasks that can be simultaneously executed in relation to the entire process. The value ranges from 0 to 1. An overall process, which is ideally conducted in parallel, can be sequentially performed. In the sequential case, however, the lead-time is calculated as the sum of the individual duration of all tasks. In total parallelisation, the lead-time is only equivalent to the duration of the longest of the parallel sub-processes. This key figure indicates the flexibility of a product's design to reduce lead-times by increasing the assembly capacities. The necessary information, represented by the duration of the sub-processes and the total time, is extracted from the diagram, as shown in Figure 6.

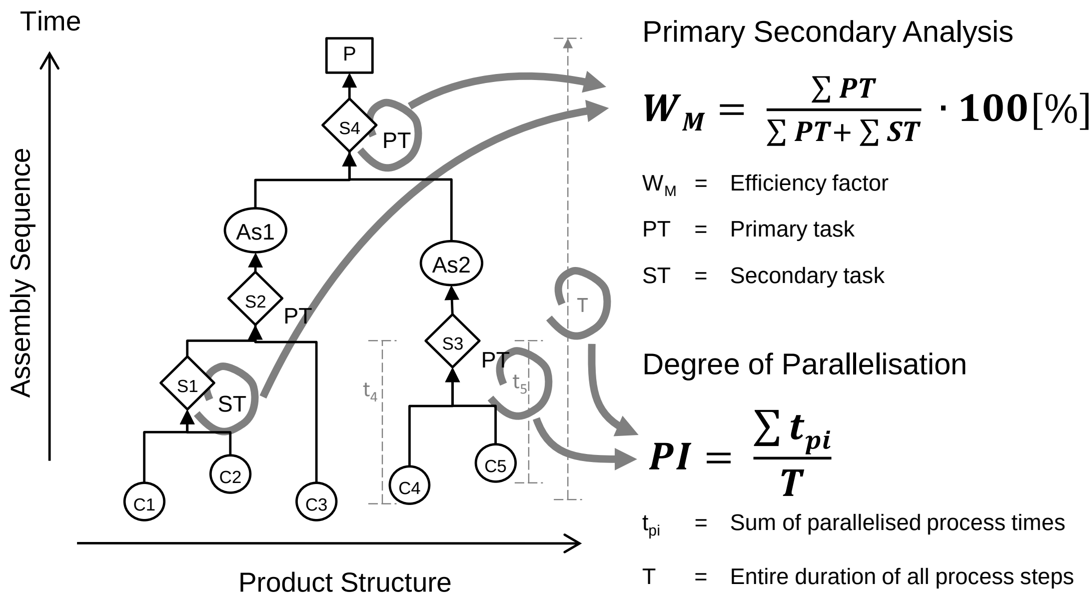

Figure 6. Support for calculating assembly key figures

5 APPLICATION OF THE APPROACH TO AIRCRAFT CABINS

To validate the approach, the method was used on parts of the cabin interior of civil aircrafts. The cabin lining parts and the overhead storage compartments were investigated. The conventional method of production determines the predominant sequential process for the assembly. The limited working space inside the aircraft fuselage leads to long installation times. The cabin installation takes place within the flight-ready aircraft in the final phase of production. As a result, the long lead-times create high costs for the manufacturer. Therefore, the aim is to reduce the aircraft's lead time by design optimisation of cabin parts, in this case modularization. The integrative product and assembly structure is applied to incorporate the particular assembly requirements in the modular product structure of the manufacturer. On the left side of the diagram shown in Figure 7 the conventional architecture is shown. The diagram shows the impacts of the design on the process, such as the high degree of sequential tasks and long idle times, and reveals the responsible time drivers. The lead-time adds up to more than 600 seconds.

Table 2. Calculation of assembly key figures

	Present structure	**Modular structure**
Primary Secondary Analysis	$\sum PT_1 = 174s; \sum ST_1 = 469s$ $\boldsymbol{W_{M1} = 27\%}$	$\sum PT_2 = 259s; \sum ST_2 = 315s$ $\boldsymbol{W_{M2} = 45\%}$
Degree of Possible Parallelisation	$\sum t_{p1} = 27s; T_1 = 643s$ $\boldsymbol{PI_1 = 0{,}042}$	$\sum t_{p2} = 117s; T_2 = 574s$ $\boldsymbol{PI_2 = 0{,}204}$

According to the aims for product structuring presented in Section 4.1, the components are merged into appropriate modules. As shown on the right side of the diagram, the degree of pre-assembly tasks is enhanced due to task parallelisation, reducing lead-time to less than 500 seconds. Additionally, a module that is a candidate for outsourcing was identified. For the evaluation of the modular structure, different key figures are calculated and compared with the conventional structure.

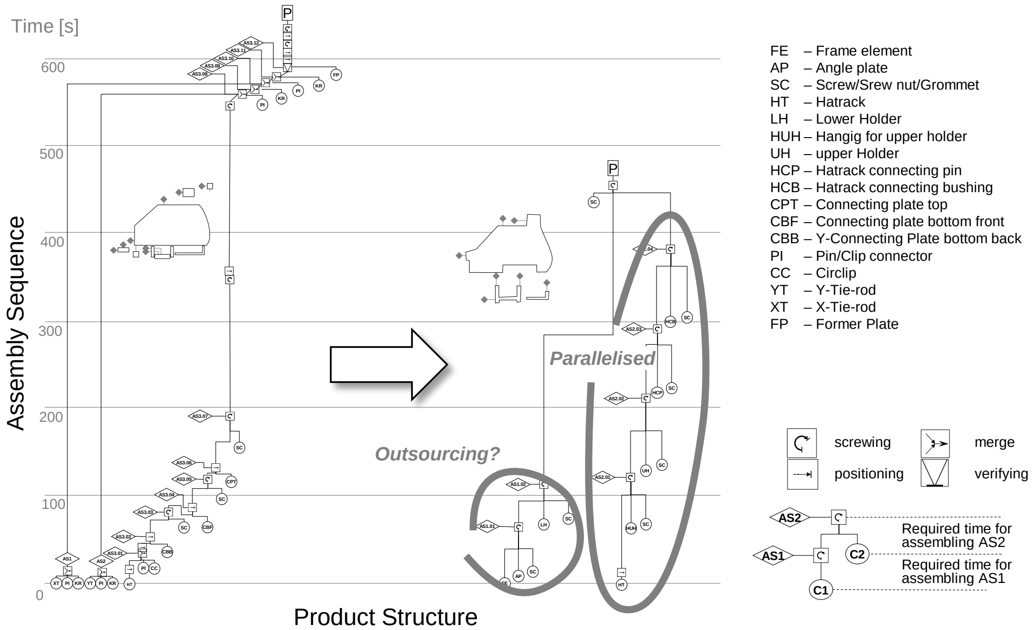

Figure 7. Modularization of an aircraft cabin (extracted detail) in iPAS representation

In the two sample figures described in Section 4.2, the modular structure performed better. The proportion of primary tasks in the process is doubled. An increase in the proportion of process steps that can be run in parallel was also achieved. With the current state of research, only a relative evaluation can be performed by comparing the different structures.

The modular product structure developed is consigned to the overall procedure for modularization. The result is shown in Figure 8. According the findings from the integrative product and assembly structure, there are two module drivers that are decisive in modularization. The external structural interfaces of the original components are grouped into one attachment module: the part count is *reduced*. Additionally, implementing *easily mountable joining principles*, such as snap and click fasteners, are possible.

The product life phase assembly was divided into two sub phases, pre and final assembly. Within pre-assembly, the preparation and testing of the modules takes place. According to the example presented in Figure 8, three modules are designed for this sub phase, as shown by the MIG. These modules are afterwards merged into a single assembly module. Consequently, only one module is handled within the final assembly phase. In connection with the application of a handling device, a further reduction in lead-time is achieved.

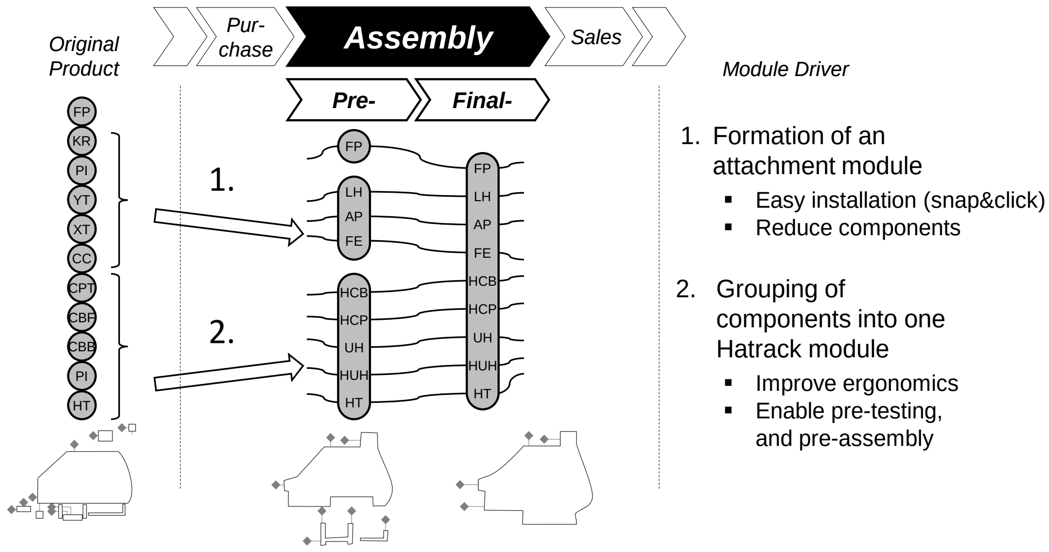

Figure 8. Modular aircraft cabin structure – pre and final assembly

6 CONCLUSION

The methodical approach presented supports product structuring for the specific requirements of assembly in the context of a holistic method for Product Life Phase Modularization. The approach focuses on closing the gap between the determination and evaluation of structuring measures. Consequently, efficient optimisation of products is achieved. The essential element of the approach is the integration of the product structure and the relating assembly sequence in one diagram. The determination of modules by working with the diagram is supported by the utilisation of specific heuristics. The time related assembly effort and its impacts on modifications are promptly shown due to the integration of an assembly time evaluation method. Assembly key figures are calculated with the help of information extracted from the diagram. The procedure was applied to the cabin of civil aircrafts as an example.

Currently, calculating the resulting assembly times is complex. The aim of further research is to optimise this task for the required effort. It is necessary to investigate how detailed the calculations must be to obtain useful results. Implementation in a computer application is considered. The interface with the holistic modularization procedure must be improved. The specific potentials of the approach, like using it for an overall evaluation, must be analysed, especially in need for compromise between the general module drivers.

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