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# PERMANENTLY ESTIMATION OF ASSEMBLY COSTS DURING PRODUCT DEVELOPMENT

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## 1. Introduction

In today's product development processes computer-based tools are indispensable for the support of synthesis and analysis steps (see Figure 1). Normally, parametric 3D-CAD-systems are used for the computer-based representation of the characteristics of a technical product (parts' structure, geometry, material, surfaces). These representations are the results of synthesis steps (Virtual Prototyping) [Weber 2011]. CAE tools are used to predict the as-is (realised) product properties according to the defined product characteristics (Virtual Engineering). In product development, the next steps are determining the deviations between the required and the as-is properties (= results from Virtual Engineering), running an overall evaluation of the deviations and drawing conclusions for the next synthesis steps (= adding or changing characteristics of the previous solution). For an efficient product development process short closed loops are necessary, i.e. generating information about the impact of modifications of product characteristics on the product properties immediately. Therefore, one important requirement is a continuous use of virtual prototypes.

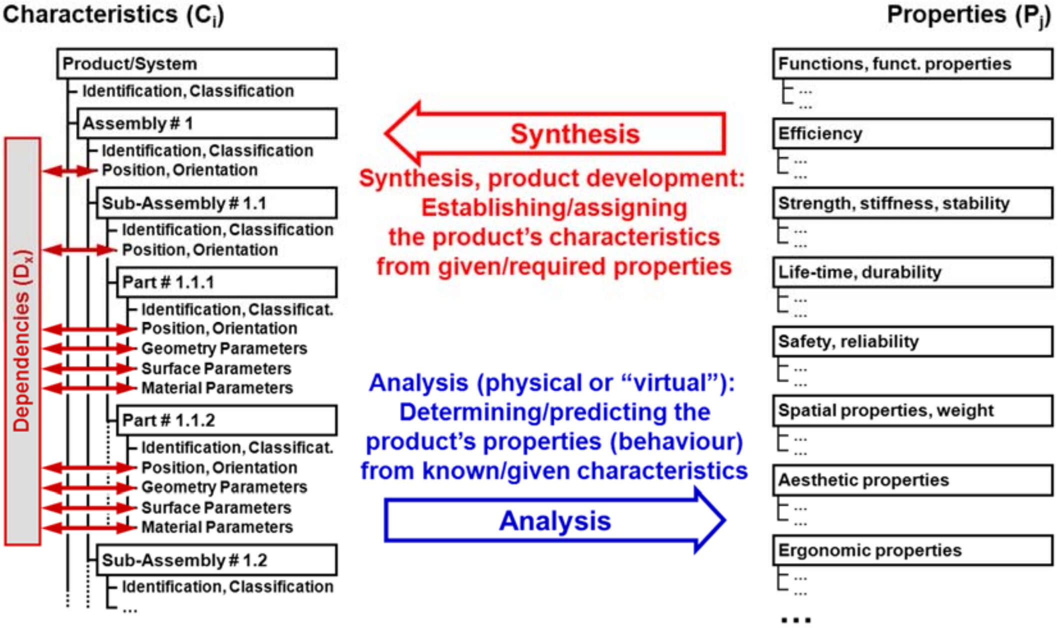



**Figure 1. Characteristics and properties, and their two main relationships [Weber 2011]**

A relevant product property is the behaviour during the technological realisation. Besides the manufacturing of individual parts, this involves the assembly of the product [Bley 2006]. For evaluating and assessment of the assembly process the *Methods Time Measurement* (MTM) is a widely used system [Karim 2011]. Currently the detailed assembly planning is usually done ***after*** product development. In this paper, a method and a tool is presented which enables a first estimation of time and costs for manual assembly ***during*** product development, based on the virtual prototype represented in a CAD-system (Figure 2).

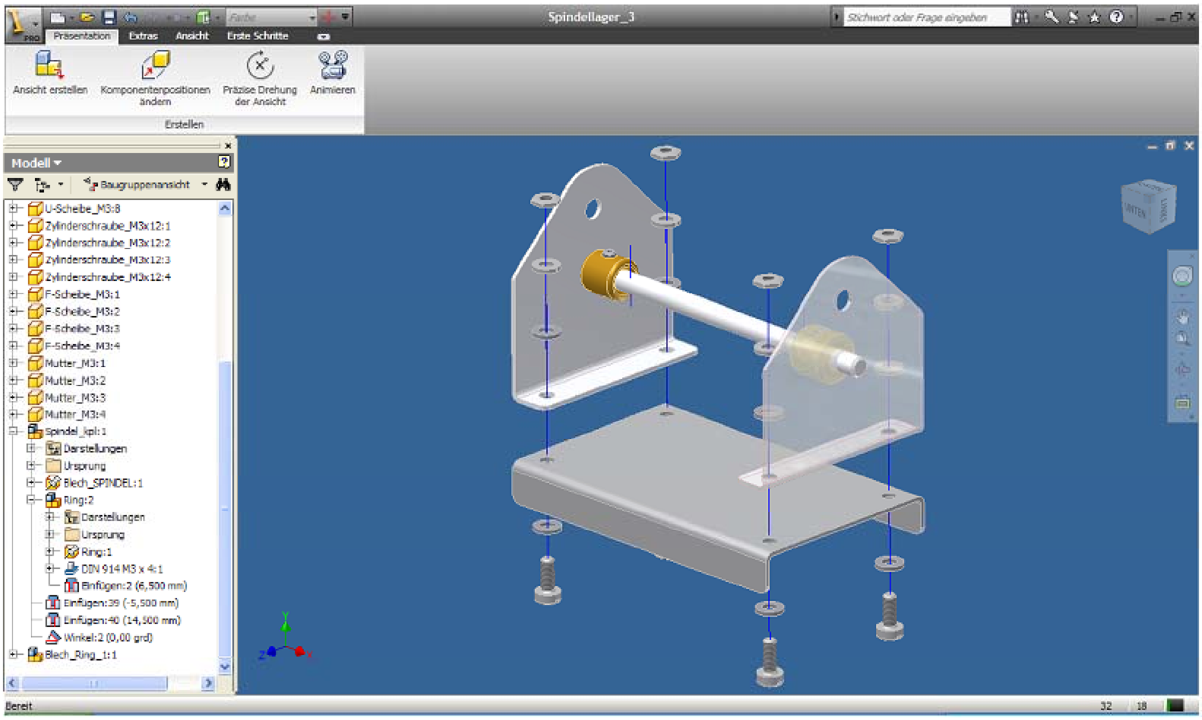



**Figure 2. Model of a "Spindellager" (spindle bearing)**

## 2. Concept

### 2.1 Determining the MTM-parameters

The MTM-system uses fundamental operations to describe a (manual) task [Antis 1968], in that case for an assembly process. The multitude of influences on the fundamental assembly operations (e.g. geometry with nominal sizes, fits, surface roughnesses, adhesion, friction coefficients) are transformed into subjective assessments (e.g. without pressure, without extensive pressure, with pressure – see also Figure 3). The fundamental operations have to be extracted from the virtual prototype. Next, for each operation a necessary operation time is assigned. Based on this and the hourly wage rate, the assembly costs can be estimated.

The planning of the assembly process using the MTM-system consists of [Deutschländer 1989]:

1. analysis of the mating parts and the joints
2. determination of the base component for the assembly process
3. identification of the assembly steps and their sequence
4. determination of the orientation of the components
5. estimation of the assembly time and costs.

Some of the steps (no. 2 and no. 3 partially) only can be done by the engineer, based on procedural experience. However, most of the steps can be automated by using the information in the parametric CAD-model. This will be shown in the following.

For the identification of assembly steps (no. 3) the mating matrix is a means. The mating matrix is built on the evaluation of the mating parts and the contact surfaces (no. 1). The sequence of the as-

sembly steps (assembly sequence of parts, but also the subassembly of groups and the assembly of the groups) has to be decided by the engineer.
For the assessment of the assembly process using the MTM-system, the following information is necessary:

- all joints (contact surface pairs [Albers 2008] between the parts during the assembly process) including tolerances and fits
- assembly supports (e.g. chamfers)
- assembly directions
- rotation angles
- mass of the components assembled

The contact surfaces, assembly supports as well as the mass are described implicitly in the CAD-model. The tolerances in the CAD-model have to be translated into the MTM-fits from which the necessary assembly forces and the assembly time can be derived (see Figure 3). The assembly direction and the rotation angle have to be interpreted and need further information, e.g. about the start position prior to the assembly process.

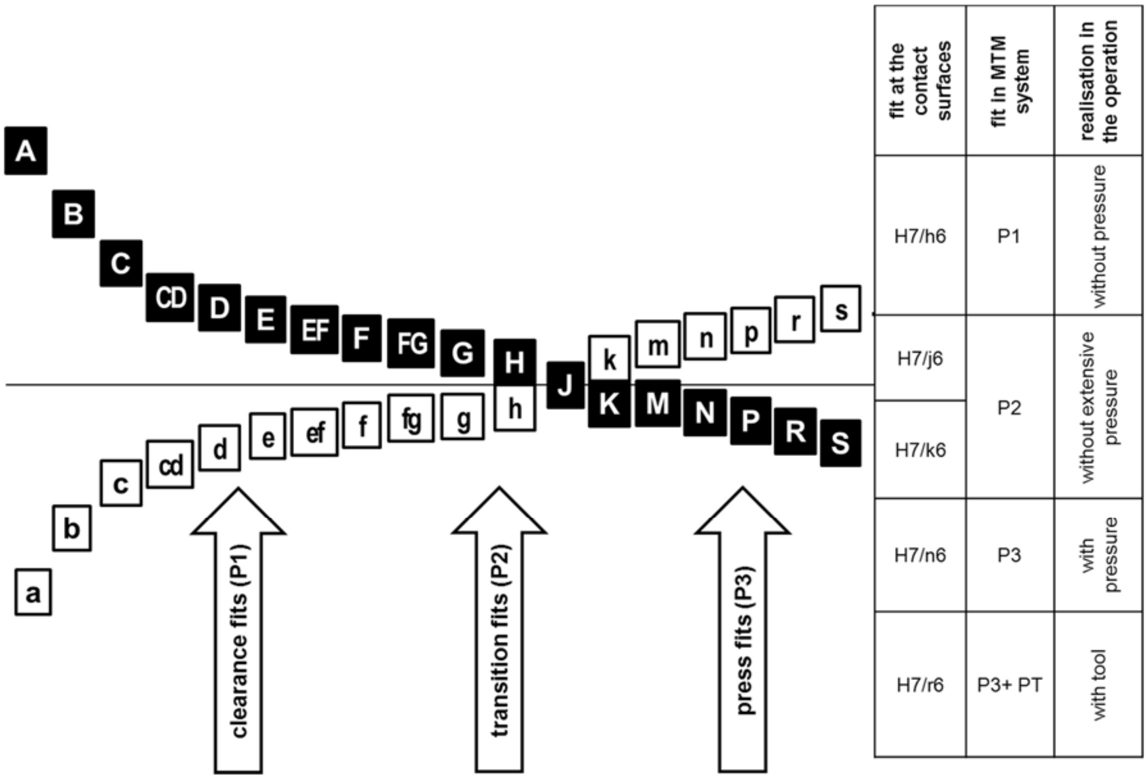



**Figure 3. Fits at the contact surfaces and in the MTM-system**

One of the major tasks is to identify the contact surfaces between the parts during the assembly process and to determine the (relevant) contact parameters. The contact surfaces in the CAD-model result from the (nominal) geometry of parts and their alignment (position, orientation). The contact surfaces are not described explicitly in the CAD-model. However, they can be detected by a face-to-face comparison (see Figure 4). This enables a good-enough identification of potential contact surface pairs.
The proposed face-to-face comparison is complex and time-consuming, especially because of the different surface types involved and various modelling strategies that may have been used to create the CAD-model. Using the constraints between the components in the CAD-model [Kirchner 2007], a bounding-box comparison and a scaling procedure with a subsequent intersection test (see Figure 5) in a pre-process helps to reduce the surface pairs which have to be tested for contact. Currently form and force connections can be interpreted for elementary contact surface pairs (see Table 1).

**Table 1. Interpretable contact surface pairs**

| | cone | cylinder | plane | sphere | torus |
|---|---|---|---|---|---|
| cone | x | | | | |
| cylinder | | x | x | x | x |
| plane | | x | x | x | |
| sphere | | x | x | x | |
| torus | | x | | | |

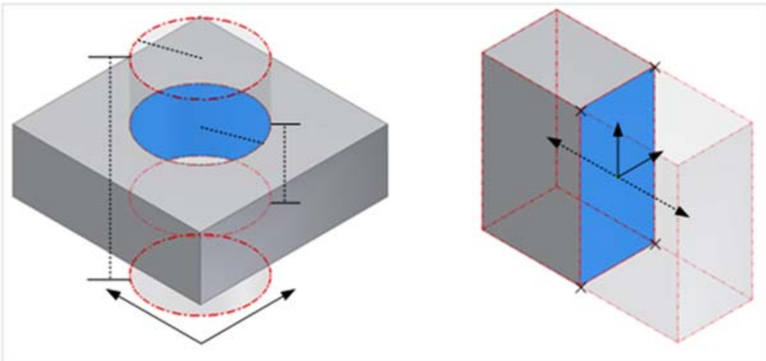


**Figure 4. Contact surfaces between two parts**

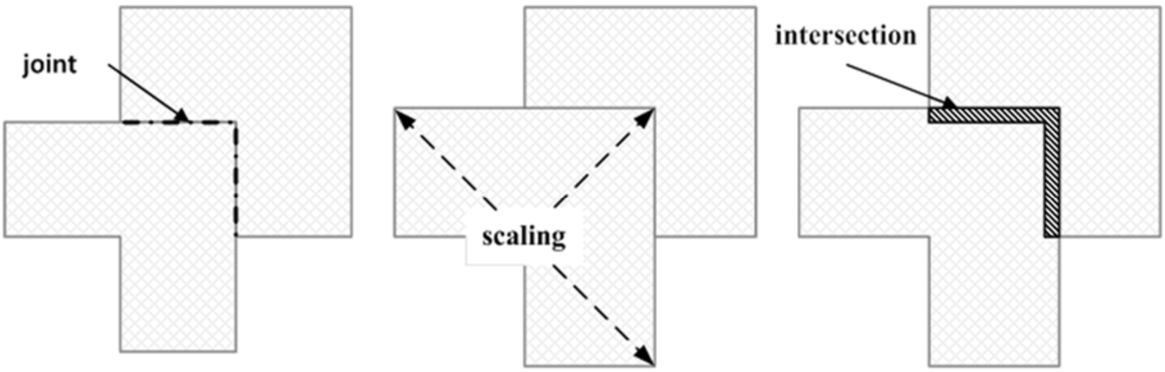



**Figure 5. Scaling of the parts with an intersection test**

The detection result is a set of contact surfaces. All contact surfaces between two components together give the joints (see Figure 6). Based on the tolerances at the contact surfaces the fits can be calculated and the MTM-fits can be assigned. Only one fit per joint may be considered for the MTM-fit. Therefore, the tightest one is used. For joints without defined fits standard values have to be used. For these two cases (no fit and more than one fit) the user gets a feedback via the GUI[1] to modify the CAD-model or define the MTM-fits manually if necessary. Assembly supports can be detected by an analysis of the neighbouring surfaces and the geometry features in the CAD-model.

Due to the fact that the CAD-model only represents the assembled condition the assembly movements currently can not be determined completely automatically. The assembly direction can be assumed only by considering the degree of freedom between the two respective components in the assembled condition for a virtual displacement. In order to estimate assembly movements a full-blown kinematic simulation with collision handling would be necessary.

[1] GUI - Graphical User Interface

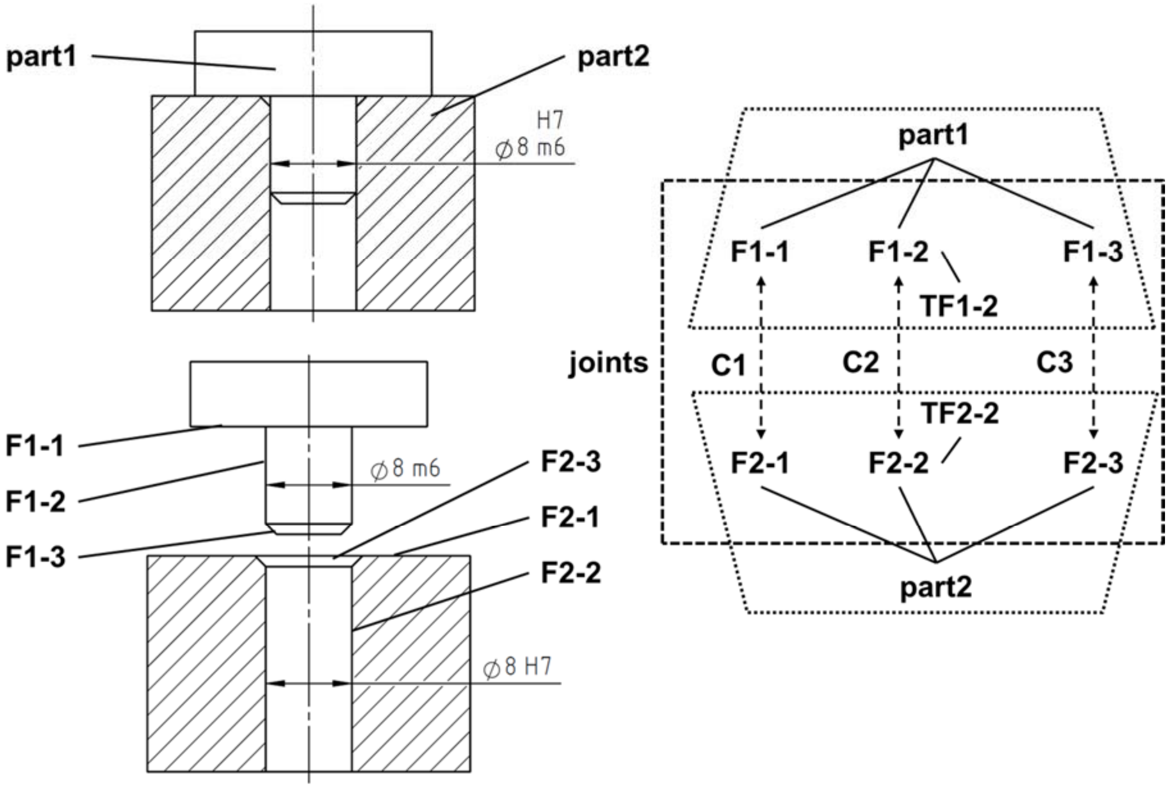



**Figure 6. Joints between two components (with C – contact surface pair, F1-1 - contact face 1 of part 1 and TF – tolerance at the contact face)**

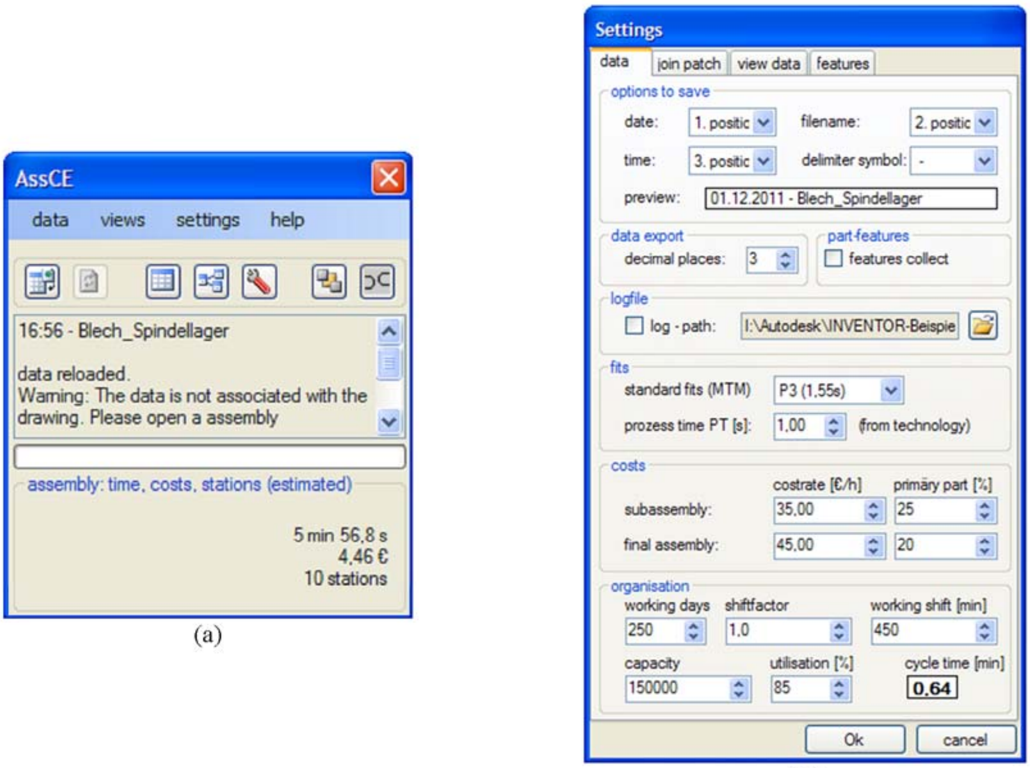
### 2.2 Integration into the design process

The mechanical engineer runs through many synthesis-analysis-evaluation loops to fulfil all necessary product properties. Normally, due to time constraints he/she can not analyse the assembly behaviour in detail after each individual synthesis step. However, for an early consideration of the assembly behaviour it would be helpful that the engineer gets a quick feedback on the estimated assembly costs after each modification of the virtual prototype.

For the efficient prediction of the assembly time and costs the analysis should be integrated into the CAD-system, so that the engineer can start an assembly analysis without leaving his/her CAD-environment.

In a next step, the assembly analysis could be run automatically every time the CAD-model of a product is modified (modification of the product characteristics). For this, system events can be used as triggers. For a new model, all relevant information for the assembly planning has to be collected. For a rapid data collection after a model modification it is reasonable to consider only modified components (see Figure 8).

The estimated assembly costs have to be visualised to the engineer directly in the CAD-system. Besides a small dialogue (always on top) for the estimated costs, a more comprehensive dialogue – normally hidden, displayed on request only – is necessary to present all collected and derived data in detail (see Figure 7).




(a) (b)

**Figure 7. Small dialogue for the estimated time and costs (a), GUI of AssCE with the settings (b)**

For corrections of inaccurately identified joints or assembly directions, a manual override is necessary. The user can manipulate the parameters of the identified joints based on the visualised analysis results.

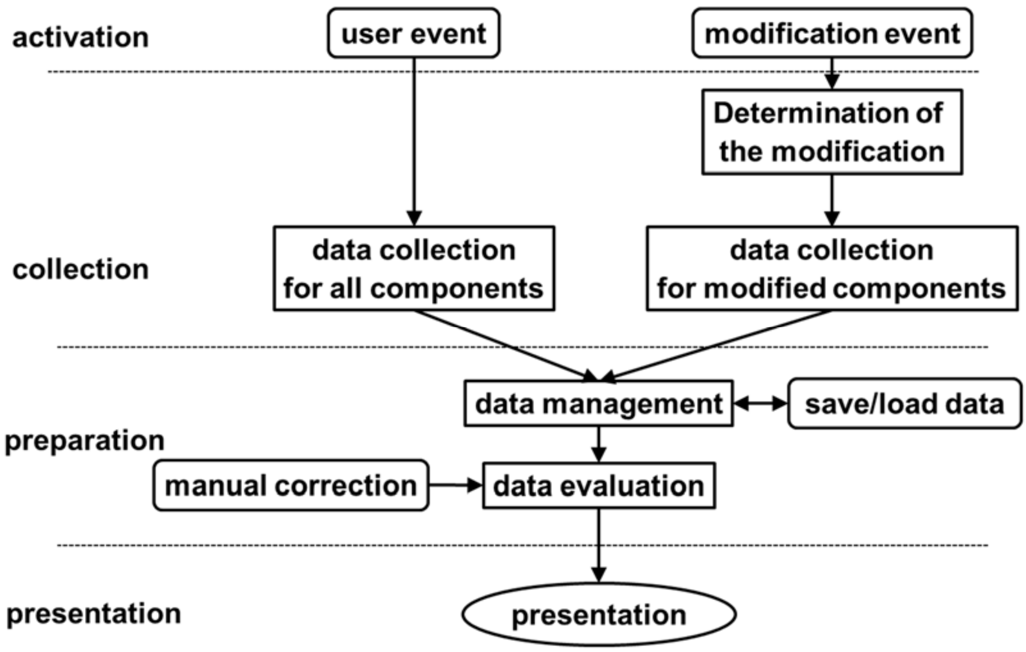



**Figure 8. Application flow**

## 3. Realisation

The described concept was realised in form of a tool called AssCE which is integrated into Autodesk Inventor 2011. Geometry, tolerance as well as material information can be determined by using the CAD-API[2]. The collected and derived data is stored in a separate database. This enables a reload of the data without a new data collection. Besides the presentation of the evaluated data via the GUI of the CAD-system (see section 2.2), the data can be exported for post-processing (e.g. for a more detailed assembly planning procedure) using the „CSV"-file format. The results can be transferred into existing CAP[3]-tools, e.g. ILMOPLAN (Interaktive Layout- und Montageplanung – interactive layout and assembly planning); ILMOPLAN uses the MTM-system like a processing language for assembly [Holle 2002]. Furthermore, the information collected in AssCE is directly usable for assembly process planning. Using organisational information, the required number of assembly stations can be estimated also early in the product development process.

## 4. Example

Figure 9 (see also Figure 2) briefly shows the application example "Spindellager" (spindle bearing) which, amongst others, was used for the verification of the developed tool. The CAD-model is a native Inventor-model. The model is fully constrained and most of the tolerances are defined. With the AssCE tool it is possible to identify 44 of the 46 joints automatically. Figure 9 also shows the small result dialogue (left) and the dialogue with the extended analysis results, including all identified fits (right). Using the small result dialogue the mechanical engineer gets a quick feedback on the assembly time, costs as well as the necessary number of assembly stations. Based on the extended analysis results, the engineer can correct the CAD-model in the CAD-system or modify the identification results manually in the extended analysis result dialogue for a new estimation or a post-process.

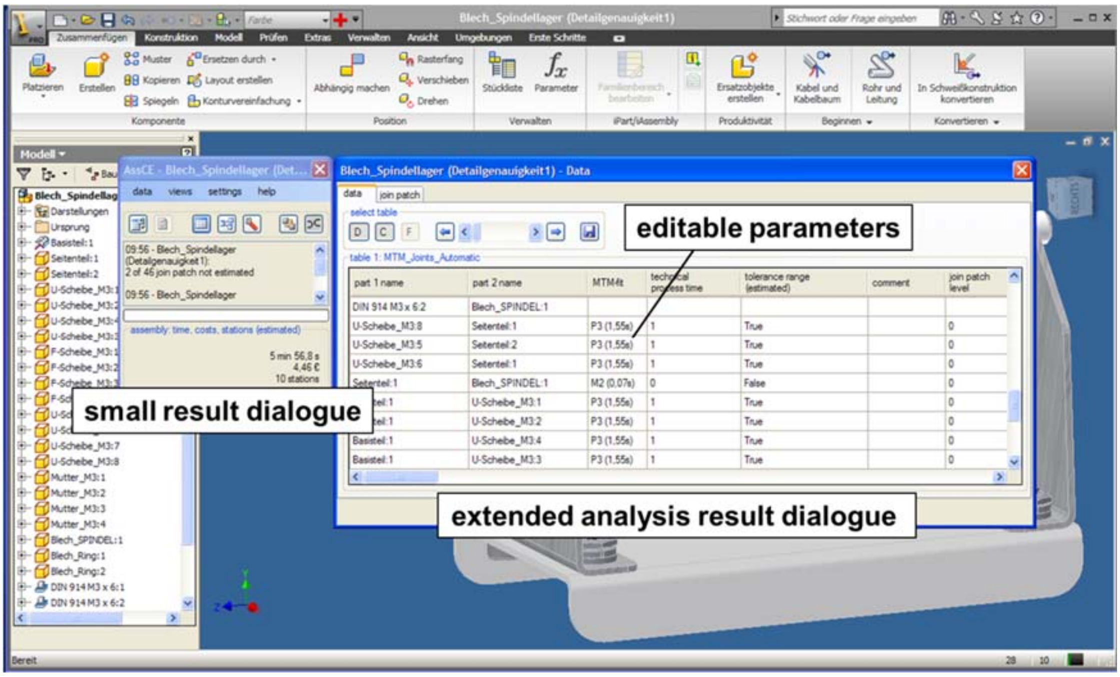



**Figure 9. Analysis results for the "Spindellager" (spindle bearing)**

## 5. Conclusion

In this paper a method and a tool are presented which enable an early and permanent estimation of the assembly time and costs as well as the necessary number of assembly stations based on the virtual

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2 API - Application Programming Interface

3 CAP - Computer Aided Planning

prototype in the CAD-system during the product development process. Thus, the mechanical engineer gets an early feedback about the impact of the defined product characteristics using the MTM-system. Furthermore, the virtual prototype can be used directly for a more detailed assembly planning in a post-process.
The model representation in the current CAD-systems enables a mostly automatic identification of the parameters required for detecting joints. But the model representation comprises no explicit information about the assembly behaviour, only about the product characteristics with some semantic information. The assembly behaviour has to be interpreted based on the product characteristics. Currently form and force connections can be interpreted (no material connections) for elementary contact surface pairs (plane, cylinder, cone, sphere, torus). Future CAD-systems also should be able to represent information about the required or as-is product behaviour in the CAD-model.

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