INTERNATIONAL DESIGN CONFERENCE - DESIGN 2012
Dubrovnik - Croatia, May 21 - 24, 2012.

ASSEMBLY TIME ESTIMATION MODEL FOR EARLY PRODUCT DESIGN PHASES – CONCEPT DEVELOPMENT AND EMPRICAL VALIDATION

N. Halfmann and D. Krause

Keywords: design for assembly, assembly time evaluation, design structure matrix, assembly sequencing

1. Introduction

The early identification and evaluation of the properties of concept alternatives is essential for the development of new product structures. Through these properties, the evaluation is conducted both from technical and economical perspectives, providing the basis for selection and further elaboration of concepts. The developer is faced with the challenge of collecting and meaningfully processing the necessary information, which remains fuzzy. In the assembly of a product, it is important to estimate the resulting assembly efforts. An essential element is the time required for the execution of each activity in the assembly process. The assembly is predominantly determined by the product design in general and the product structure in particular. This relation between product and process is illustrated qualitatively in Figure 1. The majority of new product concept definitions are conducted in relation to the existing product [Pahl and Beitz 2007]. The sequence of the assembly operations and their temporal duration has to be quantified for the concepts developed and compared to the present process. A proposed saving of assembly time can be outlined directly by presenting the result in the form of an extended assembly priority graph, which indicates the precedence of activities and the specific time.

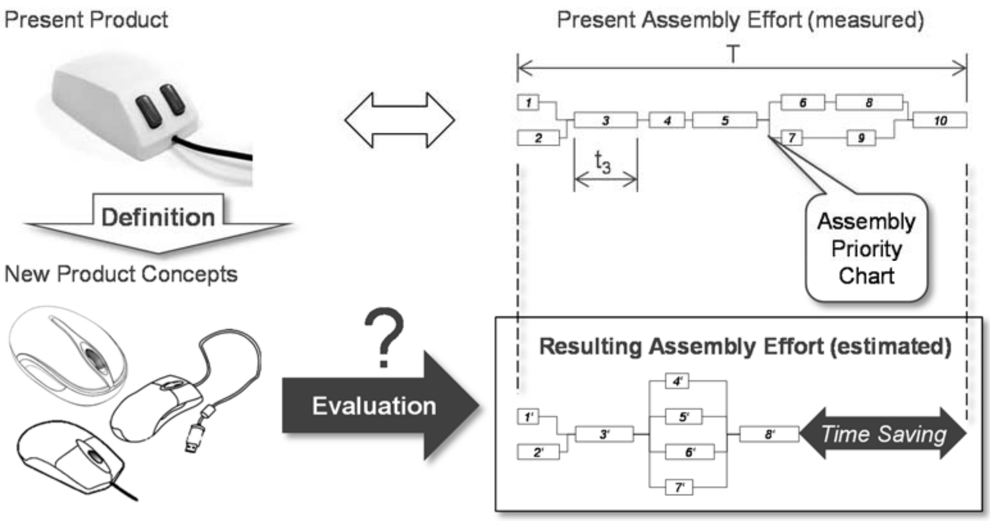

Figure 1. Definition and evaluation of new product concepts

This paper presents a model developed for estimating assembly effort. A literature review on relevant evaluation methods in the field of design for assembly is performed. Based on the research, selected methods are applied to a sample product for extensive analysis of the methodical approach. Finally, application of the model developed is implemented using a real example from the field of aircraft cabin development.

2. Tribute to assembly time calculation methods

Industrial products are usually made up of a variety of components that are generated during production at various times using various manufacturing methods. Assembly is the physical conflation of these items, with all necessary auxiliary work during and after the production of parts, into a product of higher complexity with specific function(s) within a given time. Quality and cost of the assembly are both dependent on the quantity and type as well as the conduction of assembly operations. Quantity and type are determined by the product structure, the component design and the method of production, e.g. individual or serial. The activities are subdivided into seven basic groups: joining and handling, storing, positioning, adjusting, securing and monitoring [Pahl andBeitz 2007].
The assembly effort is defined as the amount of resource or the performance provided to achieve a certain benefit. Minimisation of these efforts, resulting from the product design, i.e. production equipment and personnel, in early phases of product development is the aim of design for assembly. Various tools and methods are at the disposal of the developer to optimise product assembly. First, design guidelines are collected in catalogues. The proposed measures can be divided into the main categories of reduce, standardise, simplify and structure. According to Andreasen, these measures are conditionally valid, i.e. there may be situations where a measure is not having any positive effect and may even lead to negative effects. Therefore, product concepts developed need to be evaluated for the beneficial impacts of the applied design guidelines [Andreasen 1988].
There are various methods and tools with which the assembly effort can be analysed. Their application is performed mainly in parallel with the design process in the manner of simultaneous engineering. A comprehensive overview is given by Whitney [Whitney 2004]. There are various checklists, such as Design for Assembly (DFA) by Boothroyd and Dewhurst, Prokon by MTM, Assembly Evaluation Method (AEM) by Hitachi or the Lucas DFA procedure, to mention the most important ones. To represent these groups, the methods DFA and Prokon are considered in more detail. Both methods are based on systems of predetermined times provided in extensive tables.
In the DFA method, all parts are assessed for assembly effort using key figures. Thereby, a distinction is made between handling and joining activities, for which an individual key figure is determined for both. The values for handling and joining time are then determined using the key figures in corresponding charts, as shown in Table 1. The DFA method provides a large database for characterising various assembly tasks and activities.

Table 1. Example of DFA evaluation table [Boothroyd 2002]

		Secured by separate operation or part				Secured on insertion by snap-fit	
		No holding down required		Holding down required			
		Easy to align	Not easy to align	Easy to align	Not easy to align	Easy to align	Not easy to align
		0	1	2	3	4	5
No access or vision difficulties	0	1.5	3.0	2.6	5.2	1.8	3.3
Obstructed access or restricted vision	1	3.7	5.2	4.8	7.4	4.0	5.5
Obstructed access and restricted vision	2	5.9	7.4	7.0	9.6	7.7	7.7

The Prokon method provides only one table for the actual evaluation, including the underlying database. An additional table allows the consideration of certain assembly tasks [MTM 2006]. The fundamental difference to the DFA method is the extent of the database. While DFA goes into a detailed investigation of the handling and joining activities, Prokon remains at an approximate level. It is only focused on the design. Different processes are considered equally. The evaluation result provided is only a key figure but with the advantage that Prokon's application efforts are lower than in DFA.

3. Analytical application of selected methods

Both methods are applied to a simple assembly task. Afterwards, the results are analysed. This comparison of both methods is performed according to an empirical comparative study by [Klein 2008]. In this context, products of different part numbers were evaluated with both methods. Since DFA delivers the result as a time value while the Prokon method only provides a key figure, this difference must be compensated for in advance. A conversion factor is introduced for Prokon to achieve the necessary comparability. This factor assigns a specific amount of time to one Prokon value. The multiplication of the factor by the Prokon value results in a time value that can be directly compared to the DFA result. Figure 2 shows the results of the study.

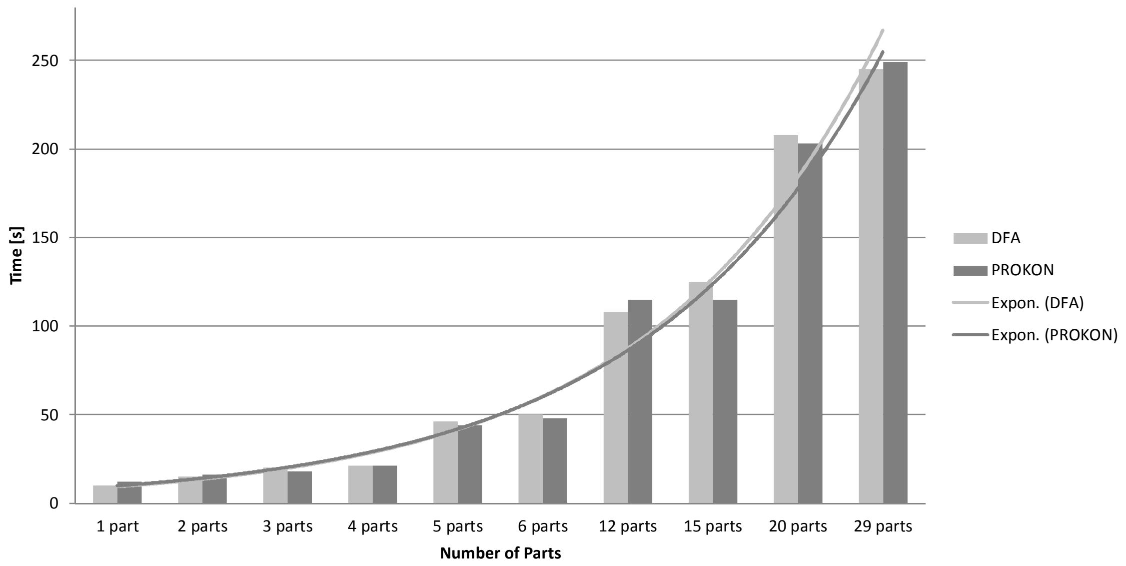

Figure 2. Comparative study of Prokon and DFA [Klein 2008]

Both methods give similar results. Only small deviations in the calculated times can be observed. Despite its approximate analysis, the application of the Prokon method delivers results of comparable quality with only one third of the necessary effort [Klein 2008].

To confirm these results, a study, shown in Figure 3, was performed. The process of attaching a clamp to a wall was assessed. Three design alternatives were investigated. Alternative A is an individual solution, consisting of the clamp, a screw and a dowel. In Alternative B, a pre-assembled impact dowel is used with the clamp. Alternative C is an integral design that combines a clamp with a snap and click attachment. The results of both methods are shown in Figure 3. The small result deviations confirm the comparability of Prokon and DFA. Both studies specifically only refer to the comparison of the results of both methods. A comparison with reality is not considered. To validate the results of the calculations, another experiment is performed.

In this study the design and assembly of a stapler is conducted. The stapler is disassembled into its parts and then reassembled. The steps are documented and their duration measured. In parallel, the assembly time is calculated using the DFA and Prokon methods. The results, using rounded values, are presented in Figure 4. First, the similarity of the results of both methods can be confirmed again. A satisfying likeness in the calculated and measured absolute values can be seen. A more detailed investigation of the process reveals various deviations between the measured and calculated values for the individual steps. Specific assembly processes, such as riveting and bolt threading in this case, are treated as more time consuming than in reality. These two examples are highlighted in Figure 4. The remaining tasks represent general handling activities, such as insert or place. The methods assign less assembly effort to these tasks compared to what is necessary in reality.

	Design A *Indiv. Parts*	Design B *Impact Dowel*	Design C *Integral Clamp*
DFA	20.4 s	13.3 s	6.8 s
PROKON	20.2 s (420 PU)	12.2 s (255 PU)	6.5 s (135 PU)
Difference	1%	9%	5%

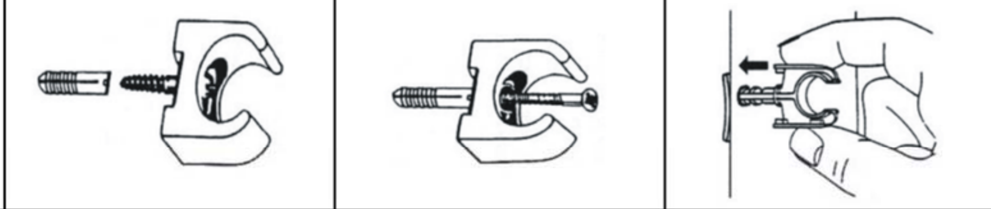

Figure 3. Comparable time calculation of design alternatives

In total, the result is the similarity of the absolute values for both calculated and measured assembly times. The finding from the detailed comparison, however, shows that the results of the methods in general cannot be validated. Therefore, the supposed similarity of the absolute values has to be regarded as accidental. Both methods should not be applied in an unchanged manner for a calculation close to reality.

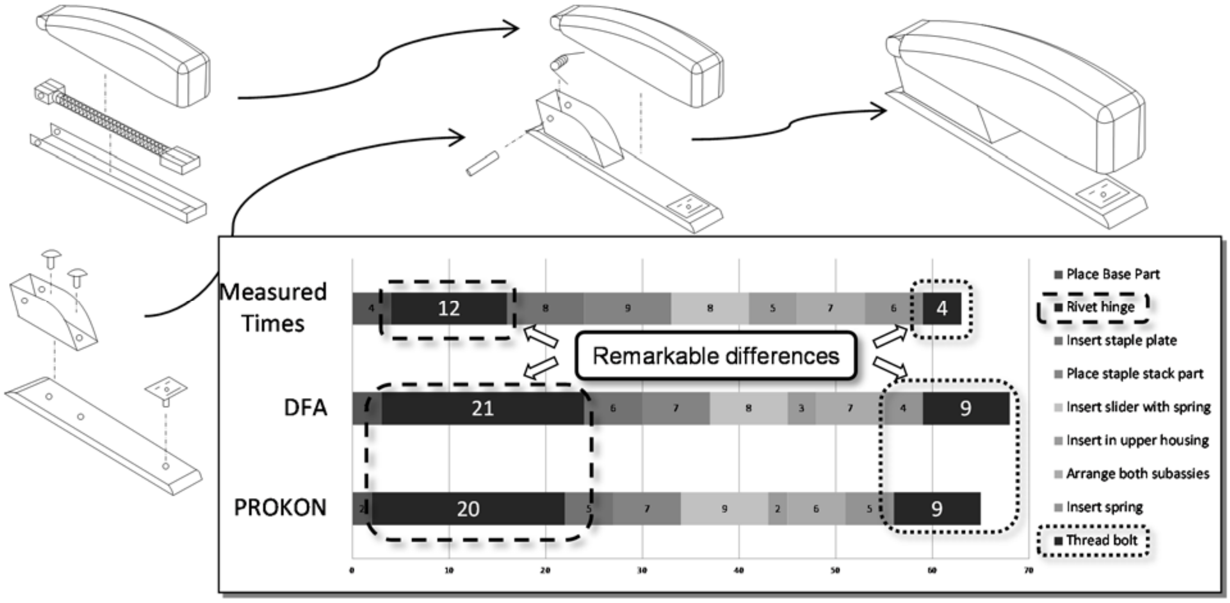

Figure 4. Time calculation and measurement of a stapler assembly

An analysis of the possible root cause leads to the conclusion that the deviations result from the underlying database of both methods. The values are provided in a global way. Potentially relevant differences, such as the production system design, i.e. how and in which environment the assembly tasks are performed, are not taken into account. In consideration of the findings from the case studies, in combination with the literature research, the requirements for an assembly time estimation model can be set. Accordingly, a model has to be developed that has the following properties:

- Application in early phases of product development
- Adaptation to specific production conditions
- Result output as a time value
- Easy application
- Focus on the individual process steps.

4. Proposal for an assembly time estimation model

The model developed for assembly time estimation is based on the Prokon method described in Section 2. The proposed procedure is presented in Figure 5. The evaluation chart represents the central element for assembly time calculation. To meet the requirement for adaptation to a specific environment an initial calibration of the evaluation chart occurs in step 0. This calibration has to be performed only once. Afterwards, the model can be used for the assessment of various concepts without reapplying the adaptation. The actual evaluation starts with an assembly process analysis (1) followed by the calculation of assembly times (2). The result can be presented in the form of an enhanced assembly priority graph (3), as described in [Reinhart 1999].

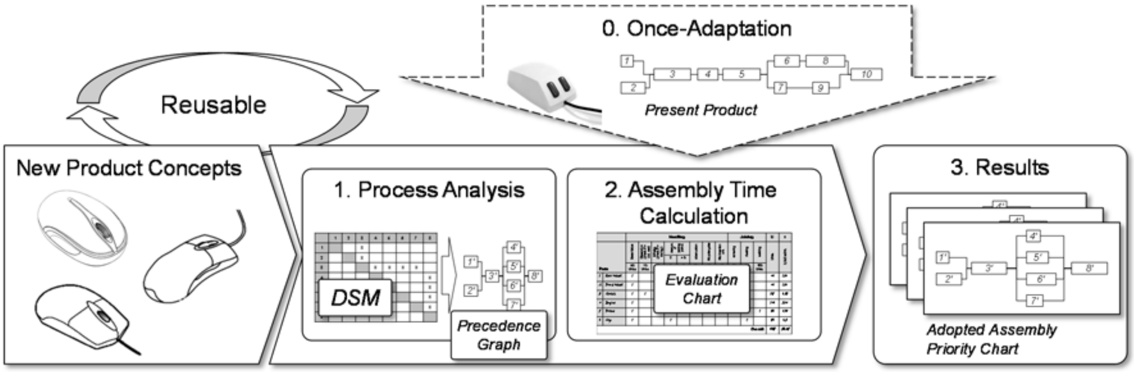

Figure 5. Proposed procedure for assembly time estimation

4.1 Process analysis and assembly time calculation

In the first step, the assembly sequence is derived using a Design Structure Matrix (DSM) [Browning 2001]. The components determined by the product concepts are listed in the rows and columns of the DSM. The precedence of the elements is analysed and represented in the DSM in the row influences column. Based on this analysis, the precedence graph can be derived.

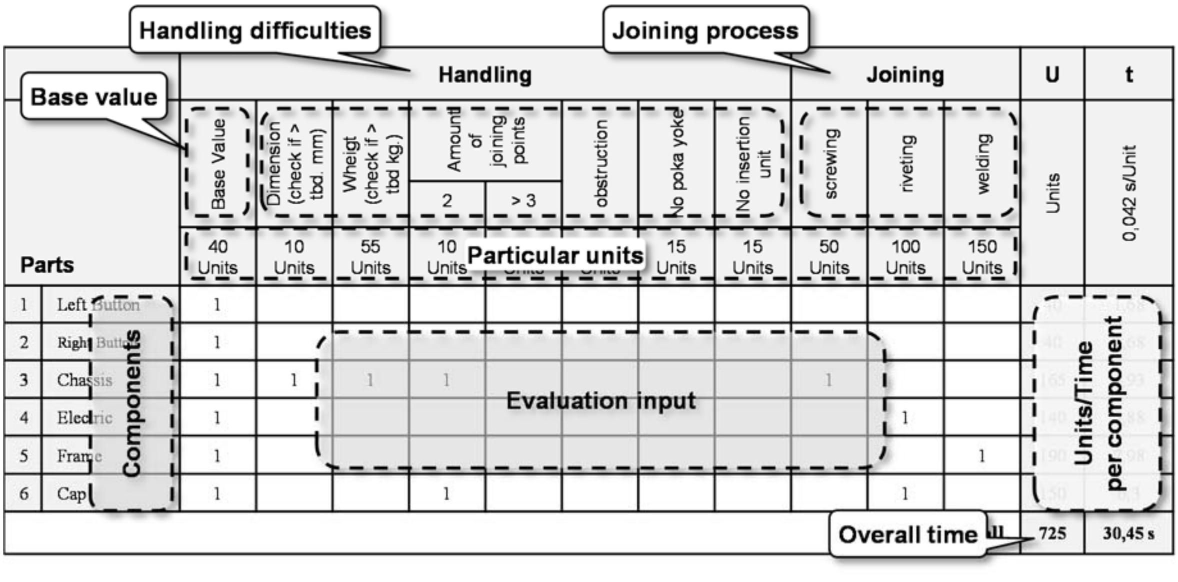

Figure 6. Evaluation chart

In the second step, assembly times are calculated using the evaluation chart. The components are listed in the relevant fields in the left part of the chart. The actual assessment of each part is conducted for the two superior categories, handling and joining. The handling effort consists of a base value as well as further handling difficulties, such as, exceeding dimensions or weight of the component, non-present insertion units or the amount of joining points. The joining effort is determined by the specific task, such as screwing, riveting or welding. Each element of these effort categories is quantified by particular units. The actual calculation is conducted by allocating handling and joining efforts to the components. For each component the units are summed up. Finally, multiplication of the conversion factor by the part-specific units represents the part-specific assembly time.

4.2 Once-adaption

The initial, non-recurring calibration of the evaluation chart is performed based on the properties of an existing product. Adaptation to the specific production environment is achieved. Therefore, the structure of the essential components and the assembly times of the current process are needed. The adaptation itself is an iterative procedure. In terms of category handling, the focus lies on the adjustment of the base value. A modification of the handling difficulties units has proved to be unnecessary as the relative quantification of the initial values is sufficiently accurate. If it turns out, however, that an adjustment was necessary, this could be done using the procedure shown in the following paragraph. The specific joining processes are directly identified and quantified in relation to the present product. In preparation for adaptation of the evaluation chart, the present product is analysed. Therefore, the assembly process times are measured. In Figure 7 this task is marked with the number 1. In the second step, the product is evaluated, applying the original chart and unchanged unit values. In the upper right part of Figure 7 the progress of the adaptation procedure is qualitatively displayed. In the graphic for the second step the comparison of the measured and the initially calculated assembly process is shown. The differences, whether a process is too long or too short, are indicated by the symbols "+", "-" or "=".

In the first part of the third step, the overall factor is adapted. Therefore, the measured total assembly Time T is divided by the total amount of calculated units.

$$F = \frac{T}{Units} \frac{[s]}{[U]} \tag{1}$$

Secondly, the base value B, as the essential indicator for the specific handling characteristics, is adapted. Therefore, the specific time for a part of the product is chosen, for which only basic handling activities are performed. In general, as in this case, it is the first part in the product's assembly process. The new base value B is calculated by the quotient of the component specific time t_c and the factor F.

$$B = \frac{t_c}{F}[U] \tag{2}$$

The first iteration is then performed. Since the two factors that influence each other have been changed, a new calculation is necessary. A new factor F_i and a new base value B_i are calculated. The iteration is repeated until a defined stop criterion for the difference between B_i and B_{i-1} is reached. Therefore, a value of 3 U(nits) was found to be suitable. In the case shown in Figure 7, the base value is changed from 40U to 30U and the factor is adjusted to 0,038 s/U.

$$| B_i - B_{i-1} | \leq 3U \tag{3}$$

In the third process status in the upper right part of Figure 7, consistency in time duration for pure handling tasks is achieved. The joining processes still show deviations from the measured values. Consequently, in step number 4, the adaptation of the process units P is performed. According to Equations (2) and (3), an iterative adaption is conducted. The difference is that, in addition to the pure process value, other activities are included, which means that in the case of the example shown in Figure 7 the duration t_p for components 3 and 6 result from the specific joining task and from the handling activities. However, the activities are already calculated using the base value B and therefore must be removed from this formula. Initially, the process value is calculated, including handling PB.

$$PB = \frac{t_p}{F}[U] \tag{4}$$

Finally, the handling value B is subtracted from the value PB. According to this, the pure process factor is calculated using the following equation:

$$P = PB - B \tag{5}$$

In consideration of Figure 6 and Figure 7, it is shown that in this example the unit for screwing is changed from 50U to 75U, for riveting from 100U to 120U and for welding from 150U to 170U. In this way, a basis for calculating the assembly time of further related product concepts is created.

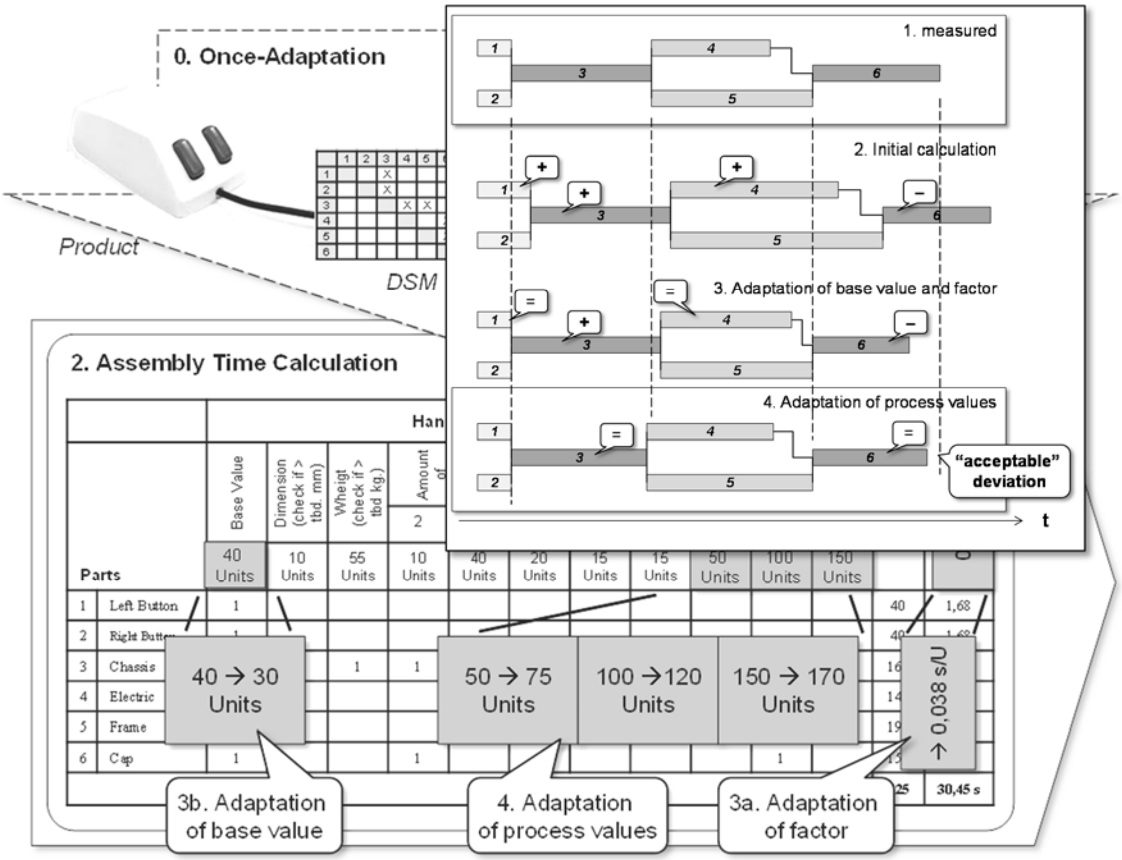

Figure 7. Adaptation procedure of the evaluation chart

The procedure for the initial adaptation of the evaluation chart is much more complex than the actual recurring application. The initial increased effort leads to a significant reduction in efforts in the actual application. The advantages are an increase in result quality and an optimised comparison of different concepts. In industrial practice only a small number of users must be trained in the entire procedure. For pure concept evaluation, knowledge of the adaptation procedure is not necessary.

5. Case study results

The assembly time estimation model was applied in the development of new aircraft cabin concepts. The requirements for the new concepts are the reduction of installation efforts in the final assembly phase and optimisation of the internal product variety.

As proposed by the model, the present cabin design is analysed for the constitution of its components and modules as well as the present assembly process. In the knowledge obtained of the specific process characteristics, the evaluation chart is adapted, as described in the previous section.

The actual definition of new concepts is based on the systematic approach modularisation for assembly, as described in [Halfmann 2011]. One of these concepts is shown in the lower left part of the following figure. The core of the concept is the definition of modules, which provides the opportunity for pre-assembly and parallelisation of production process steps.
According to the procedure, the assembly precedence is analysed using the design structure matrix. Finally, the calculation of assembly times is conducted using the adapted evaluation chart. The result is shown in the centre of Figure 8. The graphical representation of the result focusses on the fact that application of the new concept could reduce installation time by 45%.

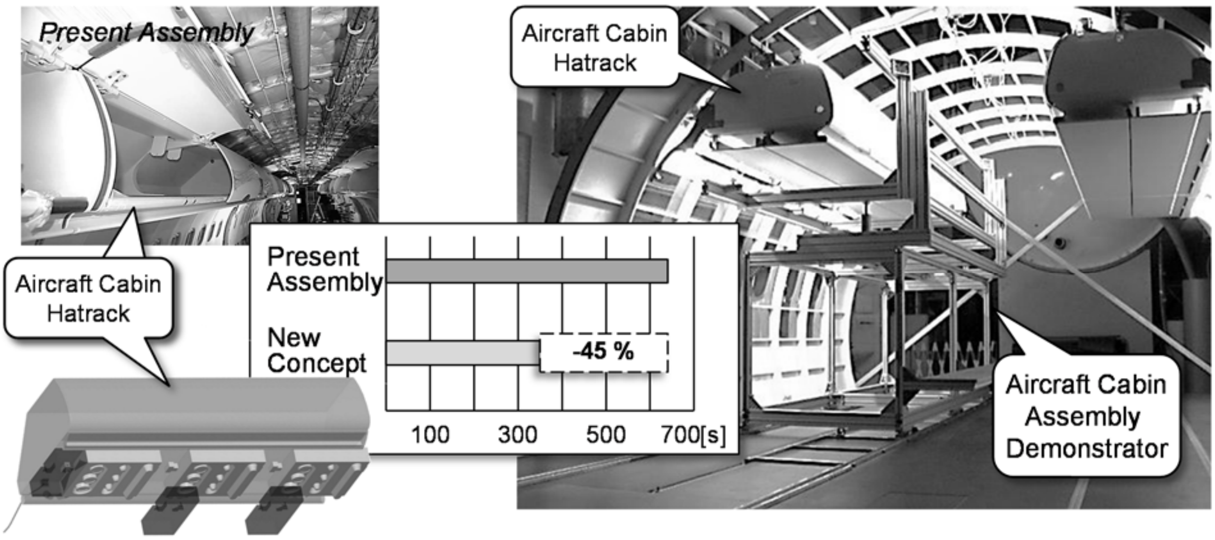

Figure 8. Case study: Aircraft cabin evaluation and model validation in technology demonstrator

An extensive test set-up was arranged to validate the results. The technology demonstrator developed is shown on the right-hand side of Figure 8. The laboratory environment enables investigations to be carried out on assembly processes on a scale of 1:1. The modules and components of the cabin concepts assessed were built as prototypes. In several test runs, the parts are installed in the fuselage. In parallel, the required activities are documented and the time required for their conduction is measured. Thereby, accuracy of the calculation was confirmed.

6. Conclusion

An early estimation of the assembly times of new product concepts with satisfactory accuracy is possible. Based on a literature review, assembly evaluation methods were analysed for their applicability to the early phases of product development. Two methods were chosen for detailed investigation. In the first case study, it was shown that the direct application of these methods leads to invalid results. Here, the calculated assembly times did not coincide with those actually measured. The generalised setup of the underlying database was identified as the decisive reason for the deviations.
Based on these results, an approach for estimating assembly times was developed. The preparation of the evaluation model predicts an initial adaptation to the specific environment. Therefore, the present product and production data is systematically used for calibration. The designated procedure supports the systematic acquisition and processing of product concept information. The easy applicability of the pure evaluation process justifies the slightly increased adaptation effort. The model was applied to a development project of aircraft cabin components. The results of the assembly time calculation could be validated using detailed investigations and time measurements in the laboratory environment of a technology demonstrator.

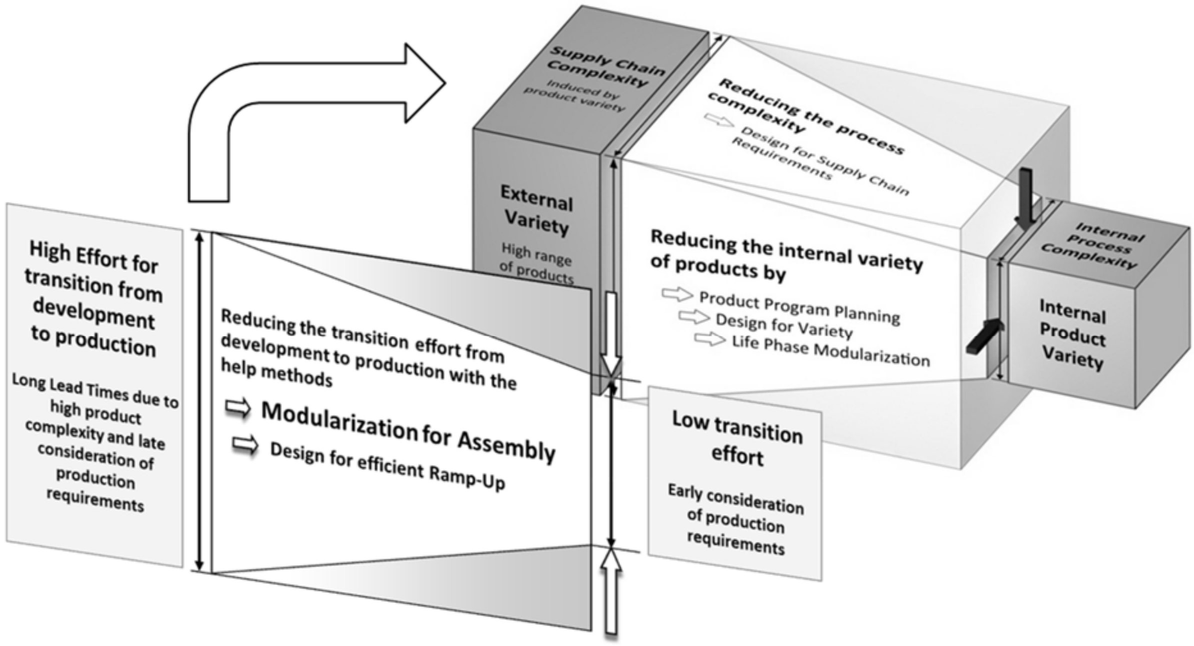

Figure 9. Modularization for assembly in the context of the integrated PKT approach for developing modular product families

In future work, the model will be applied to the assembly time estimation of further product types. In this context, a software implementation is intended to support the user and enhance the applicability of the adaptation procedure. In addition, the integration of the assembly time estimation model into the integrated PKT approach for developing modular product families is scheduled. The methodology is described in [Krause 2011] and shown in the upper right-hand side of Figure 9. It contains various methodical units of design for variety and life phases modularization to support the creation of modular product structures at the level of conceptual design. One of these methodical units is the modularisation for assembly approach by [Halfmann 2011], displayed in the front left-hand side of Figure 9. This approach supports the designer in defining product structures for assembly. One of the core elements for defining product structures is the evaluation of the measures taken. Within this evaluation, the model presented in this paper contributes to assembly effort estimation for newly defined modular product structures.

References

Andreasen, M. M., "Design for Assembly", Springer Verlag London, UK, 1988.

Boothroyd, G., "Product Design for Manufacture and Assembly", Marcel Dekker New York, USA, 2002.

Browning, T.R., "Applying the Design Structure Matrix to System Decomposition and Integration Problems: A Review and New Directions, IEEE Transactions on Engineering Management, Vol. 48, No.3, 2001, pp. 292-306.

Deutsche MTM-Vereinigung e.V., „Produktivitätsmanagement von Arbeitssystemen", Schäffer Poeschel, Stuttgart, Germany, 2006.

Halfmann, N., Krause, D., "Product and Process Evaluation in the Context of Modularisation for Assembly", Proceedings of the 18th International Conference on Engineering Design (ICED'11), T. McAloone (Ed.), DTU, Copenhagen, 2011, pp. 271-281.

Klein, B., "ProKon Approach reduces Product Complexity", Konstruktion, No.4, 2008, pp. 83-87.

Krause, D., Eilmus, S., "A Methodical Approach for Developing Modular Product Families", Proceedings of the 18th International Conference on Engineering Design (ICED'11), T. McAloone (Ed.), DTU, Copenhagen, 2011, pp. 299-308.

Pahl, G., Beitz, W., "Engineering Design", Springer Verlag Berlin, Germany 2007.

Reinhart, G., Cuiper, R., "Assembly Process and Assembly Control Development – A Holistic and Consistent Approach", CIRP Annals – Manufacturing Technology, Vol. 48, No.1, 1999, pp. 25-28.

Whitney, D. E., "Mechanical Assemblies", Oxford University Press New York, 2004.

Dipl.-Ing. Niklas Halfmann
Research Assistant
Hamburg University of Technology, Institute for Product Development and Engineering Design
Telephone: +49 (0)40-42878-3056
Telefax: +49 (0)40-42878-2296
Email: niklas.halfmann@tuhh.de
URL: http://www.tuhh.de/pkt