INTERNATIONAL DESIGN CONFERENCE - DESIGN 2004
Dubrovnik, May 18 - 21, 2004.

Assembly-oriented Design in Automotive Engineering

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Keywords: assembly-oriented design, design for manufacture and assembly, assembly information management, CAx/EDM integration

1. Introduction

To be competitive on the global market, carmakers have cut lead times in passenger car development to the bone. At the same time both the product complexity and the customer's demands with regard to quality are continuously rising. Various new strategies and tools are currently being explored to cope with these challenges: simultaneous/concurrent engineering, front-loaded development, and knowledge-/feature-based parametric design to name just a few.

Current design processes in automotive engineering as well as the engineering IT systems deployed to support them are largely single part oriented. Assembly design is seen as a process step following sequentially *after* part design, and assembly information is not managed in the same quality and quantity as part information.

Assembly-oriented design (AOD) is an approach which breaks with these traditional paradigms of part orientation. Focusing on a parallelisation of assembly design and part design as well as on an integrated and consistent information management for assembly information right from the beginning, AOD strives to realise significant benefits throughout the product life-cycle. The objective of this paper is to elaborate on this approach with a focus on the special situation in automotive engineering.

2. Terminology

So what's behind this new buzzword - "assembly-oriented design"? Even the meaning of the keyword "assembly" is two-fold: on the one hand, assembly is the "activity in which all the upstream processes of design, engineering, manufacturing, and logistics are brought together" [Whitney 1999]. In this sense, "assembly" is the noun belonging to "to assemble": it purely describes the process of putting parts together. On the other hand, assembly can be understood as a "model from general to detail that reflects certain relationships on different levels" [Zha 2001]. Assembly in the context of this paper follows this second interpretation, it is to be understood as the sum of relations between two or more product components, i.e. an assembly is a product made up of more than one component.

Similar to the term "assembly", no agreed-upon definition can be found in literature for AOD either. Some common key factors, however, form the basis for various existing approaches.

- Assembly-oriented design is often used synonymously for the more common "design for (manufacture and) assembly" (DFA/DFMA, see [Andreasen 1988, Boothroyd 2001]), thereby using "assembly" in its process meaning. [Barnes 1999] describes AOD as a proactive extension of what have so far been considered mainly reactive DFA procedures.

- Goals of existing AOD approaches and systems are generally to analyse and evaluate assembly designs in upstream processes [Barnes 1999, Zha 2001] and to generate suitable assembly sequences [Zha 2001, Whitney 1999].
- They therefore promote top-down process approaches for design. [Whitney 1999] describes such an approach based on a skeleton-like concept model, geometrical constraint chains, and assembly features.

In the context of this paper, Assembly-oriented design stands for a broader approach: it is to be understood as the targeted, consistent focusing not only of the product creation process but also of the engineering IT systems to support it on assembly aspects. This is achieved by working in assemblies from the very beginning, deriving the part designs in a top-down manner. Thus, AOD is more than design for assembly, which reduces design to a best-supporting discipline for production requirements. Living AOD puts the focus on the optimisation of development itself in order to bear fruit along the complete process chain. But first, let's step back to take a look at the status quo.

3. Today's engineering process and IT systems

Today's product creation process in automotive engineering is, for the most part, bottom-up oriented and part centred. In body-in-white design, the very first designs feature part-spreading surfaces. Yet in the next step they are broken down into individual parts, and detailing is done on the part level with only weak and limited relations to the parts' assembly context. Only in a much later step are the parts re-assembled, e.g. by adding assembly constraints, welding connections or assembly-level tolerances. Here, assembly design is seen as a process step that follows sequentially after part design. In engine and powertrain design, product structures are generally fixed right from the beginning. Then the design process is mainly part centred, with neighbouring parts being considered merely as reference geometry.

As a consequence, designers are responsible for parts, release processes are part oriented, and methodologies currently applied or promoted as state of the art focus more on the optimisation of part design than on facilitating assembly design. Feature technology as an example, while enabling the efficient and standardised design of repeatedly used part installations, does not, however, support assembly design. This can be seen by the fact that design features covering groups of components - which then might be called "assembly features" - are very rarely dealt with. Yet if they are, then we find numerous different concepts. Also parametric design calls for detailed part data before allowing the creation of assembly relationships and thus supports bottom-up design rather than top-down approaches.

IT systems currently used to support the engineering processes such as computer-aided design (CAD) and engineering data management (EDM) systems are also designed to support part-oriented working approaches.

An era ago, at the time when design was based solely on technical drawings or even later with the introduction of 2-D CAD technology, design was traditionally top-down, i.e. the initial draft was created at the drawing board on the product level. This drawing contained both the underlying part geometries and the information related to the assembly. Detailed design was done at later stages in development, with drawings of the individual parts derived from the holistic product view. With the birth of 3-D CAD systems this world was turned upside-down and a bottom-up philosophy was embraced. The more or less detailed modelling of individual parts became the first step, with assemblies then created on the basis of the information derived. Thus, the original draft on the product level must, in fact, be made outside the 3-D system and frequently exists only in the minds of the design engineers.

In current system layouts, CAD systems interwork with EDM systems in such a way that the EDM system serves as the master of the product structure, whereas the CAD system generates the part geometry and links this to the structure. EDM systems then manage this part information as well as parent-child-relationships and geometric transformations between the parts. These systems are, however, weak in managing assembly information beyond this scope. Assembly connections,

assembly level fits and tolerances, constraints or kinematics are just a few examples of assembly information which is generated within CAD systems but which cannot be handled as such within EDM systems.
Today, the importance of design concepts on the one hand and of assembly-related information on the other hand has been newly recognised, resulting in the development of suitable methodologies and system functionalities aimed at slowly moving back towards an assembly-oriented way of working. This allows the advantages achieved in productivity through the technologisation of the design process to be combined with the time and quality benefits generated by AOD. The original level of assembly-orientation has, however, not been reached again by far. Figure 1 [Burr 2003] depicts the development of design philosophies and technologies, showing that AOD is the logical next step.

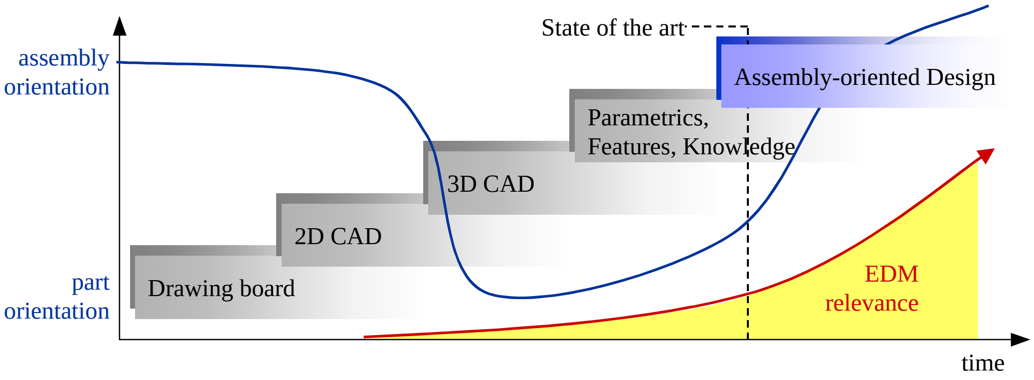


Figure 1. Paradigm shifts in design philosophy

So how can a strategy of AOD be realised, starting from the chiefly part-oriented IT technologies of today? AOD builds on a combination of design methodologies, and it poses requirements for capabilities of existing and future engineering IT systems.

4. Assembly-oriented design methodologies

Design methodologies in the context of this paper are to be understood as methodologies and practices applied during the design process, the term does not refer to general approaches to design as elaborated in [VDI 2221], for example.
AOD requires methodologies that support top-down thinking throughout the product creation process. Design as a creative process has to start on a conceptual product level, i.e. on the assembly level. It is only on a solid product level concept that component design and detailing should be based. Figure 2 describes the difference between bottom-up design, which starts with the detailing of single parts and brings those together in a later step, and top-down design, which works the other way round.
These two extremes will generally not be applicable as such: in reality a mixture of both will have to be utilised, see Figure 2c. Today’s product creation process in automotive engineering is, however, mainly bottom-up oriented and part centred, as explained in the previous chapter.

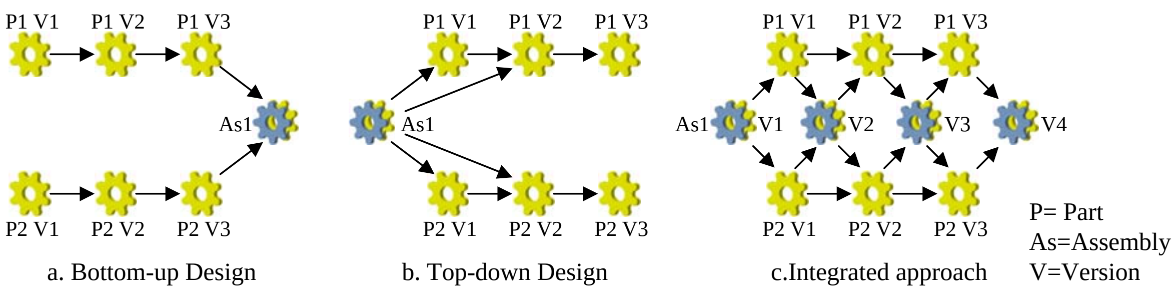


Figure 2. Bottom-up vs. top-down design

4.1 Product structuring

The foundation for a top-down process approach has to be an assembly level concept which can be erected without requiring that detailed parts exist. This concept model has to be integrated into the product structure, so that it can serve as a common basis for both part design and assembly design throughout the design process. Such an assembly level concept model is often referred to as an assembly skeleton model, an adapter model or a mating model, depending on the information bundled within it (see [Bär 2001]). Its purpose is to serve as an interface between referenced design input data from various sources (e.g. requirements, styling curves and shapes, the surrounding geometry) and all related components. Figure 3 illustrates the concept of a product structure scheme based on skeleton models.

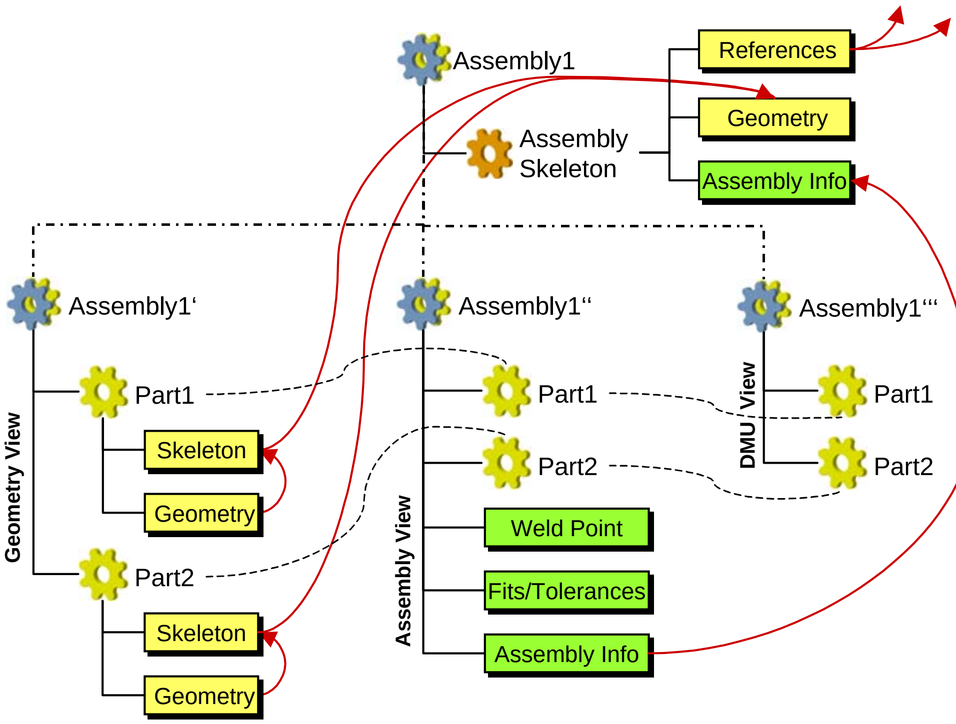


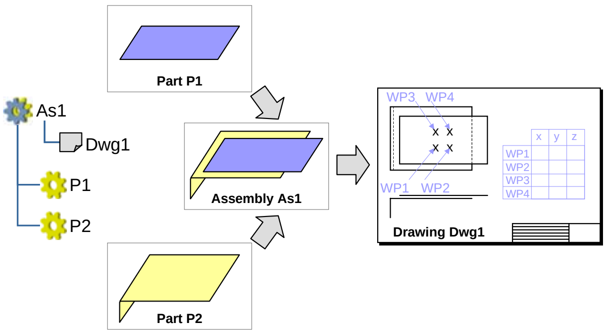
Figure 3. Assembly-oriented product structure

As the master product structure currently resides in the EDM area, whereas design happens mainly in the CAD area, such a structure has to be realised in a combined CAD and EDM environment.
A key success factor for an assembly-oriented product structure as depicted in figure 3 is the ability to handle inter-component logical links. Link "flow" has to be top-down in principle, i.e. information should be captured and managed on higher structure levels and should be passed from there to lower levels. Only in controlled exceptions should links be built between structure components on the same level. This is to keep the structure manageable and to prevent loops.
Experience has also shown that it is not advisable to keep all the information to be managed within one single product structure, but that it is necessary to handle a set of different, yet interlinked structures (separate structures for functional design, assembly planning, DMU viewing etc.), as is set out in figure 3. This also allows the structure to be kept on a manageable complexity level for each user.

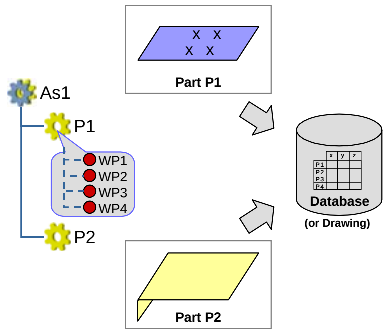
4.2 Assembly information modelling

In addition to product structuring, assembly information modelling and management are keys to successful AOD. Assembly information in this context is any product and process information that describes the assembly of more than one component including all relevant relations, e.g. parent-child-relationships, positioning information, fits and tolerances, and assembly connections.

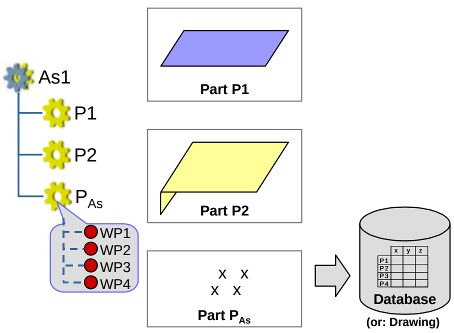
At the time of the drawing board and 2-D CAD, it was sufficient to register assembly information on assembly drawings, as this was the only document managed for an assembly (figure 4a). With 3-D CAD, the 3-D product model stepped up beside the drawing as a second master of information, today often even being the only source (“digital master”). Under these conditions, several alternatives for handling assembly information have arisen. Firstly, it is possible to just add the information, e.g. a weld point, to one or all of the parts concerned (figure 4b). Secondly, assembly information can be modelled within an additional part on the assembly level (figure 4c). Thirdly, assembly information can be added to the object which represents the assembly node itself and which then keeps both structure and assembly information (figure 4d). This option is currently promoted by leading CAx suppliers.



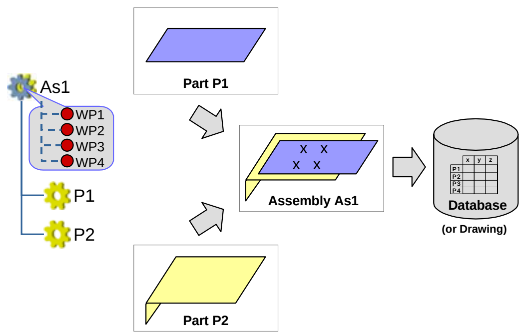
a. Assembly information on assembly drawings



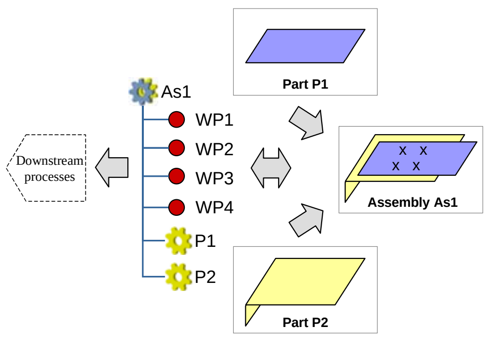
b. Assembly information within assembled part



c. Assembly information within dedicated part



d. Assembly information within assembly object



e. Assembly information as dedicated assembly level objects

Figure 4. Five ways to manage assembly information

Finally, assembly information can be modelled as assembly objects as such (figure 4e). This option offers the greatest potential: not only does it support efficient data and variant management of the assembly information, it also promotes its reuse along the process chain. However it also places the

greatest requirements on CAD and EDM systems: they need to be able to handle that information in an integrated way. This option is considered the optimal basis for AOD; in the following, the dedicated assembly information objects are referred to as generic assembly objects. This option is also applied to the product structure depicted in figure 3. Modelled in this way, a concept skeleton model including rough assembly connection data can represent a highly valuable input for production planning, thereby enabling simultaneous engineering in a very early phase of the process.
Generic assembly objects are carriers of universal assembly information, they are to be designed in such a way that they are able to model both assembly connections and assembly level tolerances as well as any other kind of assembly information. Detailed concepts for generic assembly objects are currently being developed by the authors, taking existing approaches to assembly features (e.g. [Holland 2000]) into account.

5. Assembly-oriented engineering IT systems

With the product creation process in the automotive industry currently strongly supported by engineering IT systems (in the context of the topic at hand largely CAD (as well as other CAx) and EDM systems), the AOD concepts and methodologies presented can only become reality if based on appropriate system solutions. The process-supporting IT systems must therefore follow the methodologies, and not vice versa as is often encountered.
Looking at the CAx systems which are available on the market today, the process step of detail design, and of part design in particular, is extensively covered by CAD applications. Support for earlier phases of conceptual design, which focuses more on the complete product or assembly level, is however weak. As long as this is the case, top-down approaches will reach their limits quite quickly.
So what has to be done to implement the methodologies presented? Both micro- and macroscopic aspects are to be considered. Microscopically, ways to model and manage assembly information consistently and efficiently have to be defined. To realise product structures including assembly-level skeleton models, the handling of inter-component links within the CAD systems has to be improved. Link management concepts have to be stabilised and made compatible with versioning and variant management concepts, in particular. To allow concurrent engineering, it is also essential to extend the link management topic into the EDM area. EDM system concepts will have to be strengthened in their team/design data management (TDM) functionalities.
Assembly information modelling will have to be made possible in line with the concepts introduced for generic assembly objects. Current CAD systems generally enable the modelling of parts and assemblies, and even if they allow assembly information modelling on the assembly level, e.g. through assembly features, they encapsulate this information within their assembly node objects. EDM systems are even further away from an efficient assembly information handling with functionalities generally limited to handling product structure and part information only.

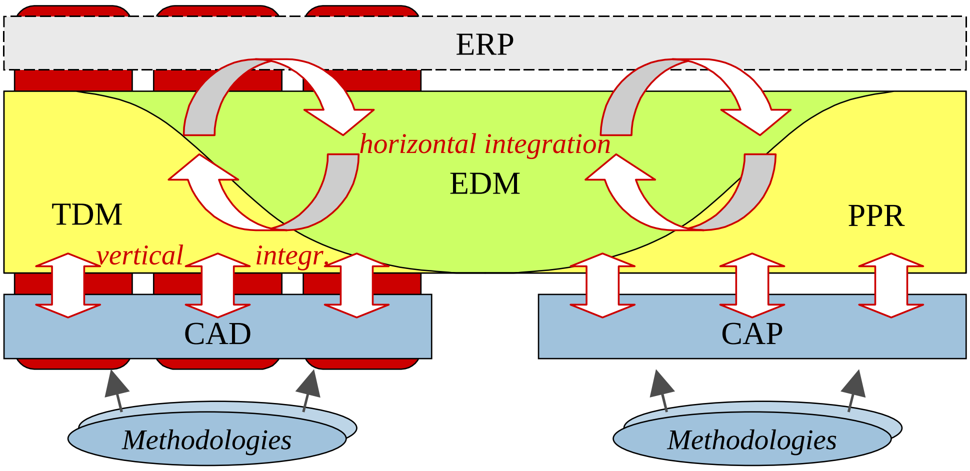


Figure 5. CAx/EDM integration

Macroscopically, the wide variety of systems has to be redefined concerning its roles and functions. As a very important aspect, the area of CAx/EDM integration has to be singled out (also presented in [Burr 2004] as related research work by the same authors). With the current subdivision of product structuring and geometry creation, putting one domain into the mastership of EDM and the other into CAD, achieving AOD will be difficult - perhaps even impossible. In order to manage assembly information along the overall process chain of automotive engineering and manufacturing, development work has to be done both on the vertical integration, i.e. between computer-aided application areas (CAx) and their respective data management systems, and on the horizontal integration to a uniform data management environment [Burr 2004, Burr 2003]. Figure 5 provides an overview on the topic of CAx/EDM integration.

Apart from the process- and system-related factors described above, the organisation will have to adapt to the new way of working. As just one example, release processes have to reflect the shift sufficiently: organisational workflows must make a commensurate shift from part-oriented to assembly-oriented processes.

6. Application in automotive engineering

In the following, two examples of processes in automotive engineering shall be reviewed with regard to their assembly orientation. Furthermore, potential limitations for AOD in automotive engineering shall be pointed out.

6.1 Example: Body-in-white assembly connections

Currently, assembly connections in body-in-white design such as welding connections are generally created in an assembly design process step that takes place after part design has been finished. Detailed part geometry is the prerequisite for the modelling of the assembly information. This procedure is heavily bottom-up oriented, and it makes parallelisation of the design phase and the production planning phase, which is a major downstream user of the connection data, difficult.
Assembly connections are currently modelled according to the options depicted in figures 4a-d. Assembly connection information is therefore generally only accessible via the creating CAD system and not via the CAD-related data management system (i.e. EDM). This makes efficient data handling and variant management, (which, in general, are the key tasks of a database system) of connections difficult, and sometimes impossible. Furthermore, the option shown in figure 4e, which is recommended for AOD, causes difficulties regarding its CAD/EDM integration. Neither CAD nor EDM systems are currently ready for this approach.
Thus, efforts are currently in the pipeline to realise assembly-oriented connection creation based on a product structure as proposed in figure 3 and on generic assembly objects as proposed in figure 4e.

6.2 Example: Assembly level tolerances

The current tolerancing process is also bottom-up oriented: first the parts are toleranced, and then the tolerance chains are analysed in order to check and align the chosen tolerances with the assembly tolerances and fits. Optimisation then takes place via modifications on the part level, with another analysis loop on top.
The goal should be to go in the opposite direction - top-down. Driven by the original requirements - the key clearances and fits - a tolerance synthesis process should derive the part tolerances as a result. This way, optimisation of tolerances, and thus of quality and costs, would happen on the assembly level.

6.3 Potential limitations

Consistent AOD may be especially difficult to adapt to automotive engineering in some respects.
Firstly, an assembly-oriented product structure including component-spreading links on various levels applied to automotive designs may lead to a complexity that is hard to handle. Efficient complexity management is therefore a key factor in the development and implementation of detailed assembly-

oriented methodologies. Secondly, this complexity has to be made compatible with the distributed and highly concurrent engineering environment in automotive engineering. Currently, not only different parts but also different kinds of assembly information are created by different departments in a concern. And these are often supported by a variety of external engineering partners working with different IT systems, at different sites or even on different continents. Thirdly, efforts to standardise part usages and vehicle platforms may, on the initial view, support or call for part-oriented working.

Real-life design will therefore have to be a combination of both assembly-oriented and part-oriented aspects, with a focal point lying on the assembly-oriented approach. Finding the optimal mixture will be the key to success.

7. Conclusion

The current engineering process in the automotive industry is chiefly part oriented. What counts most, however, is the optimisation of complete assemblies; designing a car is much more than just designing a bunch of parts.

Assembly-oriented design (AOD) is introduced as an approach which optimises the development process in a way that benefits both development itself and downstream production processes. It breaks with the paradigm of part-orientation prevailing today and promotes a top-down approach towards the creation of complex assemblies such as passenger cars. It combines different aspects of methodology and engineering system design in order to open up potentials in both development and downstream process steps. Whereas design for manufacture and assembly (DFA/DFMA) subordinates development to the optimisation of the production process, AOD promotes an integrative approach which offers potentials along the complete process chain.

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