CHAPTER 6

Computer Integrated Technologies and Knowledge Management

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1. INTRODUCTION

The rapidly growing globalization of industrial processes is defining the economic structure worldwide. The innovative power of a company is the deciding factor for success in gaining market acceptance. Strengthening innovation, however, relies on the ability to structure the design phase technically so that innovative products are generated with consideration of certain success factors such as time, expense, quality, and environment. Furthermore, these products should not only be competitive but also be able to maintain a leading position on the world market. The opportunity to increase innovation lies in deciding on novel approaches for generating products based on future-oriented, computer-integrated technologies that enable advances in technology and expertise. In the end, this is what guarantees market leadership.

In recent years, progress in product development has been made principally through the increasing use of information technology and the benefits inherent in the use of these systems. In order to fulfill the various requirements on the product development process in respect to time, costs, and quality, a large number of different approaches have been developed focusing on the optimization of many aspects of the entire development process.

This chapter provides an overview of the computer integrated technologies supporting product development processes and of the current situation of knowledge management. Section 2 discusses the design techniques affected by computer-aided technologies and the corresponding tools. Section 3 gives a general introduction of concepts of computer integrated technologies and describes basic technologies and organizational approaches. Section 4 explains possible architectures for software tools that support product development processes. Section 5 gives a wide overview of the application and development of knowledge management.

2. DESIGN TECHNIQUES, TOOLS, AND COMPONENTS

2.1. Computer-Aided Design

2.1.1. 2D Design

Like traditional design, 2D geometrical processing takes place through the creation of object contours in several 2D views. The views are then further detailed to show sections, dimensions, and other important drawing information. As opposed to 3D CAD systems, 2D CAD design occurs through conventional methods using several views. A complete and discrepancy-free geometrical description, comparable to that provided by 3D CAD systems, is not possible. Therefore, the virtual product can only be displayed to a limited extent. Two-dimensional pictures still have necessary applications within 3D CAD systems for hand-sketched items and the creation of drawing derivations.

Despite their principal limitation compared to 3D CAD systems, 2D systems are widely used. A 3D object representation is not always necessary, for example, when only conventional production drawings are required and no further computer aided processing is necessary. In addition, a decisive factor for their widespread use is ease of handling and availability using relatively inexpensive PCs.

The main areas of 2D design are the single-component design with primitives geometry, sheet metal, and electrical CAD design for printed circuit boards.

Depending on the internal data structure of the computer, classical drawing-oriented and parametrical design-oriented 2D CAD systems can be differentiated. This distinction has an essential influence on the fundamental processing principles and methodical procedures followed during the design phase. The drawing-oriented systems are then implemented efficiently in the detailing phases while new-generation parametrical systems support the development in early concept phases. With efficient equation algorithms running in the background, extensive calculations and parametrical dependencies for simulation purposes can be applied.

The essential goal in using design-oriented, 2D CAD systems is creation of manufacturing plans and documentation. From the exact idea of the topology and dimensions of the technical entity to the input of the geometry and ending with the detailing of the technical drawing and preparation of the parts list, this computer-supported process corresponds to a large degree with conventional strategies.

The technical drawings are created with the aid of geometrical elements available within the system. The following geometrical elements can be used: points, straight lines, parallel lines, tangents, circles, arcs, fillets, ellipses, and elliptical arcs such as splines. Furthermore, equidistant lines may be created. Editing commands such as *paste, delete, join, extend, trim,* and orientation operations such as translation and rotation, exist for element manipulation purposes. Further design clarification and simplification is provided by the help functions of scaling, duplicating, locating, and mirroring on symmetrical axes. Detail work may be simplified with the use of zoom functions, and snap points aid in dimensioning and positioning of geometrical elements. The technical drawings are then completed with the use of hatching, dimensioning, and labeling.

The following strategies are recommended for the completion of drawings using 2D CAD systems:

- Do default settings for drawing parameters such as scale ratios, line characteristics and hatching, font, and measurement standards.
- Call up and blend in predefined frames with text and form fields.
- Use construction lines for added support.
- Create contour and surface in different views.
- Apply eventual cutouts and hatching
- Set measurements, tolerances, etc.
- Transfer generated objects to predefined printing or storage mediums.

An example of a complex assembly drawing is presented in Figure 1.

With the use of layers, drawing information of all types may be distributed over any desired number of named and editable layers. The layers simplify the drawing process because momentarily irrelevant information can be easily blended out. Additional text in different languages or measurement systems or norms can also be called up and implemented.

Grouping techniques allow for the summarizing of geometrical elements through various selection processes and in turn ease further working processes.

The majority of systems provide function libraries for the simplification of drawing preparation and the efficient use of results. The following areas may be simplified with the use of function libraries:

- Creation and manipulation of geometrical elements
- Geometrical calculations
- Access to saved elements using search criterion
- Creation of groups and layers
- Utilization of drawing elements such as dimensioning, hatching, and text
- Use of standard dialogs for value, point, or font input

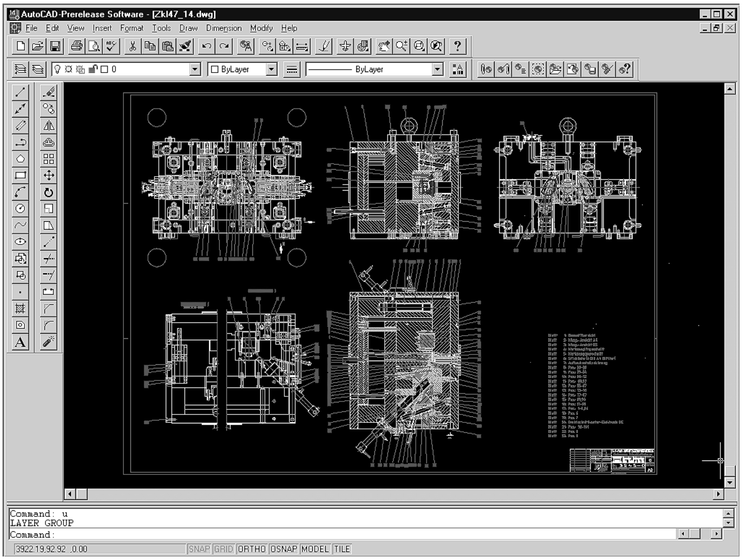

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Figure 1 An Example of a 2D Drawing. (AutoCAD System. Reproduced with permission of Autodesk®)

Geometry macros are internal computer representations of dimension and form-variable component geometries of any complexity. The macros are easily called up from a database and copied by the user. The user may then easily insert the copied macro into the current object representations. The advantages of the geometry macros are seen especially when working with standard and repeat parts.

A spatial representation is desirable for a variety of tasks where primarily 2D representations are utilized. Therefore, in many systems an existing function is available for isometric figures that provide an impression of the object's spatial arrangement without the need for a 3D model. This approach is sufficient for the preparation of spare parts catalogs, operating manuals, and other similar tasks. Prismatic bodies and simplified symmetric bodies may also be processed. For the use of this function it is necessary to present the body in front and side views as well as plan and rear views where required. After the generation of the isometric view, the body must be completed by blending out hidden lines. This happens interactively because the system actually does not have any information available to do this automatically. So-called 2½ systems generate surface-oriented models from 2D planes through translation or rotation of surface copies. The main application for these models lies in NC programming and documentation activities.

To reduce redundant working steps of geometrical modifications, the dimensioning of the part must be finished before the computer-supported work phases. This approach, which underlies many CAD systems today, is connected to the software's technical structure. In geometry-oriented dimensioning, the measurement alone is not inferred but rather the totality of geometrical design of the entity. The supporting role played by the system for interactive functioning is limited to automatic or semiautomatic dimension generation. The dimensional values are derived from the geometry specified by the designer. The designer is forced to delete and redo the geometry partially or completely when he or she wishes to make changes. This creates a substantial redundancy in the work cycle for the project.

The principal procedures of dimension-oriented modeling in parametric 2D CAD systems often correspond to conventional 2D systems. For the generation of geometrical contours, the previously mentioned functions, such as lines, circles, tangents, trimming, move, and halving, are used. The essential difference is the possibility for free concentration on the constructive aspects of the design. In parametrical systems, on the other hand, the measurements are not fixed but rather are displayed as variable parameters. Associative relationships are built between the geometry and measurements, creating a system of equations. Should the geometry require modification, the parameters may be varied simply by writing over the old dimensions directly on the drawing. This in turn changes the geometrical form of the object to the newly desired values. The user can directly influence the object using a mouse, for example, by clicking on a point and dragging it to another location, where the system then calculates the new measurement. The changes cause a verification of the geometrical relationships as well as the consistency of the existing dimension in the system.

Another advantageous element of the parametrical system is the ability to define the above-mentioned constraints, such as parallel, tangential, horizontal, vertical, and symmetrical constraints. Constraints are geometrical relationships fixed by formula. They specify the geometrical shape of the object and the relevant system of equations necessary for geometry description. Thus, a tangent remains a tangent even when the respective arc's dimension or position is changed. With the constraints, further relationships can be established, such as that two views of an object may be linked to one another so that changes in one view occur the related view. This makes the realization of form variations fairly simple.

Modern CAD systems include effective sketching mechanisms for the support of the conceptual phase. For the concept design, a mouse- or pen-controlled sketching mechanism allows the user to portray hand-drawn geometries relatively quickly on the computer. Features aiding orientation, such as snap-point grids, and simplifying performing the alignment and correction of straight, curved, orthogonal, parallel, and tangential elements within predetermined tolerances. This relieves the user of time-consuming and mistake-prone calculations of coordinates, angles, or points of intersection for the input of geometrical elements. When specifying shape, the parametrical system characteristics come into play, serving to keep the design intent. The design intent containing the relative positioning is embodied by constraints that define position and measurement relationships. Component variations are easily realizable through changes of parameter values and partially with the integration of calculating table programs in which table variations may be implemented.

The existing equation system may be used for the simulation of kinematic relations. Using a predetermined, iterative variation of a particular parameter and the calculation of the dependent parameter, such as height, simple kinematic analysis of a geometrical model is possible. This simplifies packaging analysis, for example.

2.1.2. 3D Design

2.1.2.1. Surface Modeling The geometrical form of a physical object can be internally represented completely and clearly using 3D CAD systems, is contrast to 2D CAD systems. Therefore, the user has the ability to view and present reality-like, complex entities. Thus, 3D CAD systems provide the basis for the representation of virtual products. Through 3D modeling and uniform internal computer representation, a broader application range results so that the complete product creation process can be digitally supported. This starts with the design phase and goes through the detailing, calculation, and drawing preparation phases and on to the production. Because of the complete and discrepancy-free internal computer representation, details such as sectional drawings may be derived automatically. Also, further operations such as finite element analysis and NC programs are better supported. The creation of physical prototypes can be avoided by using improved simulation characteristics. This in turn reduces the prototype creation phase.

Due to the required complete description of the geometry, a greater design expenditure results. Because of the greater expenditure, special requirements for user-friendliness of component geometry generation of components and their links to assemblies and entire products are necessary.

3D CAD systems are classified according to their internal computer representations as follows (Grätz 1989):

- Edge-oriented models (wire frames)
- Surface-oriented models
- Volume-oriented models

The functionality and modeling strategy applied depend on the various internal computer representations.

Edge-oriented models are the simplest form of 3D models. Objects are described using end points and the connections made between these points. As in 2D CAD systems, various basic elements, such as points, straight lines, circles and circular elements, ellipses, and free forming, are available to the user and may be defined as desired. Transformation, rotation, mirroring, and scaling possibilities resemble those of 2D processing and are related to the 3D space.

Neither surfaces nor volumes are recognizable in wire frame models. Therefore, it is not possible to make a distinction between the inside and outside of the object, and section cuts of the object cannot be made. Furthermore, quantifiable links from simple geometrical objects to complex components are not realizable. This is a substantial disadvantage during the practical design work. An arbitrary perspective is possible, but in general a clear view is not provided. Among other things, the blending out of hidden lines is required for a graphical representation. Because of the lack of information describing the object's surfaces, this cannot take place automatically but must be carried out expensively and interactively. Models of medium complexity are already difficult to prepare in this manner. The modeling and drawing preparation are inadequately supported. Another problem is the consistency of the geometry created. The requirements for the application of a 3D model are indeed given, but because of the low information content the model does not guarantee a mistake-free wire frame presentation (Grätz 1989).

Surface-oriented systems are able to generate objects, known as free-form surfaces, whose surfaces are made up of numerous curved and analytically indescribable surfaces. One feature visible in an internal computer representation of free-form surfaces is their interpolated or approximated nature. Therefore, various processes have been developed, such as the Bézier approximation, Coon's surfaces, the NURBS representations, and the B-spline interpolation (see Section 4.1).

As with all other models, the computer internal representation of an object implies characteristic methods and techniques used in generating free-form surfaces. In general, basis points and boundary conditions are required for the surface description. Free-form surfaces, such as the one portrayed in Figure 2, can be generated using a variety of techniques. A few examples for the generation of free-form surfaces will be described later.

In addition to the simple color-shaded representations, photorealistic model representations may be used for the review and examination of designs. The models are portrayed and used in a reality-like environment and are supported by key hardware components. This allows for the consideration of various environmental conditions such as type and position of the light source, the observer's position and perspective, weather conditions, and surface characteristics such as texture and reflectivity. Also, animation of the object during design is possible for the review of movement characteristics. Through these visualization methods it is possible to assess a product's design before prototype production begins and aid the preparation of sales brochures and other documents.

A characteristic feature and major disadvantage of surface models is the fact that the surfaces are not automatically correlated to form a body. This has important consequences for the designer. It results in a distinct modeling technique for the user that offers only limited functionality with regard to realization of the design tasks. For example, from the outset it is not defined whether a surface should face the inside or the outside of the object. Therefore, the designer must be careful to ensure a closed and complete model during design phases. Intersections are not recognizable by the system

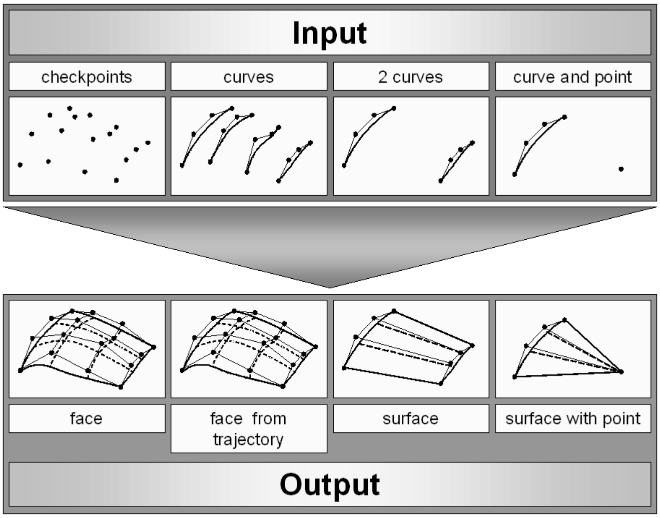

Figure 2 Modeling Processes for Free-Form Surfaces.

because of missing information describing the solid during cutting operations. The intersections are represented only by contour lines that are interactively hatched.

Surface models are applied when it is necessary to generate a portrait of free-formed objects. Such models are used in the automobile, shipbuilding, and consumer goods industries, for example. The surface formations of the model, which are distinguished into functional and esthetic surfaces, can be used as ground-level data for various applications employed later on. This includes later applications such as the generation of NC data from multiaxis processing. Another area of application is in FEM analysis, where the surface structure is segmented into a finite element structure that is subsequent to extensive mechanical or thermal examinations. With surface models, movement simulations and collision analyses can be carried out. For example, mechanical components dependent on each other can be reviewed in extreme kinematic situations for geometrical overlapping and failure detection.

2.1.2.2. Solid Modeling A very important class of 3D modelers is generated by the volume systems. The appropriate internal computer representation is broken down into either boundary representation models (B-reps) or Constructive Solid Models (CSGs). The representation depends on the basic volume modeling principles and the deciding differences between the 3D CAD system classes.

Volume modelers, also known as solid modelers, can present geometrical objects in a clear, consistent, concise manner. This provides an important advantage over previously presented modeling techniques. Because each valid operation quasi-implicitly leads to a valid model, the creativity of the user is supported and the costly verification of geometric consistency is avoided.

The main goal of volume modeling is the provision of fundamental data for virtual products. This data includes not only the geometry but also all information gathered throughout the development process, which is then collected and stored in the form of an integrated product model. The information allows for a broad application base and is available for later product-related processes. This includes the preparation of drawings, which consumes a large portion of the product development time. The generation of various views takes place directly, using the volume model, whereby the formation of sections and the blending out of hidden lines occurs semiautomatically.

Normally, volume models are created using a combination of techniques. The strengths of the 3D volume modeling systems lie in the fact that they include not only the complete spectrum of well-known modeling techniques for 2D and 3D wire frames and 3D surface modeling but also the new, volume-oriented modeling techniques. These techniques contribute significantly to the reduction of costly input efforts for geometrically complex objects.

The volume model can be built up by linking basic solid bodies. Therefore, another way of thinking is required in order to describe a body. The body must be segmented into basic bodies or provided by the system as basic elements (Spur and Krause 1984). Each volume system comes with a number of predefined simple geometrical objects that are automatically generated. The objects are generated by a few descriptive system parameters. Spheres, cubes, cones, truncated cones, cylinders, rings, and tetrahedrons are examples of the basic objects included in the system.

Many complex components can be formed from a combination of positioning and dimensioning of the basic elements.

Complex components are created in a step-by-step manner using the following connecting operations:

- Additive connection (unification)
- Substractive connection (differential)
- Section connection (average)
- Complementing

These connections are known as Boolean or set-theoretical operations. For object generation using Boolean operations, the user positions two solids in space that touch or intersect one another. After the appropriate functions are called up (unification, average, complementing, or differential), all further steps are carried out by the system automatically and then present the geometrical object.

The sequence of the operations when the set-theoretical operations are applied is of decisive importance. Some CAD systems work with terms used for manufacturing techniques in order to provide the designer with intuitive meanings. This allows for the simple modeling of drilling, milling, pockets, or rounding and chamfering. This results because each process can be represented by a geometrical object and further defined as a tool. The tool is then defined in Boolean form and the operation to perform the removal of material from the workpiece is carried out. To correct the resulting geometry, it is necessary that the system back up the complete product creation history. This is required to make a step by step pattern that can be followed to return the set-theoretical operations to their previous forms.

Set-theoretical operations provide an implementation advantage where complex model definitions must be created with relatively few input commands. These definitions are, if even realizable, extremely costly and time consuming by conventional methods. The disadvantage is that a relatively high conceptual capability is required of the user.

Solid models with a number of free-form surfaces are realized using surface-oriented modeling techniques that correspond to the surface model presented. With one of these techniques, *sweeping,* one attains a 3D body through an intermediate step when creating a 2D contour. The 2D contour is expanded to three dimensions along a set curve. The desired contours are generated with known 2D CAD system functions and are called up as bases for sweep operations.

In rotational sweeping, objects are generated through the rotation of surfaces, as well as closed or open, but restricted, contour lines around a predefined axis. The axis may not cut the surface or contour. A prismatic body originates from the expansion of a closed contour line. Shells or full bodies can be generated with sweep operations. With sweep-generated shells, movement analysis and assembly inspection can occur. The analysis takes place by the bodies' movement along a curve in space.

The modeling strategy implemented depends heavily on the actual task and the basic functionality offered by the CAD system. This means that the strategy implemented cannot be arbitrarily specified, as most CAD systems have a variety of alternative approaches within the system. For the user, it is important that a CAD system offer as many modeling methods as possible. Modeling, such as surface and solid modeling, is important, and the ability to combine and implement these methods in geometrical models is advantageous to the user. Because of the numerous modeling possibilities offered, the CAD system should have as few restrictions as possible in order to allow the user to develop a broad modeling strategy. Figure 3 shows a surface-oriented model of a bumper that was created using a simple sweep operation of a spline along a control curve. Using a variable design history, the air vent may be positioned anywhere on the bumper's surface without time-consuming design changes during modeling. The cylindrical solid model that cuts and blends into the surface of the bumper demonstrates that no difference exists between a solid and surface model representation. Both models may be hybridized within components. A CAD system supporting hybridized modeling creates a major advantage because the designer realizes a greater freedom of design.

2.1.3. Parametrical Design

Another development in CAD technology is parametrical modeling (Frei 1993). The function of parametrical systems displays basic procedure differences when compared to conventional CAD systems. The principal modeling differences were explained in the section on parametrical 2D CAD systems.

In parametrical model descriptions, the model can be varied in other areas through the selection and characterization of additional constraints.

Boundary conditions can be set at the beginning of the design phase without fixing the final form of the component. Therefore, generation of the geometry takes place through exact numerical input and sketching. The designer can enter the initial designs, such as contour, using a 2D or 3D sketcher. In this manner, geometrical characteristics, such as parallel or perpendicular properties, that lie within

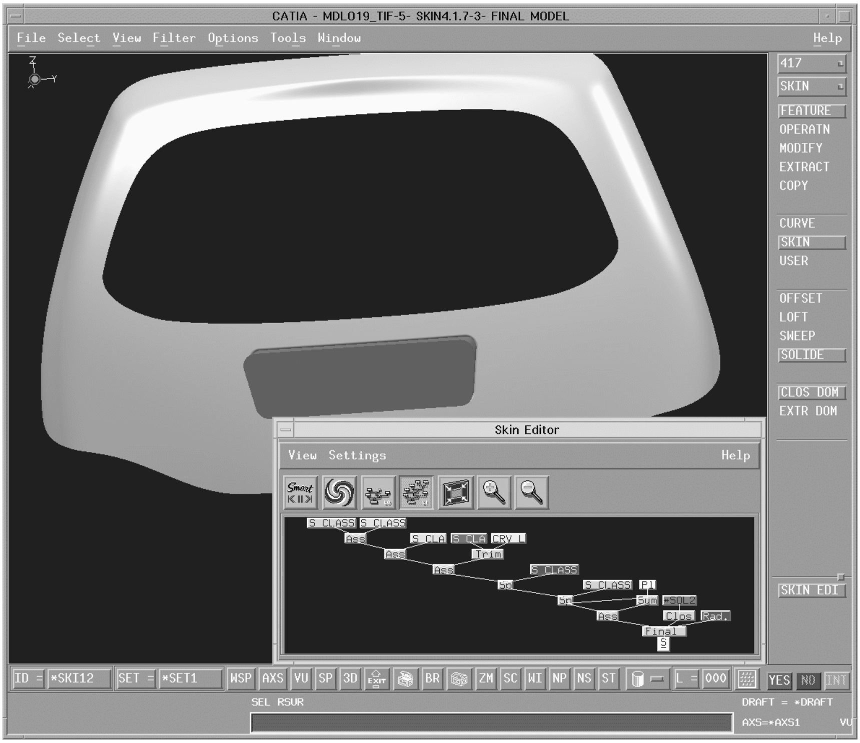

Figure 3 Hybrid Surface and Solid Model. (CATIA System, Dassault Systèmes)

set tolerances are automatically and correctly recognized. The characteristics may also be set through predetermined constraints. Subsequently, the user can develop the initial dimensions using operations that essentially resemble those of conventional measurement determination. Through associativity, the adaptation of the model presented takes places automatically.

Beginning with the first contour sketches, the designer attains the desired solid object through further modeling using operations such as sweeping. The design history is of great importance at this point of the development process. The history can subsequently be modified, influencing the geometry of the model. Because of the associative relationship between the dimensioning and the solid model, the geometry of a component is easily varied in every design phase. Based on the parametrical method implemented, the designer can define conditions for parallel, tangential, or perpendicularity characteristics. Also, complex parametrical dependencies from the system can be solved simultaneously using nonlinear equations.

Because of the parametrical relationships created in the background of the process, the user is in a position to modify the dimensions and topology of the geometry later in the project. Costly reworking of the model due to changes of the boundary conditions is avoided.

Complete process chains may be built up associatively. Downstream activities, including drawing creation and detailing, make up a large percentage of the design time. Here the generation of various views directly from the existing solid model may take place because the formation of sections and the blending out of hidden lines occurs automatically. The main advantage of this approach over previous CAD systems is due to the above-mentioned preservation of the bidirectional relationship between the solid model and the drawing derived from the model. This associative connection allows the designer to take geometrical modifications directly from a drawing, even if the designer has progressed substantiality into the detailing phase. Conversely, changes to the solid model are automatically reflected in the drawing.

The effect and the functionality of the parametric concepts do not end with the completion of the geometry. Rather, they are encompassed in all areas of product development. Solid modeling, calculations, drawing preparation, NC programming, simulation, and documentation are connected together in an associative chain so that modifications made in one area automatically take place in the other areas.

For the designer, it is important that both parametric and nonparametric geometry can be combined and implemented during the development of a component. Therefore, complex components must not be completely described parametrically. The designer decides in which areas it is advantageous to present the geometry parametrically.

2.1.4. Feature Technology

Most features in commercial CAD systems are built upon a parametrical modeler. The ability to define one's own standard design elements also exists. These elements can be tailored to the designer's way of thinking and style of expression. The elements are then stored in a library and easily selected for implementation in the design environment. Additional attributes such as quantity, size, and geometrical status can be predetermined to create logical relationships. These constraints are then considered and maintained with every change made to an element. An example of a design feature is a rounding fillet. The fillet is selected from the features library and its parameters modified to suit the required design constraints.

The library, containing standard elements, can be tailored to the user's requirements for production and form elements. This ensures consistency between product development and the ability to manufacture the product. Therefore, only standard elements that match those of available production capabilities are made available. Feature definition, in the sense of concurrent engineering, is an activity in which all aspects of product creation in design, production, and further product life phases are considered.

In most of today's commercially available CAD systems, the term *feature* is used mainly in terms of form. Simple parametric and positional geometries are made available to the user. Usually features are used for complicated changes to basic design elements such as holes, recesses, and notches. Thus, features are seen as elements that simplify the modeling process, not as elements that increase information content. With the aid of feature modeling systems, user-defined or company-specific features can be stored in their respective libraries. With features, product design capabilities should be expanded from a pure geometric modeling standpoint to a complete product modeling standpoint. The designer can implement fully described product parts in his or her product model. Through the implementation of production features, the ability to manufacture the product is implicitly considered. A shorter development process with higher quality is then achieved.

By providing generated data for subsequent applications, features represent an integration potential.

2.1.5. Assembly Technology

Complex products are made up of numerous components and assemblies. The frequently required design-in-context belongs to the area of assembly modeling. Thereby, individual parts that are relevant to the design of the component are displayed on the screen. For instance, with the support of EDM functionality, the parts can be selected from a product structure tree and subsequently displayed. The part to be designed is then created in the context already defined. If the assembly is then worked on by various coworkers, the methods for shared design are employed. For example, changes to a component can be passed on to coworkers working on related and adjacent pieces through system-supported information exchange.

An example of a complex assembly in which shared design processes are carried out is the engine in Figure 4. The goal is to be able to build and then computer analyze complex products. The assembly modeling will be supported by extensive analysis and representation methods such as interference checks as well as exploded views and section views.

Besides simple geometrical positioning of the component, assembly modeling in the future will require more freedom of modeling independent of the various components. Exploiting the association between components permits changes to be made in an assembly even late in the design phase, where normally, because of cost and time, these modifications must be left out. Because the amount of data input for assemblies and the processing time required to view an assembly on the screen are often problematic, many systems allow a simplified representation of components in an assembly, where suppression of displaying details is possible. But often the characteristics of simplified representation are to be defined by the user. It is also possible for the CAD system to determine the precision with which the component is displayed, depending on the model section considered. Zooming in on the desired location then provides a representation of the details.

A representation of the assembly structure is helpful for the modeling of the assembly. Besides the improved overview, changes to the assembly can be carried out within the structure tree and parts lists are also easily prepared.

The combination of assemblies as a digital mock-up enables control over the entire structure during the design process. Thereby, interference checks and other assembly inspections are carried out using features that make up the so-called packaging analyses of the software. For the check of collision, voxel-based representations are suitable as well. Importing and portraying assemblies from other CAD systems is also advantageous. This is possible with the creation of adequate interfaces.

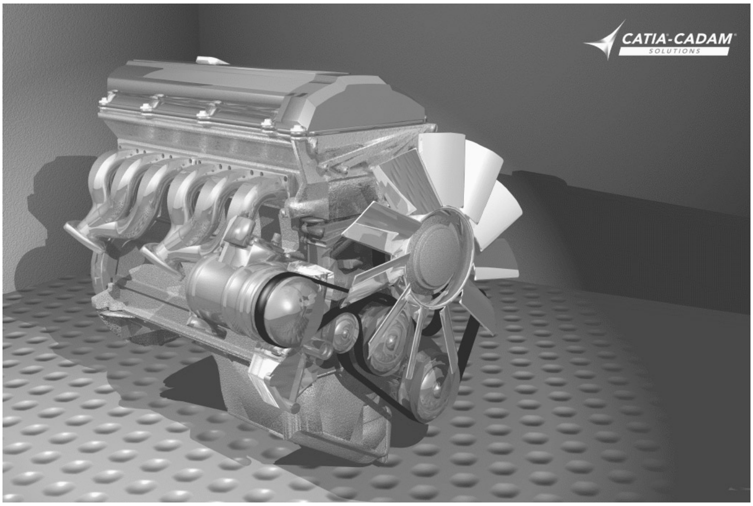

Figure 4 An Engine as a Complex Assembly. (CATIA System, Dassault Systèmes)

An important functionality in assembly modeling is the definition of geometric and functional tolerances that are supported by the respective CAD module (Figure 5). Thereby, the geometrical and functional tolerance definitions are carried out based on assembly specifications and international standards. Special analysis functions are utilized for the control of complex assemblies and products.

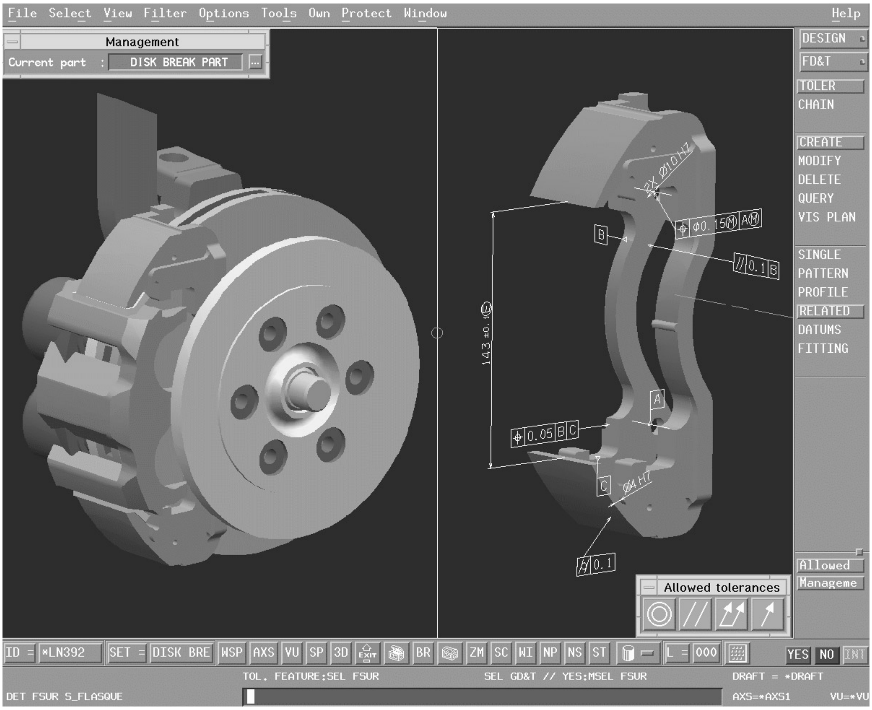

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Figure 5 Definition of Tolerances in an Assembly. (CATIA System, Dassault Systèmes)

For example, the fly-through function allows the user to navigate in real time through complex assemblies. This enables visual inspections, which among other things, help in the recognition of component interference.

The design of complex assemblies requires sharing of the design processes through teamwork. This shared group work is supported by software that enables conferences over the Internet/intranet in which text, audio, and video information may be exchanged.

2.1.6. Further Technologies

Further applications in the process chain of product development can be carried out based on the 3D models created in early phases. For example, most commercial CAD systems are composed of modules and are implemented for the realization of a geometric model and other development-oriented solutions. Because the CAD systems are compatible with one another, an unhindered exchange of data is possible right from the beginning of the design through production stages. The systems must meet the requirements for continuity and openness, which are indispensable for the development of complex products. Continuity means that the product data are entered only once. They are saved in a central location and are available for use in carrying out other tasks without extensive conversion being required between the various forms of data. Openness means that, besides the ability to process data on various hardware platforms, it is possible to connect with other program systems within the same company and to external sites such as suppliers and other service providers. Further differentiation results from homogeneous and heterogeneous system environments. Using a common database for the application modules, for example in STEP format, means that conversion or interface problems between the individual applications are avoided. External application programs and data exchange between the purchaser and the supplier are simplified by the use of data exchange formats such as IGES, SET, and VDAFS. A uniform user interface improves the usability and comfort of the user.

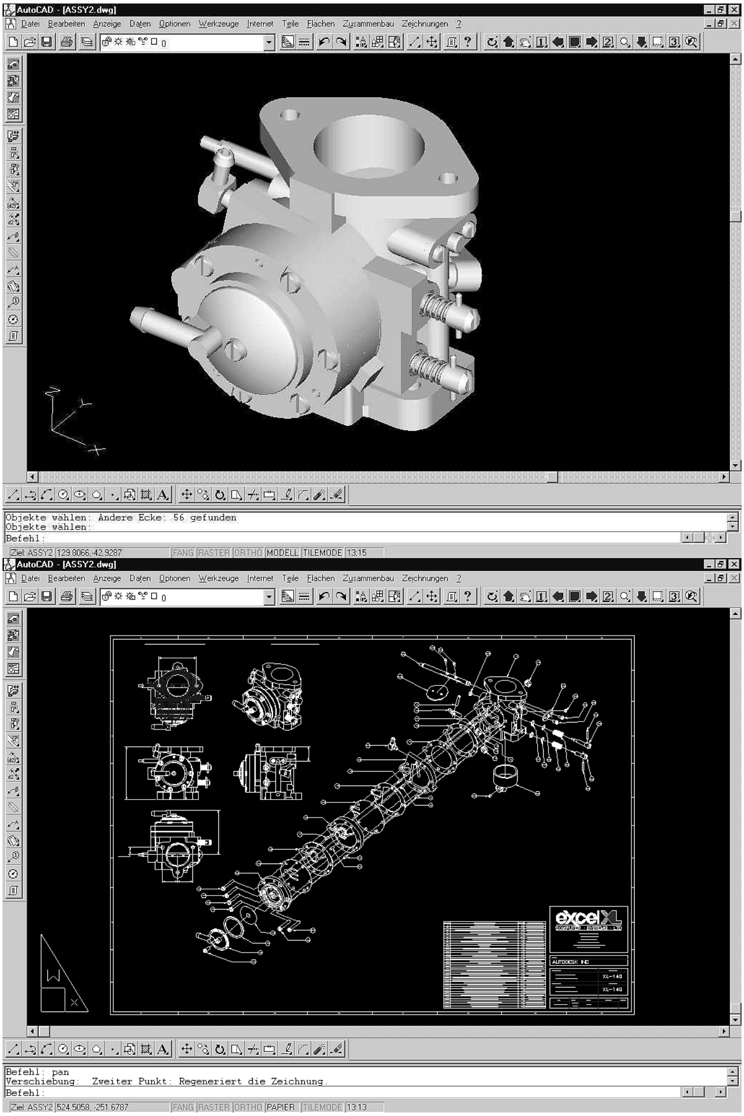
The application modules can be related to the various tasks within the development process. In the various phases of the virtual product development, different modules come into play depending on the task involved. The following principal tasks are presented:

- *Drawing preparation:* Drawings can be derived from the solid model and displayed in various views and measurements (Figure 6). This includes the representation of details as well as component arrangements. For higher work efficiency, it should be possible to switch between the 2D drawing mode and the 3D modeling mode at any time without suffering from conversion time and problems. A further simplification of the work results if the drawing and measurement routines provide and support the drawings in standardized formats, for example.
- *Parts list generator:* The preparation of a parts list is important for product development, procurement, and manufacturing. This list is automatically generated from the CAD component layout drawing. The parts list can then be exchanged through interfaces with PPS systems.
- *Analysis and simulation applications:* Analysis and simulation components enable the characteristics of a product to be attained and optimized earlier in the development phase. The costly and time-consuming prototype production and product development are thereby reduced to a minimum.

The strength characteristics can be calculated with finite element methods (FEMs). Besides stress–strain analyses, thermodynamic and fluid dynamic tests can be carried out. Preprocessors enable automated net generation based on the initial geometric model. Most CAD systems have interfaces for common FEM programs (e.g., NASTRAN, ANSYS) or have their own equation solver for FEM tests. Based on the substantial data resulting from an FEM test, it is necessary for postprocessing of results. The results are then portrayed in deformation plots, color-coded presentations of the stress–strain process, or animations of the deformation.

Material constants, such as density, can be defined for the components of the solid model. Then other characteristics, such as volume, mass, coordinates of the center of gravity, and moment of inertia can be determined. These data are essential for a dynamic simulation of the product. For kinematic and dynamic simulations, inelastic solid elements with corresponding dynamic characteristics are derived from the solid model (Figure 7). Various inelastic solid elements can be coupled together from a library. The complete system is built up of other elements such as a spring and damper and then undergoes a loading of external forces. The calculation of the system dynamics is usually carried out using a commercial dynamics package. A postprocessor prepares a presentation of the results for display on a screen. An animation of the system can then be viewed.

- *Piping:* Piping can be laid within the 3D design using conduit application modules, as shown in Figure 8. Design parameters such as length, angle, and radius can be controlled. Intersections or overlapping of the conduit with adjacent assemblies can also be determined and repaired. The design process is supported through the use of libraries containing standard piping and accessories. The parts lists are automatically derived from the piping design.



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Objekte wählen:
Befehl:
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Befehl: pan
Verschiebung:  Zweiter Punkt: Regeneriert die Zeichnung.
Befehl:
```

Figure 6 3D Model and the Drawing Derived from the Model. (AutoCAD System. Reproduced with permission of Autodesk®)

- *Weld design:* Weld design can also be supported by using appropriate application modules (Figure 9). Together, designers and production engineers can determine the required joining techniques and conditions for the assemblies. Thereby, the weld type and other weld parameters such as weld spacing and electrodes are chosen for the material characteristics of the components to be joined. Process information such as weld length and cost and time requirements can be derived from the weld model.
- *Integration of ECAD design:* The design of printed circuit boards and cable layouts are typical application examples of 2D designs that are related to the surrounding 3D components. With the design of printed circuit boards, layout information, such as board size and usable and unusable area, can be exchanged and efficiently stored between and within the MCAD and ECAD systems. For the design of cable layouts (Figure 10), methods similar to those used for conduit design are implemented. This simplifies the placement of electrical conductors within assemblies.

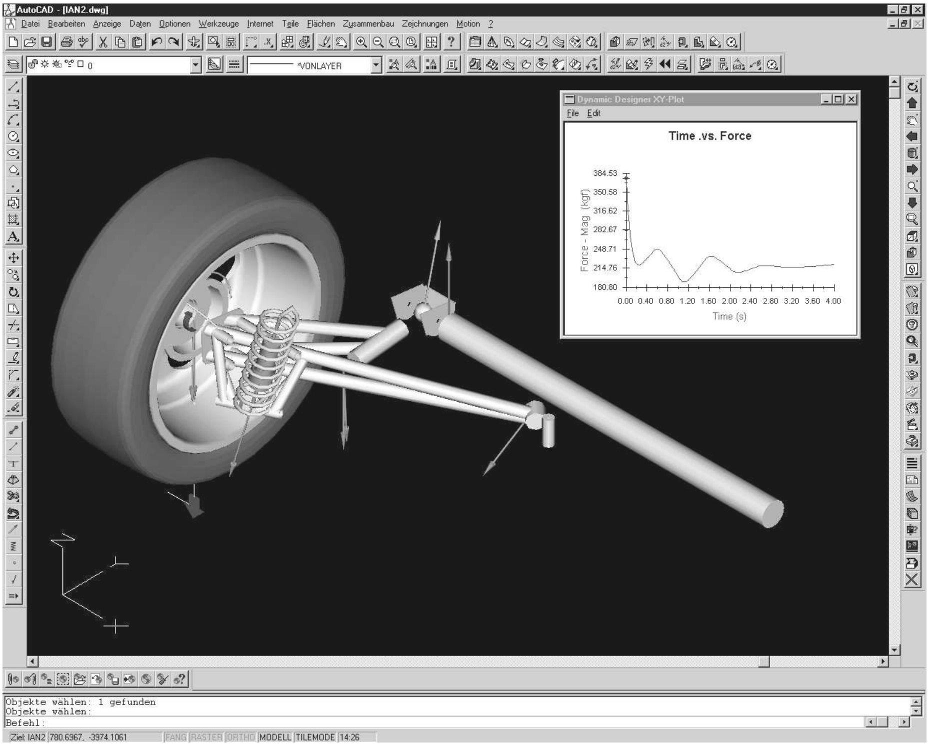

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Figure 7 Kinematic Simulation of a 3D Model. (System AutoCAD. Reproduced with permission of Autodesk®)

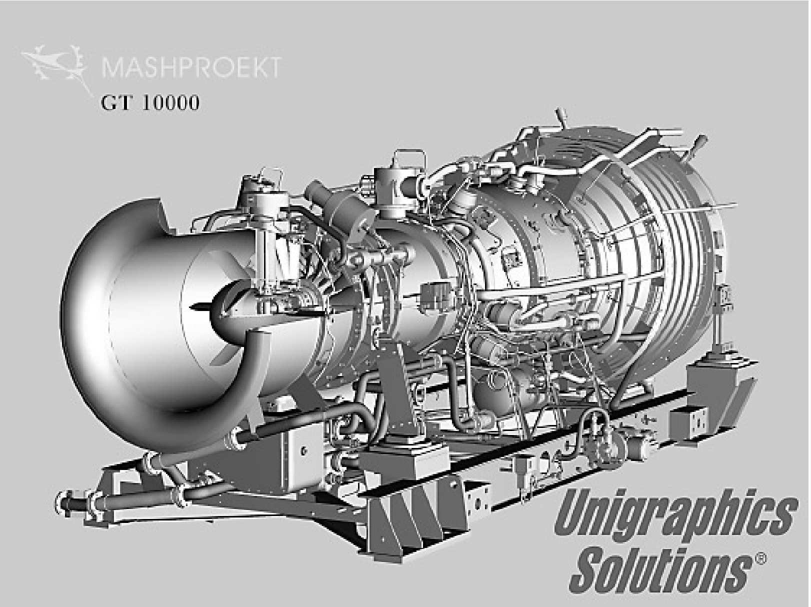


Figure 8 Pipe Laying in a 3D Assembly. (Unigraphics. Reproduced with permission of Unigraphics Solutions)

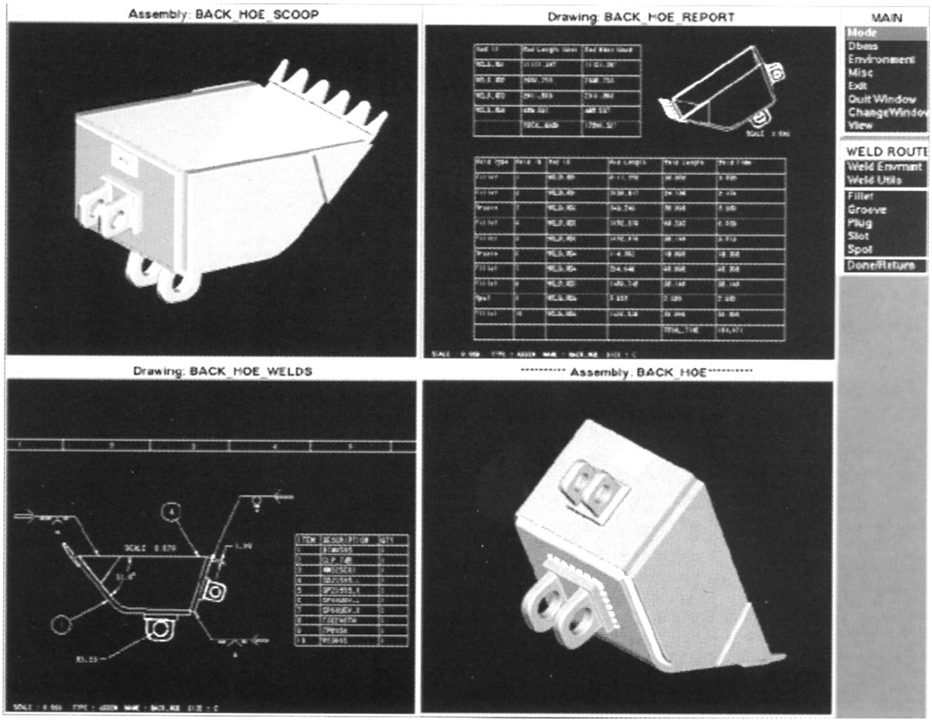


Figure 9 Example of a Weld Design. (System Pro/WELDING, PTC) Reprinted by permission of PTC.

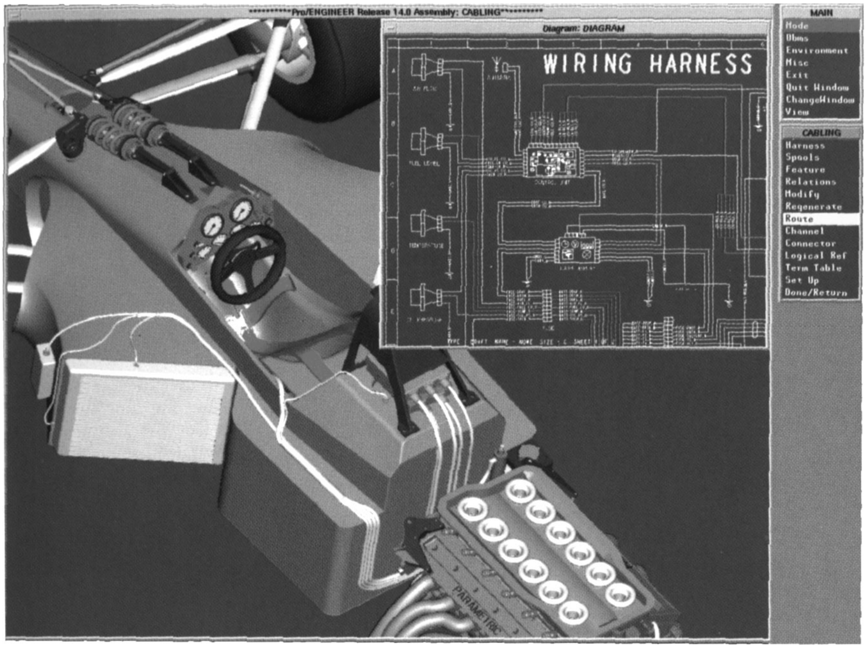


Figure 10 2D Design of a Wiring Harness. (Pro/DIAGRAM System, PTC) and Parametric Cable Layout in the 3D Assembly. (Pro/CABLING, PTC) Reprinted by permission of PTC.

- *Integration of process planning:* Product data can be taken directly from production planning. The machine tool design and planning can take place parallel to the design of the product. NC programs and control data can be derived from the finished 3D description of the geometry, although the model requires supplemental information for mountings and other devices. The tool paths are determined under consideration of the additional technical information of the different processes, such as drilling, milling, turning, eroding, and cutting. The generation of NC data in diverse formats, such as example COMPACT II, CLDATA, and APT, is carried out using a postprocessor. The NC programs derived from an optimized design can be checked by simulation.

  In addition to the three- and five-axis milling machines used for conventional production tasks, rapid prototyping processes are applied for quick design verification. For example, the process of stereo lithography can be applied. Rapid prototyping reduces the period of development and allows for the quick generation of physical prototypes for product review and evaluation purposes. A variety of materials, from plastics to metals, are used in rapid prototyping, enabling the prototypes to be presented in the most frequently used materials so that material characteristics can be easily reviewed (Gebhardt and Pflug 1995). The control data for the laser stereo lithography are generated from the geometry data.

  When molds for injection molding are made, die geometry is taken into consideration because of the possibility of material shrinkage. Rheological calculations are carried out using preprocessors (e.g., Moldflow, Cadmould 3D). The set-up of the tools takes place using catalogs provided by the machine manufacturer. Subsequently, NC data are generated for the part shape and machining plates.

  With complete product models, simulation and robot programming can take place for the various manufacturing processes. The programming and simulation take place offline. The programs generated are then sent on to the robots for execution of the process.

Only through comprehensive integration of the complete virtual product development process, with the many different working steps, can the existing potential for development time, costs, and overall productivity be optimized (VDI-EKV 1992, Krause 1992).

2.2. CAD Interfaces

2.2.1. General Explanations

Despite the lack of a clear definition for the term *interface,* its use has become quite frequent. In general, an interface can be defined as a link forming a common boundary between integrating systems. It is a system of conditions, rules, and agreements that defines the terms of information exchange between communicating systems or system components (Anderl 1993).

CAD interfaces interconnect internal CAD system components and provide a link to other software and hardware components. They connect internal CAD system components such as geometrical modeling, object representation, and realization of calculation operations to a CAD database and standardized CAD files.

CAD interfaces can be classed as device interfaces (hardware interfaces) and software interfaces (Grabowski and Anderl 1990) or, alternatively, as internal and external interfaces. Internal interfaces provide links within the application environment, enabling the exchange of information between other system programs or ensuring undisturbed communication with the user. External interfaces require a common or uniform representation of the information to be exchanged. They transmit product data, by means of graphical peripheries, to the user. The standardization of external interfaces is of special importance for the transmission of product data. Because of the exchange of data between various CAD systems, uniform data formats are required.

In Figure 11, CAD components and interfaces are displayed.

From an application in use, access to the product data and methods of a CAD system is provided through application interfaces. In the course of using a CAD system through a standardized interface, the integration of such an external application interface becomes increasingly important. Standardized application interfaces allow access to the methods employed by the various CAD systems.

Product data represent all data such as geometry, topology, technological information and organizational data to define the product. This data is generated during the design process, enhanced by the application and then internally mapped.

2.2.2. Standardization of CAD Interfaces

The primary objectives for the standardization of interfaces are:

- The unification of interfaces
- The prevention of dependencies between system producer and user
- The prevention of repeated working of redundant data

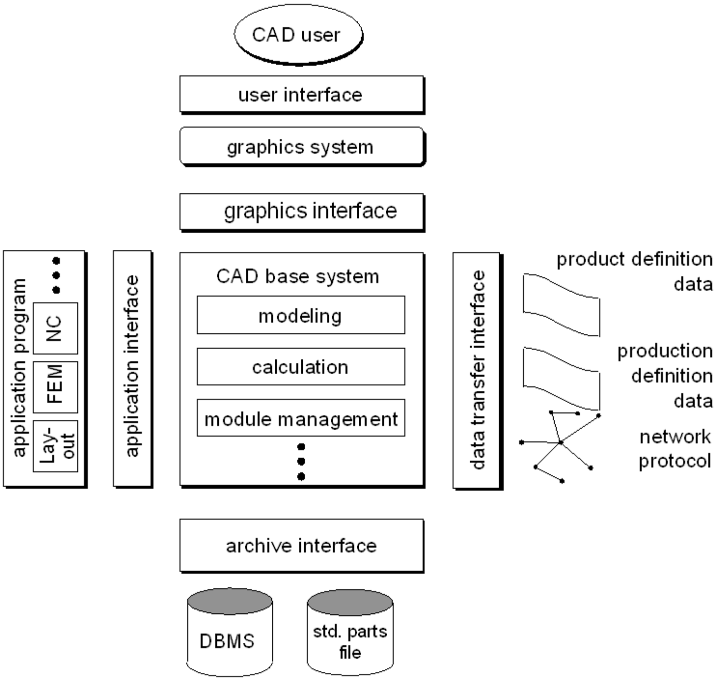


Figure 11 CAD Components and Interfaces.

The standardization of interfaces leads to the following advantages (Stanek 1989):

- The possibility of an appropriate combination of system components
- Selection between various systems
- Exchange of individual components
- Expandability to include new components
- Coupling of various systems and applications
- Greater freedom in the combining of hard and software products

2.2.2.1. Interfaces for Product Data Exchange The description of product data over the entire product life cycle can be effectively improved through the use of computer-supported systems. For this reason, uniform, system-neutral data models for the exchange and archiving of product data are desired. These enable the exchange of data within CAD systems and other computer-aided applications.

The internal computer models must be converted into one another through so-called pre- and postprocessor conversion programs. To minimize the costs of implementing such processors, a standardized conversion model is applied. The conversion models standardized to date are still of limited use because they can only display extracts of an integrated product model. Interfaces such as

- initial graphics exchange specification (IGES)
- standard d'echange et de transfert (SET)
- Verband der Automobilindustrie-FlächenSchnittstelle (VDA-FS)

have been designed and to some extent nationally standardized for geometry data exchange, mainly in the area of mechanical design (Anderl 1989).

IGES is recognized as the first standardized format for product-defined data to be applied industrially (Anderl 1993; Grabowski and Anderl 1990; Rainer 1992). The main focus is the transfer of design data. IGES is for the mapping of:

- 2D line models
- 3D wire models
- 3D dimensional surface models
- 3D solid models
- Presentation models for technical drawings

Considering the further demands on CAD/CAM systems, the integration of additional data in IGES format has been realized. Examples are the data for FEM, factory planning, and electronic/electrical applications.

The interface standard VDA-FS was developed by the German Automotive Industry Association for the transfer of CAD free-form surface data. VDA-FS is standardized and described in Standard DIN 66301 and has proven efficient for use in many areas, but its efficiency has been demonstrated principally in the German automotive industry (Grabowski and Glatz 1986; Nowacki 1987; Scheder 1991).

The STEP product model (Standard for the Exchange of Product Model Data) offers the only standardized possibility for efficiently forming the product data exchange and system integration in the CAx world (Wagner and Bahe 1994).

With the development of ISO 10303 (Product Data Representation and Exchange), also called STEP, the objective is to standardize a worldwide accepted reference model for the transfer, storage and archiving, and processing of all data needed for the entire product life cycle (Anderl 1993; Düring and Dupont 1993; Krause et al. 1994; McKay et al. 1994).

STEP can be seen as a toolbox for describing application-oriented product information models using basic elements, so-called integrated resources, while considering previously defined rules and standardized methods (Holland and Machner 1995).

ISO 10303 can be subdivided into:

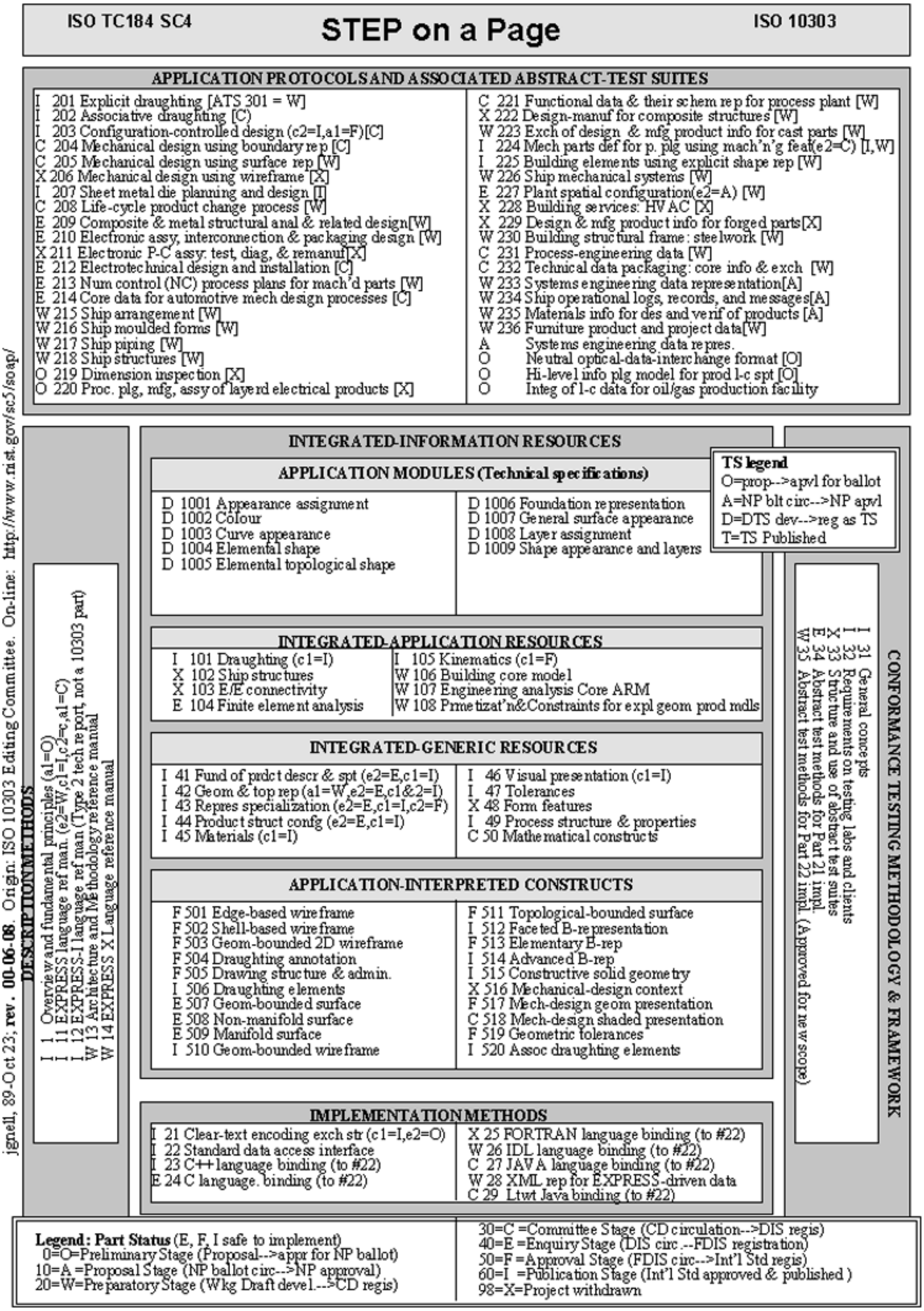
- Generic and application-oriented information models
- Application protocols
- Methods for specification and implementation
- Concepts for examination and testing

Independent application specifications are referred to as generic models. An overview of the series is as follows (Figure 12):

- Series 0: fundamentals, principles
- Series 10: description or specification methods
- Series 20: implementation methods
- Series 30: test methods and criterion
- Series 40: application-independent base models
- Series 100: application-dependent base models
- Series 200: application protocols
- Series 300: abstract test methods
- Series 500: application-specific, interpreted design

The core of consists of information models in which the representational form of the product data is defined. Information models can be broken down into three categories: generic resources, application-related resources, and application protocols. Similar to a toolbox system, the generic resource models define application-independent base elements that may be used in application-specific resources or directly in application protocols. An example is geometrical information, which is required in most application models. Application-related resources are especially tailored to the demands of specific branches but also serve for the definition of application protocols. Application protocols form implementable parts for STEP. They define a section of the information structure that is needed to support a specified application.

The description methods used for defining the information structure, validation, and test methods as well as implementation methods are standardized. The object-oriented modeling language EXPRESS as well as its graphical form EXPRESS-G are implemented for the presentation of the information structures (Scholz-Reiter 1991). Validation and test methods define the specifications with which the STEP processors are examined. The following elements are included in partial models of the generic resources:



ISO TC184 SC4 **STEP on a Page** ISO 10303

APPLICATION PROTOCOLS AND ASSOCIATED ABSTRACT-TEST SUITES

I 201 Explicit draughting [ATS 301 = W]
I 202 Associative draughting [C]
I 203 Configuration-controlled design (c2=I,a1=F)[C]
C 204 Mechanical design using boundary rep [C]
C 205 Mechanical design using surface rep [W]
X 206 Mechanical design using wireframe [X]
I 207 Sheet metal die planning and design [I]
C 208 Life-cycle product change process [W]
E 209 Composite & metal structural anal & related design[W]
E 210 Electronic assy, interconnection & packaging design [W]
X 211 Electronic P-C assy: test, diag, & remanuf[X]
E 212 Electrotechnical design and installation [C]
E 213 Num control (NC) process plans for mach'd parts [W]
E 214 Core data for automotive mech design processes [C]
W 215 Ship arrangement [W]
W 216 Ship moulded forms [W]
W 217 Ship piping [W]
W 218 Ship structures [W]
O 219 Dimension inspection [X]
O 220 Proc. plg, mfg, assy of layerd electrical products [X]
C 221 Functional data & their schem rep for process plant [W]
X 222 Design-manuf for composite structures [W]
W 223 Exch of design & mfg product info for cast parts [W]
I 224 Mech parts def for p. plg using mach'n'g feat(e2=C) [I,W]
I 225 Building elements using explicit shape rep [W]
W 226 Ship mechanical systems [W]
E 227 Plant spatial configuration(e2=A) [W]
X 228 Building services: HVAC [X]
X 229 Design & mfg product info for forged parts[X]
W 230 Building structural frame: steelwork [W]
C 231 Process-engineering data [W]
C 232 Technical data packaging: core info & exch [W]
W 233 Systems engineering data representation[A]
W 234 Ship operational logs, records, and messages[A]
W 235 Materials info for des and verif of products [A]
W 236 Furniture product and project data[W]
A Systems engineering data repres.
O Neutral optical-data-interchange format [O]
O Hi-level info plg model for prod l-c spt [O]
O Integ of l-c data for oil/gas production facility

DESCRIPTION METHODS

I 1 Overview and fundamental principles (a1=O)
I 11 EXPRESS language ref man. (e2=W,c1=I,c2=c,a1=C)
I 12 EXPRESS-I language ref man (Type 2 tech report, not a 10303 part)
W 13 Architecture and Methodology reference manual
W 14 EXPRESS X Language reference manual

INTEGRATED-INFORMATION RESOURCES

APPLICATION MODULES (Technical specifications)

D 1001 Appearance assignment
D 1002 Colour
D 1003 Curve appearance
D 1004 Elemental shape
D 1005 Elemental topological shape
D 1006 Foundation representation
D 1007 General surface appearance
D 1008 Layer assignment
D 1009 Shape appearance and layers

TS legend
O=prop-->apvl for ballot
A=NP blt circ-->NP apvl
D=DTS dev-->reg as TS
T=TS Published

INTEGRATED-APPLICATION RESOURCES

I 101 Draughting (c1=I)
X 102 Ship structures
X 103 E/E connectivity
E 104 Finite element analysis
I 105 Kinematics (c1=F)
W 106 Building core model
W 107 Engineering analysis Core ARM
W 108 Prmetizat'n&Constraints for expl geom prod mdls

INTEGRATED-GENERIC RESOURCES

I 41 Fund of prdct descr & spt (e2=E,c1=I)
I 42 Geom & top rep (a1=W,e2=E,c1&2=I)
I 43 Repres specialization (e2=E,c1=I,c2=F)
I 44 Product struct confg (e2=E,c1=I)
I 45 Materials (c1=I)
I 46 Visual presentation (c1=I)
I 47 Tolerances
X 48 Form features
I 49 Process structure & properties
C 50 Mathematical constructs

APPLICATION-INTERPRETED CONSTRUCTS

F 501 Edge-based wireframe
F 502 Shell-based wireframe
F 503 Geom-bounded 2D wireframe
F 504 Draughting annotation
F 505 Drawing structure & admin.
I 506 Draughting elements
E 507 Geom-bounded surface
E 508 Non-manifold surface
E 509 Manifold surface
I 510 Geom-bounded wireframe
F 511 Topological-bounded surface
I 512 Faceted B-representation
F 513 Elementary B-rep
I 514 Advanced B-rep
I 515 Constructive solid geometry
X 516 Mechanical-design context
F 517 Mech-design geom presentation
C 518 Mech-design shaded presentation
F 519 Geometric tolerances
I 520 Assoc draughting elements

IMPLEMENTATION METHODS

I 21 Clear-text encoding exch str (c1=I,e2=O)
I 22 Standard data access interface
I 23 C++ language binding (to #22)
E 24 C language. binding (to #22)
X 25 FORTRAN language binding (to #22)
W 26 IDL language binding (to #22)
C 27 JAVA language binding (to #22)
W 28 XML rep for EXPRESS-driven data
C 29 Ltwt Java binding (to #22)

CONFORMANCE TESTING METHODOLOGY & FRAMEWORK

I 31 General concepts
I 32 Requirements on testing labs and clients
X 33 Structure and use of abstract test suites
E 34 Abstract test methods for Part 21 impl.
W 35 Abstract test methods for Part 22 impl. (Approved for new scope)

Legend: Part Status (E, F, I safe to implement)
0=O=Preliminary Stage (Proposal-->appr for NP ballot)
10=A =Proposal Stage (NP ballot circ-->NP approval)
20=W=Preparatory Stage (Wkg Draft devel.-->CD regis)
30=C =Committee Stage (CD circulation-->DIS regis)
40=E =Enquiry Stage (DIS circ.--FDIS registration)
50=F =Approval Stage (FDIS circ-->Int'l Std regis)
60=I =Publication Stage (Int'l Std approved & published)
98=X=Project withdrawn

jgnell, 89-Oct 23; **rev. 00-06-08**. Origin: ISO 10303 Editing Committee. On-line: http://www.nist.gov/sc5/soap/

Figure 12 Overview of the ISO 10303 Structure.

- Base model
- Geometric and topological model
- Tolerance model
- Material model
- Product structure model
- Representation model and
- Process model

The significance of STEP goes much further than the exchange and archiving of product models. The innovative character of STEP development sets new standards for CAD systems. The functional requirements for new systems stem from partial models such as tolerance, form/feature, or PSCM models. In certain circumstances, STEP may be considered a reference model for the internal computer representation of CAD systems.

2.3. Engineering Data Management

Engineering data management (EDM, also an abbreviation for electronic document management or enterprise data management) is data modeling of a complete enterprise. In other words, the data modeling goes beyond the intrinsic product data. A common synonym for EDM is ‘‘product data management’’ (PDM), in which emphasis is put on the handling of product-related engineering data. *Engineering data management* was coined as a broader term. All definitions combined provide the perception that EDM is the management and support of all information within an enterprise at any point in time (Ploenzke 1997).

For the support of data modeling within a company, software systems, so-called EDM systems, exist. With these systems, various tasks are carried out depending on the product, company, and level of integration, such as the management of (Kiesewetter 1997):

- Drawing data
- CAD model data
- Parts lists
- Standard libraries
- Project data
- NC data
- Software
- Manufacturing plans
- Tools and equipment production facilities

In addition, EDM systems serve for classification and object parameter management. Generally, EDM systems provide a set of specific functions for the modeling of product and process data. Because of their specific origins, the various EDM systems focus on a variety of main functions and strengths, but all provide a basic functionality for document management as well as functions for the support of change, version, and release management. The complete functionality of an EDM system as a central information system for the product development process is made up of a broad spectrum of functions. These functions can be broken down into application-related and system-overlapping functions (Ploenzke 1997).

- *Application-related functions:* The main priority for an EDM system is the management of all product data and documentation. Application-related functions provide task-specific support of the data management. Classical data management functions such as additions, modifications, and deletions are extended to integrate additional capabilities. For example, in the case of drawing management, automatic extraction of metadata from the CAD drawing header is implemented in the EDM database or used for classification of the components.
- *System-overlapping functions:* Data and document management requires an application-neutral infrastructure that provides functions for an organized handling of the management processes. These overlapping system and application functions support the data and document management through functions created for variant and version management and ensuring the editing status of the document. Also, these functions support the provision of central services such as user management, privacy, and data protection.

Support provided by the use of an EDM system is aimed at the integration of the information flow and processes into the business processes. Integration and transparency are the essential aspects for the EDM system to process every demand and provide the right information at the right time. The storage, management, and provision of all product-related data create the basis for:

- The integration of application systems for technical and commercial processes as well as for office systems in a common database
- The task-oriented supply of all operations with actual and consistent data and documentation
- The control and optimization of business processes

Metadata are required for the administration of product data and documentation, enabling the identification and localization of product data. Metadata represent the information about the creator, the data of generation, the release status, and the repository. The link between all relevant data is made by the workflow object, which is a document structure in which documents of various formats are filled out along a process chain. This structure is equivalent to part of the product structure and, after release, is integrated into the product structure. In general, this is the last step of a workflow.

The modeling and control of a process chain are the task of the workflow management, whereas access control is the task of document management. The users concerned in the workflow are managed by groups, roles and rights. The systems applied are integrated in the EDM system. Linking a special document with the editing system is the responsibility of the document management program.

2.4. Architecture and Components

The reference architecture, from Ploenzke (1997) (Figure 13) describes the individual components of an EDM system from a functional point of view and illustrates the connections between the respective system components.

The core of the reference architecture is the engineering data. The application-oriented and system-overlapping functions are applied to the core data. The engineering data are found within the model data and broken down into product-defined data and metadata. Model data, such as drawing data, parts lists, text files, raster data from document, and data in other formats, are not interpreted by the EDM system but are still managed by the EDM System. Metadata is interpreted by the EDM system and contains information regarding the management and organization of the product data and documents.

The application-oriented functions support the management of the model data. Although the model data may be made up of various kinds of data, the management of these data, with the help of application oriented functions, must be able to summarize the data logically in maps and folders. Also, relationships between the documents and product data can then be determined. Important application-oriented functions are (Ploenzke 1997):

- General data management
- Drawing data management

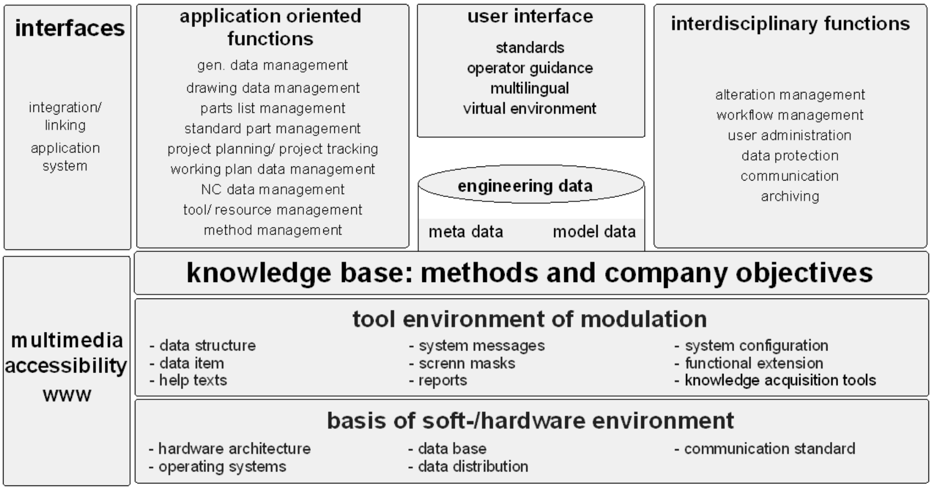


Figure 13 Reference Architecture of an EDM System. (From Ploenzke 1994. Reprinted by permission of CSC Ploenzke.)

- Classification
- Parts list management
- Standard parts management
- Project planning and management
- Production plan management
- NC data management
- Machine tool and equipment management
- Method management

System-overlapping functions support the business processes over numerous steps, such as change and workflow management. Furthermore, central system services such as user management and data security are provided. Important system-overlapping functions are (Ploenzke 1997):

- Change management
- Workflow management
- User administration
- Data security
- Data protection
- Communication
- Archiving

Besides the core components of the reference architecture, the following system components belong to the system environment (Ploenzke 1997):

- User interface
- Machine environment
- Interfaces
- Basic software and hardware environment

The user interface forms the direct interface to the user and thus must provide the look and functions desired by the user. The application environment provides methods for customizing the interface. This allows the adaptation of the EDM system to company-specific conditions and for maintenance of the system. Programming interfaces known as application procedural interfaces (APIs) enable the launching and integration of application modules for the functional extension of an EDM system. The basic software and hardware environment forms the respective operation platform of an EDM system. With the status of the technology today, client–server-based EDM systems come into operation with connecting databases. These provide the various users with the necessary client programs, increasing the economical utilization of today's workstations (Krause et al. 1996).

EDM can also be termed an enabling technology. The reference architecture is an integration platform for systems, functions, and data. Company-specific conditions and a dynamic control process, however, cause the transformation of each EDM system installation into an almost nontransferable case. Nevertheless, the EDM reference architecture forms the basis of system integration for CAD integration, PPS coupling, or archiving, regardless of the company-specific focus.

The necessity for integration and transparency of the data leads to the broad scope of functionality enabled by an EDM system. The primary functions are combined in numerous modules. The level of performance of the individual modules varies from system to system and is determined by the company philosophy and strengths of the supplier (Figure 14).

Many functions that serve for the basic control of data in the EDM already stem from other systems such as CAD or PPS systems. These functions are combined in the EDM system and make feasible the creation and management of an information pool. This supports company-wide availability and enables faster information searches (Figure 15). The information pool, known as the vault, is a protected storage area that enables the availability of all documents and ensures that no unauthorized access occurs. Access to documents held in other systems is possible through logins to the various systems. After logging off, the document is available only in a read-only form. Therefore, logging off copies the document to local memory. Logging in and opening a changed document is associated with the saving of a new version of the document. All customary EDM systems on the market are able to manage a centralized or decentralized vault.

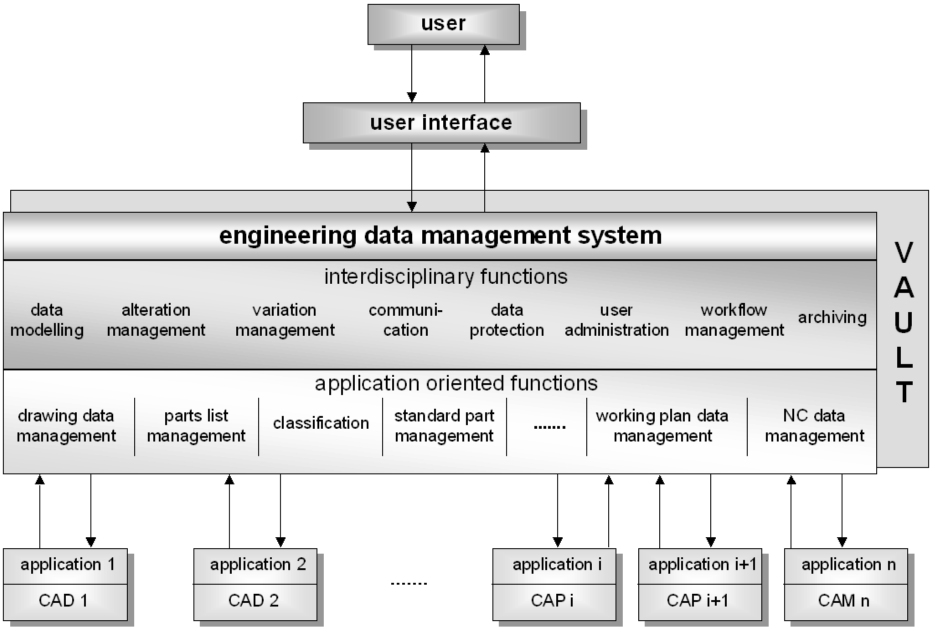


Figure 14 Architecture of an EDM System with Integrated Applications. (From Stephan 1997)

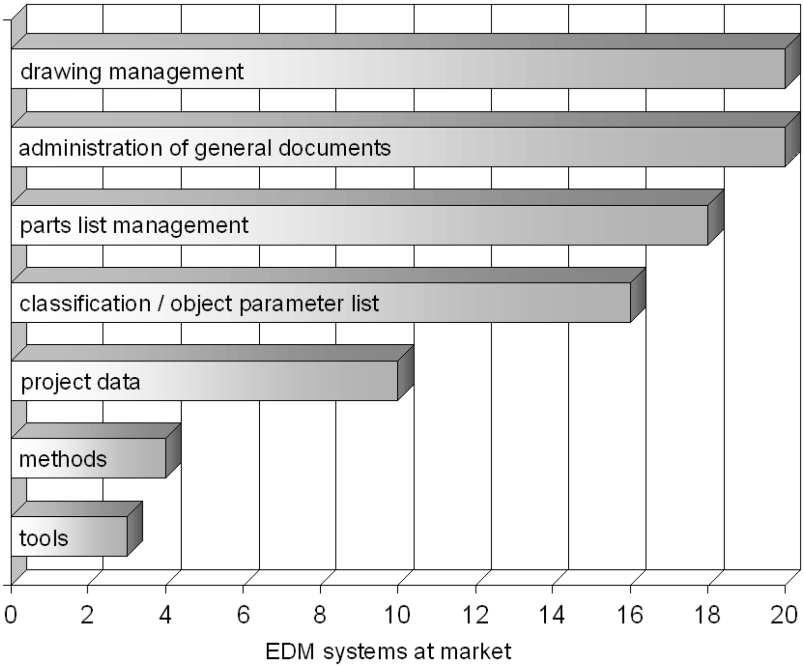


Figure 15 Availability of Function Modules in EDM Systems. (From Ploenzke 1997. Reprinted by permission of CSC Ploenzke.)

2.5. Calculation Methods

2.5.1. General Explanation

Increasing demands for product performance necessitates a secure component configuration. The factor of safety is determined by calculations performed on the system. The following goals should be achieved:

- Assurance against failure
- Testing of product functionality
- Assessment of external effects
- High strength-to-weight ratio
- Optimal material utilization
- Achievement of an economical production process

The most important computer-supported calculation processes are:

- Finite element methods (FEM)
- Boundary element methods (BEM)
- Finite different methods (FDM)

These methods can be applied for problems in which differential equations describe any continua. The methods have different approaches for performing calculations. FEM assumes a variational formulation, BEM a formulation by means of integrals, and FDM uses differential equations. Due to the mathematical formulation, it is irrelevant whether the computational problem comes from mechanics, acoustics, or fluid mechanics. In all three methods, the discretization of the structure is common and is required in order to derive the mathematical formulations for the desired tasks.

The processes commercially available have integrated interfaces that enable them to work with geometries already developed in CAD systems. To prepare the geometry model, various support mechanisms for the particular calculation systems are offered.

Beyond FEM, BEM, and FDM, there are other calculation systems that are based on problem-specific model creation. These systems, however, are usually applied only in conjunction with an associated model. Two examples are the calculation of suspensions and the determination and layout of weld contacts.

The general sequence of a calculation is equivalent to that of an information handling process. Input in the form of the geometry, material, and forces is transformed using mathematical and physical rules to calculated results. In the majority of cases, the object geometry and material properties are simplified. Also, the stress–strain or loading characteristics are often idealized, which eases the calculation task and reduces time. In many cases assumptions and simplifications are made because otherwise the calculation of the problem might be too extensive or impossible.

2.5.2. Finite Element Methods

FEM is the most commonly used calculation process today. Their implementation spectrum covers many different areas. For example, they are applied in:

- Statics in civil engineering
- Crash research in the automotive industry
- Electromagnetic field research for generator design
- Material strength and life cycle determination in mechanical engineering
- Bone deformation in biomechanics

FEM has found its place in the field of structural mechanics. It is used for calculations in:

- Stress and deformation
- Natural shape and eigenfrequency
- Stability problems

Because complex structures, in respect to their mechanical or thermal behavior, are no longer solvable analytically, the structure must be broken down into smaller elements. The FEM process enables the breakdown of a larger structure into elements, thus enabling the description of component behavior. Therefore, very complex entities are solvable. Calculation problems from real-world applications are usually quite complex. For example, in crash testing it is necessary to reproduce or simulate the complete vehicle structure even when it consists of many different components and materials (Figure 16).

The finite elements are described geometrically using a series of nodes and edges, which in turn form a mesh. The formation of the mesh is calculable. The complete behavior of a structure can then be described through the composition of the finite elements.

An FEM computation can be divided into the following steps:

- Breakdown of the structure into finite elements
- Formulation of the physical and mathematical description of the elements
- Composition of a physical and mathematical description for the entire system
- Computation of the description according to requirements
- Interpretation of the computational results

The FEM programs commercially available today process these steps in essentially three program phases:

1. *Preprocessing:* Preparation of the operations, mesh generation
2. *Solving:* Actual finite element computation
3. *Postprocessing:* Interpretation and presentation of the results

Preprocessing entails mainly geometric and physical description operations. The determination of the differential equations is implemented in the FEM system, whereby the task of the user is limited to selecting a suitable element type.

In the following sections, the three phases of an FEM computation will be presented from a user's point of view.

2.5.2.1. FEM Preprocessing The objective of the preprocessing is the automation of the meshing operation. The following data are generated in this process:

- Nodes
- Element types
- Material properties
- Boundary conditions
- Loads

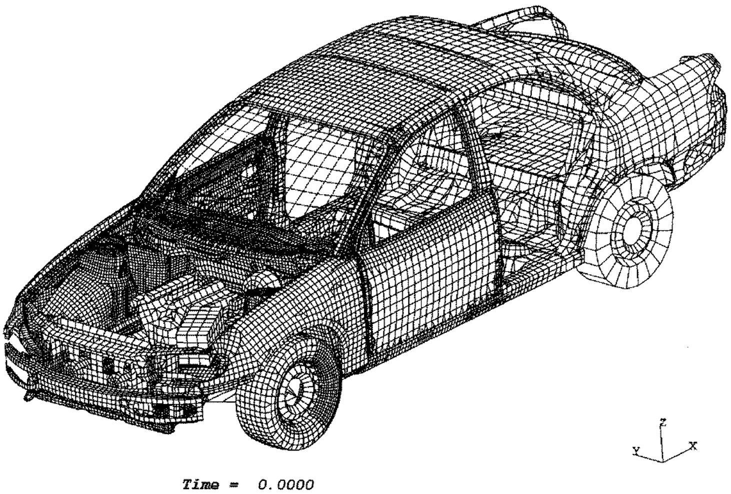


Figure 16 Opel Omega B Crash Model, 76,000 elements. (From Kohlhoff et al. 1994. Reprinted by permission of VDI Verlag GmbH.)

The data sets may be generated in various ways. For the generation of the mesh, there are basically two possibilities:

- Manual, interactive modeling of the FEM mesh with a preprocessor
- Modeling of the structure in a CAD system with a subsequent automated or semiautomated mesh generation

The generation of the mesh should be oriented towards the expected or desired calculation results. This is meaningful in order to simplify the geometry and consider a finer meshed area sooner in the FEM process. In return, the user must have some experience with FEM systems in order to work efficiently with the technology available today. Therefore, completely automatic meshing for any complex structure is not yet possible (Weck and Heckmann 1993).

Besides interactive meshing, commercially available mesh generators exist. The requirements of an FE mesh generator also depend on the application environment. The following requirements for automatic mesh generators, for both 2D and 3D models, should be met (Boender 1992):

- The user of an FE mesh generator should have adequate control over the mesh density for the various parts of the component. This control is necessary because the user, from experience, should know which areas of the part require a higher mesh density.
- The user must specify the boundary conditions. For example, it must be possible to determine the location of forces and fixed points on a model.
- The mesh generator should require a minimum of user input.
- The mesh generator must be able to process objects that are made up of various materials.
- The generation of the mesh must occur in a minimal amount of time.

The mesh created from the FE mesh generator must meet the following requirements:

- The mesh must be topologically and geometrically correct. The elements may not overlap one another.
- The quality of the mesh should be as high as possible. The mesh can be compared to analytical or experimental examinations.
- Corners and outside edges of the model should be mapped exactly using suitable node positioning.
- The elements should not cut any surfaces or edges. Further, no unmeshed areas should exist. At the end of the mesh refinement, the mesh should match the geometrical model as closely as possible. A slight simplification of the geometry can lead to large errors (Szabo 1994).
- The level of refinement should be greater in the areas where the gradient of the function to be calculated is high. This is determined with an automatic error estimation during the analysis and provides a new point for further refinement.

Various processes have been developed for automatic mesh generation. The motivation to automate the mesh generation process results from the fact that manual generation is very time consuming and quite prone to mistakes. Many processes based on 2D mesh generation, however, are increasingly being suggested for 3D processes.

The most frequently used finite element forms for 2D are three- and four-sided elements and for 3D are tetrahedrons and hexahedrons. For automatic mesh generation, triangles and tetrahedrons are suitable element shapes, whereas hexahedrons provide better results in the analysis phase (Knothe and Wessels 1992).

2.5.2.2. FEM Solution Process In the solution process, equation systems are solved that are dependent on the type of examination being carried out. As a result, various algorithms must be provided that allow for efficient solution of the problem. The main requirements for such algorithms are high speed and high accuracy.

Linear statistical examinations require only the solution of a system of linear equations. Dynamically nonlinear problems, on the other hand, require the application of highly developed integration methods, most of which are based on further developments of the Runge–Kutta method.

To reduce the computing time, matrices are often converted. This permits a more effective handling of the calculations. The objective is to arrange the coefficients with a resulting diagonal matrix. An example of an FEM calculation sequence is shown in Figure 17.

2.5.2.3. FEM Postprocessing Because the calculation results of an FEM computation only deliver nodes and their displacement and elements with the stresses or eigenforms in numerical rep-

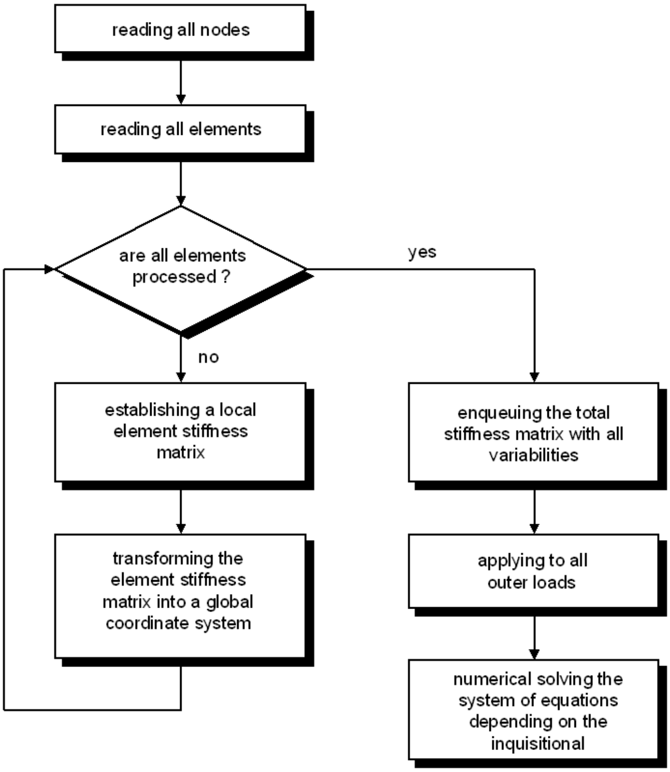


Figure 17 Sequence of a Finite Element Calculation.

resentation, postprocessors are required in order to present the results in a graphical form (Figure 18).

The postprocessing manages the following tasks:

- Visualization of the calculated results
- Plausibility control of the calculation

The performance and capability of postprocessors are constantly increasing and offer substantial presentation possibilities for:

- Stress areas and main stresses
- Vector fields for forces, deformation and stress characteristics
- Presentation of deformations
- Natural forms
- Temporary deformation analysis
- Temperature fields and temperature differences
- Velocities

It is possible to generate representations along any curve of the FEM model or, for example, to present all forces on a node. Stress fields of a component can be shown on the surface or within the component. The component can thus be reviewed in various views.

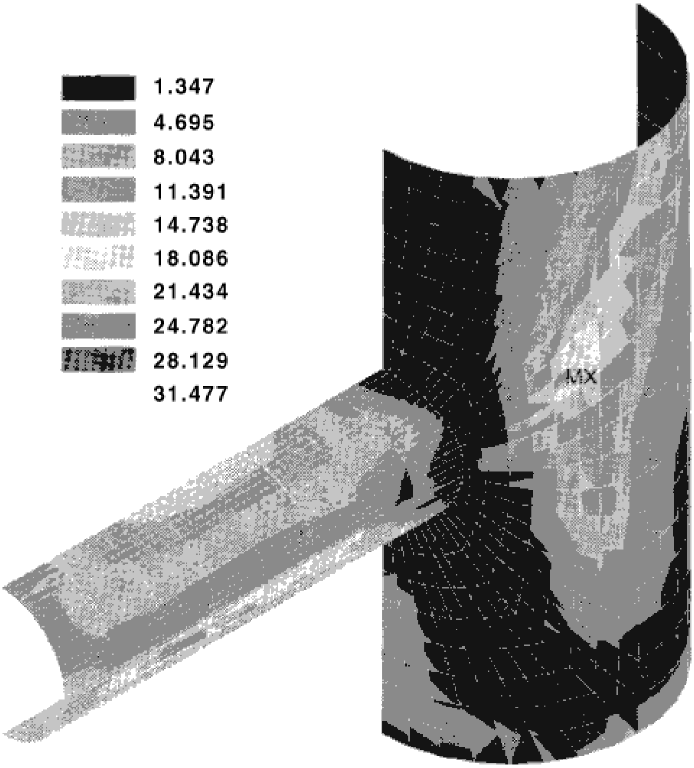


Figure 18 FEM Postprocessing Resulting from a Standard Pipe Formation. (From CAD-FEM 1995)

3. CONCEPTS

3.1. Process Chains

A process chain is a set of rules or steps carried out in a specific order in order to carry out the completion of a defined process. Processes can be executed either in sequence or in parallel. A typical example of a product development process chain is portrayed in Figure 19.

A process chain is characterized as:

- A process, divided into subtasks, in which contributions to the creation of virtual products take place
- A series of systems in which computer support for product-related subtasks is guaranteed
- A series of systems for organized support of the complete proces
- Mechanisms for the adequate exchange of data between systems

Computer support of process chains is related, on one hand, to the processing and management of product data and, on the other hand, to the organization of the supported process and the handling of associated data.

The processing and management of product data entail all tasks that concern the generation, storage, transfer, and function-related editing and provision of data (Reinwald 1995).

General classification of process chains suggests a determination of the depth of integration of the product data handling. Classification can be divided into:

- Coupled/linked process chains
- Integrated process chains
- Process chains with common data management

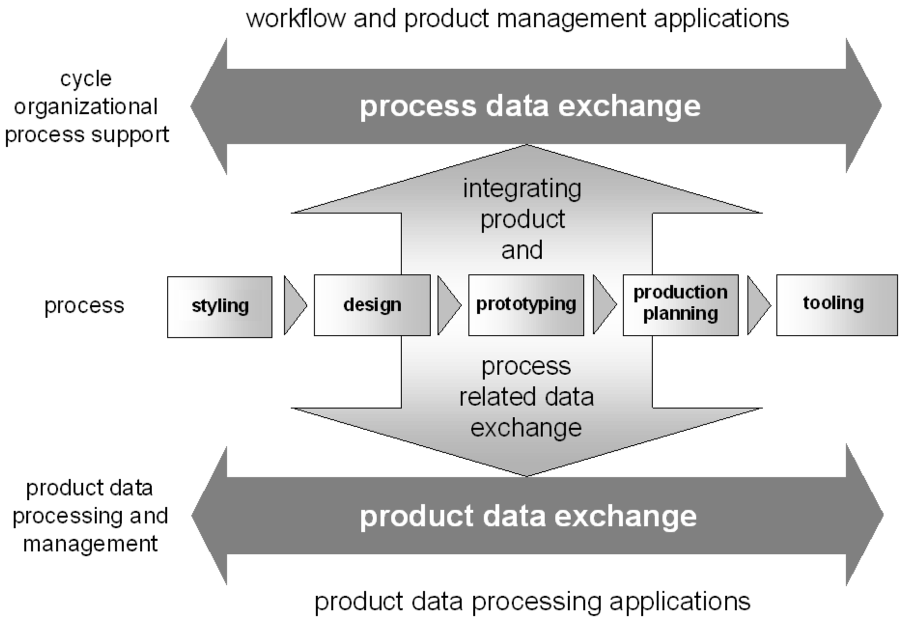


Figure 19 Layout of a Computer-Supported Process Chain.

The exchange of data within a coupled process chain takes place directly between the supporting systems. Thereby, information transferred between two respective systems is aided with the help of system-specific interfaces. This realization of information transfer quickly reaches useful limits as the complexity of the process chains increases. This is because the fact that the necessary links grow disproportionately and the information from the various systems is not always transferable (Anderl 1993).

Characteristic of integrated process chains is a common database in the form of an integrated product model that contains a uniform information structure. The information structure must be able to present in a model all relevant product data in the process chain and to portray the model with the use of a homogenous mechanism. A corresponding basis for the realization of such information models is offered by the Standard for the Exchange of Product Model Data (ISO 10303—STEP) (ISO 1994).

Basic to a process chain with common product data management based on an EDM system is the compromise between coupled and integrated process chains. With the use of common data management systems, organizational deficiencies are avoided. Thus, the EDM system offers the possibility of arranging system-specific data in comprehensive product structures. The relationship between documents such as CAD models and the respective working drawing can be represented with corresponding references. A classification system for parts and assemblies aids in locating the required product information (Jablonski 1995).

On the other hand, with joint product data management, conversion problems for system-specific data occur in process chains based on an EDM system. These problems exist in a similar form in coupled process chains. This makes it impossible to combine individual documents into an integrated data model. References within various systems, related to objects within a document rather than the document itself, cannot be made.

Besides requiring support for the processing of partial tasks and the necessary data transfer, process chains also require organized, sequential support. This includes planning tasks as well as process control and monitoring. Process planning, scheduling, and resource planning are fundamental planning requirements.

The subject of process planning involves segmenting the complete process into individual activities and defining the sequence structure by determining the order of correlation.

In the use of process plans, the following points are differentiated:

- One-time, detailed process planning (all processes are executed similarly)
- Case-by-case planning of individual processes

- One-time, rough planning of a generic process, followed by deeper detailing and specification of individual processes.

The first basic approach is typical for the majority of commercial work flow management systems. Because these systems are intended for routine tasks, their application is unproblematic only when they concern the support of completely determinable processes. Product development processes are characterized by the fact that their achievements are not precisely predictable in advance. For that reason they are treated as nondeterministic processes.

The second approach requires an independent sequence for each process path. This corresponds to the generation of a network plan using methods such as CPM (critical path method), MPM (metra potential method), and PERT (program evaluation and review technique). These techniques, as part of the project management, are employable for activities such as proper scheduling (Burghardt 1988).

The third approach involves the strategic use of rough supplementary outlines of generic processes with those of detailed, individual processes. A requirement for successful implementation of the strategy is the ability of the supporting system to map process structures hierarchically.

For scheduling, a closed sequence plan is assumed to exist. The activities and correlations must be determined beforehand. Therefore, the minimum task of the scheduling part of the process is the calculation and determination of time limits, critical paths, and buffer times. The CPM, MPM, and PERT methods are implemented for this purpose, and the incorporation of these operations leads to the calculation of complete process and buffer times using both forward and backward calculations.

The duration of a procedure depends significantly on the use of resources required for fulfilment of the process. In this respect, interaction exists between the scheduling and capacity planning (Burghardt 1988).

Capacity planning for the product-development process involves proper quantity and time allocation of coworkers, application system capacities, and other partial tasks of an individual process (Golm 1996). Therefore, the goal of capacity planning is to ensure the on-schedule processing of the entire process and the uniform utilization of resources.

3.1.1. Tasks of Process Control and Monitoring

The task of process control and monitoring is to guarantee the fulfilment of the process based on the sequence, schedule, and capacity planning determinants. The following individual tasks must then be resolved:

- Activation of processable actions
- Process monitoring of contents
- Process monitoring of time

3.2. Integrated Modeling

Modeling of virtual products includes all phases of the product life cycle, from product planning to product disposal. The aim is complete integration of all the development processes for efficient product development.

The following system characteristics are strived for through the integration of design and production planning systems:

- Increased productivity during product development
- Acceleration of the product development process
- Improvement of product and technical documentation quality

An increase in the productivity of product development phases through the integration of design and manufacturing plans is based on preventing the loss of information. A loss of information often occurs between coupled and unrelated systems because of integration difficulties. With a lack of proper integration, detection and editing of data take place numerous times for the same information content. Therefore, using product models derived from information within both the design and manufacturing data, it is possible to integrate specific work functions. The models then serve as a basis for all system functions and support in a feature approach-type form.

The feature approach is based on the idea that product formation boundaries or limits are explicitly adhered to during design and production planning stages. This ensures that the end result of the product envisioned by the designer is not lost or overlooked during the modeling phase. To realize the form and definition incorporated by the designer in a product, it is essential that an integrated design and production planning feature exist.

Accelerating the product development process is achievable through the minimization of unnecessary data retrieval and editing. Efforts to parallel the features of concurrent engineering tasks require integrated systems of design and production planning.

Higher product and documentation quality is achievable with the use of integrated systems. Through integration, all functions of a product model are made available to the user. Any errors that may occur during data transmission between separate systems are avoided.

Because of the high responsibility for cost control during product development, estimates for design decisions are extremely necessary. Cost estimates reveal the implications of design decisions and help in avoiding costly design mistakes. For effective estimation of costs to support the design, it is necessary to be able to access production planning data and functions efficiently. Integrated systems provide the prerequisites for the feedback of information from the production planners to the designers, thus promoting qualitatively better products. The following forms of feedback are possible:

- Abstract production planning experience can be made available to the designer in the form of rules and guidelines. A constant adaptation or adjustment of production planning know-how has to be guaranteed.
- Design problems or necessary modifications discovered during the production planning phases can be directly represented in an integrated model.
- Necessary modifications can be carried out in both production planning and design environments.

3.3. Methodical Orientation

The virtualization of product development is a process for the acquisition of information in which, at the end of the product development, all necessary information generated is made available. Assuming that humans are at the heart of information gathering and that the human decision making process drives product development, the virtual product-creation methods must support the decision maker throughout the product creation process.

Product-creation processes are influenced by a variety of variables. The form the developed product takes is determined by company atmosphere, market conditions, and the designer's own decisions. Also influential are the type of product, materials, technology, complexity, number of model variations, material costs, and the expected product quantity and batch sizes.

Product development is not oriented toward the creation of just any product, but rather a product that meets the demands and desires of the consumer while fulfilling the market goals of the company. The necessary mechanisms must provide a correlation between the abstract company goals and the goals of the decisions made within the product development process. For example, to ensure the achievement of cost-minimization objectives, product developers can use mechanisms for early cost estimation and selection, providing a basis for the support of the most cost-effective solution alternatives (Hartung and Elpet 1986). To act upon markets characterized by individual consumer demands and constant preference changes, it is necessary to be able to supply a variety of products within relatively short development times (Rathnow 1993; Eversheim 1989). This means that product structuring must take into account the prevention of unnecessary product variation and that parallel execution of concurrent engineering is of great importance.

Methods that are intended to support the product developer must be oriented toward not only the contents of the problem but also the designer's way of thinking. Therefore, a compromise must be made between the methodical problem solving strategy and the designer's creative thought process.

The product-development methods can be separated into process-oriented and product-oriented categories. The main concern in process-oriented product development is the design. The objective is the indirect improvement of the design or, more precisely, a more efficient design process. Product-oriented methods concern the product itself and the direct improvement of the product.

Various process-oriented methods are discussed below. Fundamental to VDI 2221 guidelines is the structuring of the product-development process into partial processes or phases. This structuring takes place independently of the developed product, the company, market conditions, and the decision maker. The demand for a general strategy results in individual steps being described at very abstract levels. Consideration of product, company, and market-related influences is incorporated into the design throughout all processes. The impact of individual influences on methods can only be clarified with examples. The worth of a new method lies in the general systemizing of the product development process. This method is not suitable for immediate derivation of concrete product development processes. Rather, it describes an ideal, flexible product-development process. The structure and content of the development process are then molded by the product, company, or market-related influences (VDI-Gesellschaft Entwicklung Konstruktion 1993).

Another example of process-oriented methods is the concurrent engineering method, which covers all topics from product development to equipment and production planning. The primary objective of simultaneous engineering is the reconfiguration of the development process, with the intention of reducing development time while improving product quality. As opposed to the traditional approach, in which a series of steps is followed and feedback occurs through long loops, the development tasks within concurrent engineering allow for the parallel execution of many tasks. Therefore, development times are substantially reduced and the old system of following predetermined steps is avoided. This concept relies heavily on the exchange of information between the various departments. This should extend beyond company boundaries to include the equipment manufacturer in order to tie production equipment planning into the product development process. The main focus in the implementation of these methods, besides the use of computer aided technology, is the reorganization of the company structure. In the foreground are measures to stimulate the exchange of information, such as the formation of interdisciplinary teams (Eversheim et al. 1995; Krause et al. 1993; Bullinger and Warschat 1996).

The design-to-cost method is a product-development approach that bases design decisions on cost-sensitive criteria. Here, evaluation standards are not only production costs but also the costs incurred throughout the life of the product. This method is particularly applicable for complex products with relatively long life cycles. The method is broken down into target costing, cost-oriented design, and cost control. Within target costing, a goal for final costs is broken down for individual product components. The final cost is determined from the results of a market analysis or from a clear depiction of customer demands. Relative cost and manufacturing cost data can be used to aid the development of design alternatives that fall within the early cost-oriented design process. With the aid of cost estimate models, the life cycle costs of each alternative are assessed and the most cost effective variant selected. In the area of cost control, the design costs are compared to and contrasted with the original end cost objective. If the cost objective is not met, deviation analyses are necessary to determine required alternatives.

Product-oriented techniques are characterized by product formation, task formulation, and the objectives pursued. Product-oriented tasks vary considerably, according to the multitude of products and tasks. A few examples of these techniques and technique groupings are presented later in this chapter.

Design rules and guidelines specify how a product is designed according to previously determined objectives. Well-known design rules and guidelines exist particularly for production, assembly, ergonomic, and logistics-oriented processes as well as resource-efficient and recycling-oriented product design (Pawellek and Schulte 1987; Krause 1996; Pahl and Beitz 1993; Kriwet 1995).

Simulation technology has become important in the field of product development. The primary objective in the implementation of simulation technology is the early acquisition of information on product characteristics before the product even exists. The knowledge gained aids in the assessment of the respective development results. Costly and time-consuming mistakes during development phases can be recognized early and avoided. Through an iterative strategy, it is also possible to optimize systematically particular product characteristics or qualities (Frepoli and Botta 1996; Schönbach 1996).

One requirement for the application of simulation techniques is the creation of a model, which allows for the investigation and breakdown of real product tasks. With the use of computers, it is possible to design complex models that allow answers to relevant design questions to be found. These models were previously realizable only through the tedious production of prototypes. The application of simulation technology is especially helpful when numerous product variations must be considered, a situation not economically feasible with prototypes.

In the future, systems must be able to provide all relevant information in the user-desired form and make additional mechanisms available that reveal the consequences of a decision made during product development. The provision of information must include not only product specific data but also comprehensive information. Data covering all topics from design guidelines and rules to design, solution, and measurement catalogs to company individual knowhow is necessary. Solutions developed for similar products need to be accessible not only in general form but in a form that takes product-related tasks and context into account.

3.4. Rapid Prototyping

Due to the ever-increasing demand for shorter product development cycles, a new technology known as rapid prototyping (RP) has emerged. RP is the organizational and technical connection of all processes in order to construct a physical prototype. The time required from the date the order is placed to when the prototype is completed can be substantially reduced with the application of RP technology (Figure 20).

RP is made up of generative manufacturing processes, known as RP processes, and conventional NC processes as well as follow-up technologies. In contrast to conventional working processes, RP processes such as stereo lithography, selective laser sintering, fused deposition modeling, and laminated object manufacturing enable the production of models and examples without the use of forming tools or molds. RP processes are also known as free-form manufacturing or layer manufacturing.

Prototypes can be divided into design, function, and technical categories. To support the development process, design prototypes are prepared in which proportion and ergonomic models are

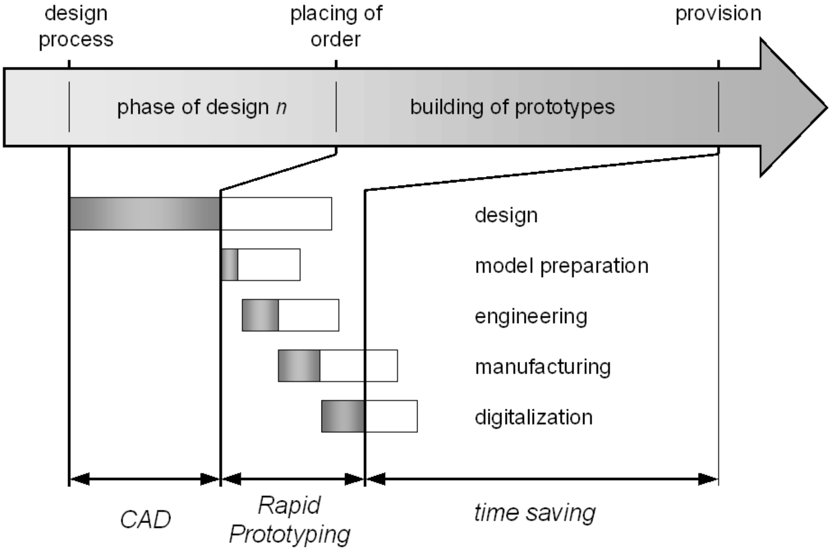


Figure 20 Acceleration Potential through CAD and RP Application.

incorporated. Design prototypes serve for the verification of haptic, esthetic, and dimensional requirements as well as the constructive conception and layout of the product. RP-produced examples are made from polycarbonates, polyamides, or wood-like materials and are especially useful for visualization of the desired form and surface qualities.

For function verification and optimization, a functional product example is required. The application of production series materials is not always necessary for this purpose. Functional prototypes should, however, display similar material strength characteristics. On the other hand, technical prototypes should be produced using the respective production series materials and, whenever possible, intended production line equipment. The latter serve for purposes such as customer acceptance checks and the verification of manufacturing processes.

Prototypes can be utilized for individual parts, product prototypes, and tool prototypes. Normally, product prototypes consist of various individual prototypes and therefore require some assembly. This results in higher levels of dimension and shape precision being required.

The geometric complexity represents an essential criterion for the selection of the suitable prototype production process. If, for example, the prototype is rotationally symmetric, the conventional NC turning process is sufficient. In this case, the presently available RP processes provide no savings potential. However, the majority of industry-applied prototypes contain complex geometrical elements such as free-form surfaces and cut-outs. The production of these elements belongs to some of the most demanding tasks in the area of prototype production and is, because of the high amount of manual work involved, one of the most time-consuming and cost-intensive procedures. RP processes, however, are in no way subjected to geometrical restrictions, so the build time and costs of producing complex geometrical figures are greatly reduced (König et al. 1994).

Another criterion for process selection is the required component measurements and quality characteristics such as shape, dimensional accuracy, and surface quality.

3.4.1. Systemization of Rapid Prototyping Processes

With the implementation of CAD/CAM technology, it is possible to produce prototypes directly based on a virtual model. The generation of the geometry using RP processes takes place quickly without the requirement of molds and machine tools. The main feature of the process is the formation of the workpiece. Rather than the conventional manufacturing process of a clamped workpiece and material removal techniques, RP processes entail the layering of a fluid or powder in phases to form a solid shape.

Using CAD models, the surfaces of the components are fragmented into small triangles through a triangulation process. The fragments are then transformed into the de facto RP standard format known as STL (stereo lithography format). The STL format describes the component geometry as a closed surface composed of triangles with the specification of a directional vector. Meanwhile, most

CAD systems now provide formatting interfaces as part of the standard software. Another feature of this process is that CAD-generated NC code describing the component geometry allows for a slice process in which layers of the object may be cut away in desired intervals or depths.

Starting with the basic contour derived from the slicing process, the workpiece is subsequently built up in layers during the actual forming process. Differences exist between the RP processes in process principles and execution.

RP processes can be classified by either the state of the raw material or the method of prototype formation. The raw materials for RP processes are in either fluid, powder, or solid states (Figure 21). As far as the method of prototype creation, the component forming can either be processed into direct, 3D objects or undergo a continuous process of layers built upon one another (Figure 22).

3.5. Digital Mock-up

Today the verification and validation of new products and assemblies relies mainly on physical mock-ups. The increasing number of variants and the need for higher product and design quality require a concurrent product validation of several design variants that are based on digital mock-ups. A digital mock-up (DMU) can be defined as "a computer-internal model for spatial and functional analysis of the structure of a product model, its assembly and parts respectively" (Krause et al. 1999).

The primary goal of DMU is to ensure the ability to assemble a product at each state of its development and simultaneously to achieve a reduction in the number of physical prototypes. Oriented to the product development cycle, tools for DMU provide methods and functionality for design and analysis of product components and their function. Modeling methods are divided into several categories: space management, multiple views, configuration management of product variants and versions, management of relations between components, and also incomplete models. Simulations are targeted to analyze the assembly and disassembly of a product as well as the investigation and verification of ergonomic and functional requirements. Constituent parts of a DMU tool are distinguished into either components or applications. Components are the foundation of applications and consist of modules for data organization, visualization, simulation models, and DMU/PMU correlations. Main applications are collision checks, assembly, disassembly, and simulation of ergonomics, functionality, and usage aspects. Because a complex product like an airplane can consist of more than 1 million parts, handling a large number of parts and their attributes efficiently is necessary. This requires that DMU methods are optimized data structures and algorithms.

Besides basic functions such as the generation of new assemblies, the modification of existing assembles and the storage of assemblies as product structures with related parts in heterogeneous databases, advanced modeling methods are required in order to ensure process-oriented modeling on the basis of DMU. The main methods in this context are (BRITE-EURAM 1997):

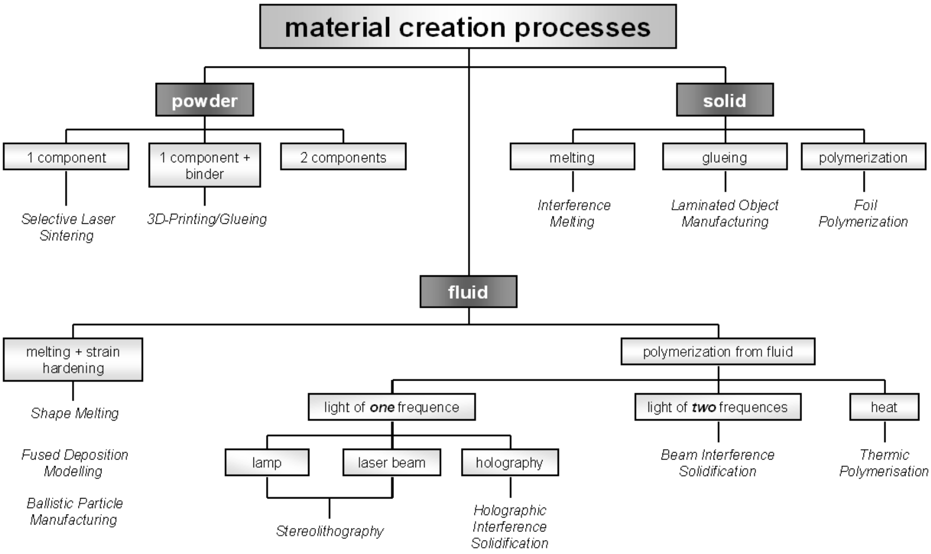


Figure 21 Classification of RP Processes with Respect to the Material-Generation Process. (From Kruth 1991)

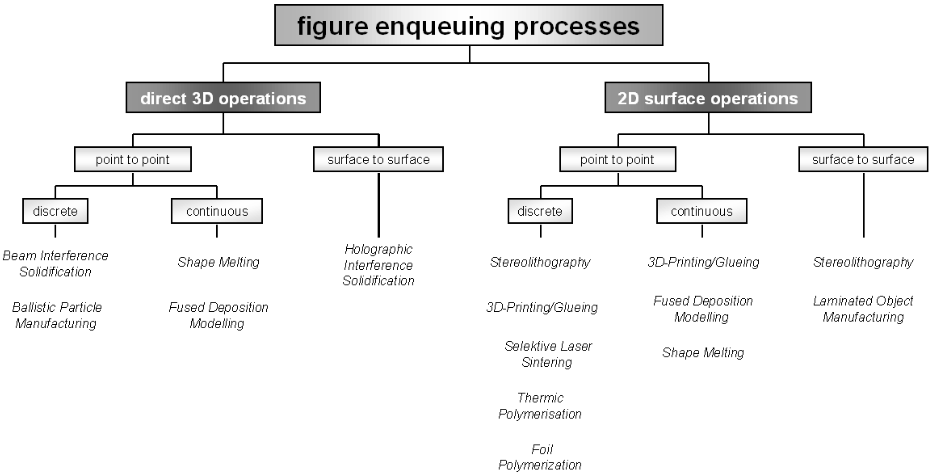


Figure 22 Classification of RP Processes with Regard to the Form-Generation Process. (From Kruth 1991)

- *Organization of spaces:* Allocating and keeping open functional and process-oriented spaces in DMU applications. The major problem is the consideration of concurrent requirements concerning the spaces.
- *Organization of views:* A view is an extract of the entire structure in a suitable presentation dedicated to particular phases and applications.
- *Handling of incomplete models:* Incomplete and inconsistent configurations during development process are allowable in order to fulfill the user's requirements regarding flexibility. Examples are symbolically and geometrically combined models with variable validity.
- *Configuration management of product structure:* Management of versions, variants, and multi-use.

Besides these methods in a distributed, cooperative environment, consequent safety management has to be taken into account. Therefore, a role- and process-related access mechanism must be implemented that allows the administrator to define restrictions of modeling related to roles. The application of such technologies enables a company to manage outsourced development services.

4. ARCHITECTURES

4.1. General Explanations

Product modeling creates product model data and is seen as a decisive constituent of the computer-supported product development activities. Product creation includes all the tasks or steps of product development, from the initial concept to the tested prototypes. During product modeling, a product model database is created and must support all relevant data throughout the product's life cycle.

Product modeling is made up of interconnected parts: the product model and the process chain. The product model is related to the product database and the management and access algorithms. The process chain, besides usually being related to the operational sequence of the product development, is in this context all the necessary product modeling processes required to turn the initial idea into a finished product. The product modeling processes consist of technical and management-related functions. The product model data are the most important factor determined from the development and planning activities.

The term *product model* can be logically interpreted to mean the accumulation of all product-related information within the product life cycle. This information is stored in the form of digitalized product model data and is provided with access and management functions. Modeling systems serve for the processing and handling of the product model data.

As with many other systems, the underlying architecture for CAD systems is important for extensibility and adaptability to special tasks and other systems. Compatibility with other systems, not just other CAD systems, is extremely important for profitable application. Product data should be

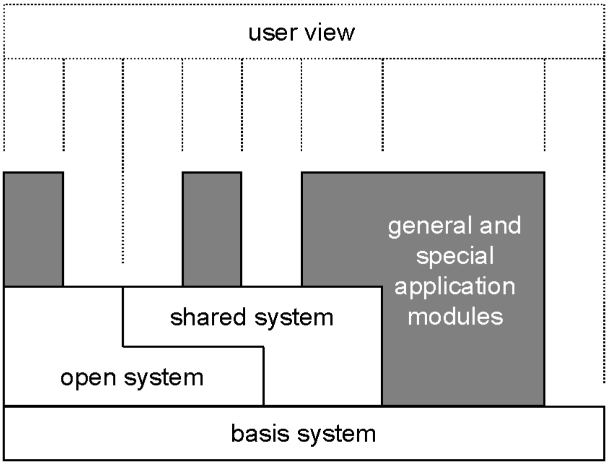


Figure 23 Classes of CAD Systems.

made universally employable throughout the product development process because bridges between media and format changes are error-prone and not often automated.

Enhancements of existing CAD systems, in the form of general and specialty application modules, are important in order to allow customer-specific adaptations to already-provided functionality.

The various classes of CAD systems, which may appear in combination with one another (Figure 23), include the basic system, general and specialty application software, and open and shared systems.

A basic CAD system is made up of a computer internal representation (CIR) of the product model, a core modeler with functionality for management and processing of the CIR, and a user interface for visualization of the CIR and interaction with the user (Figure 24).

4.2. Integration of Application Modules and Core Modeler

Many companies require not only a modeler for geometrical elements but also application modules to integrate into their product development process and for computer internal imaging of the processes. Calculation modules and simulation software belong in this category. Such application modules must integrate with the modeler to form a functional entity (Figure 25).

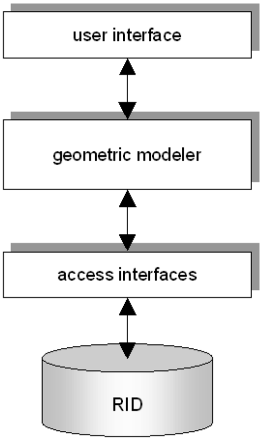


Figure 24 Basic CAD System.

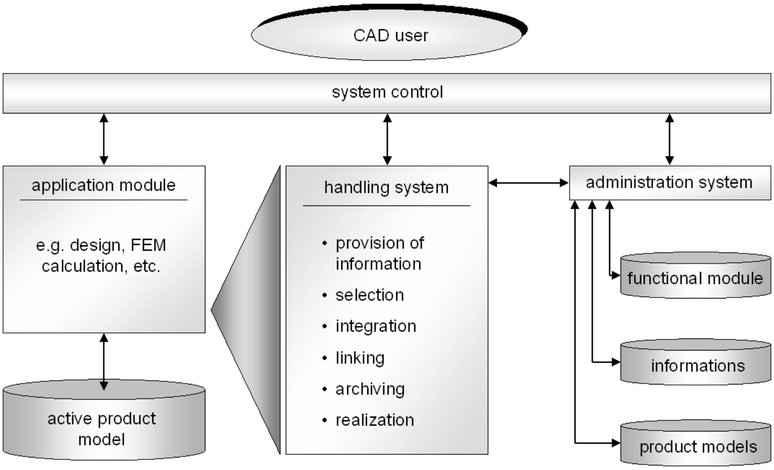


Figure 25 Modeler with Application Modules. (From Krause et al. 1990)

The application modules can be subdivided, according to their area of employment, into general and specialty modules. General application modules for widespread tasks, such as FEM modules or interfaces to widely used program systems, are commercially marketed by the supplier of the CAD system or by a system supplier of complementary software. Specially adapted extensions, on the other hand, are usually either created by the user or outsourced.

A thoroughly structured and functionally complete application programming interface (API) is a particular requirement due to the inability of the user to look deeper into the system.

Honda implemented a CAD system with around 200 application software packages (Krause and Pätzold 1992), but the user was presented with a Honda interface as a uniform medium for accessing the new plethora of programs. This enabled relative autonomy from the underlying software in that as the user, switching between systems, always dealt with the same user interface.

A further step towards autonomy, stemming from the basic system in use, is met only when application modules use an interface already provided. If this does not occur, the conversion to another base system is costly and time consuming. Sometimes it is even cheaper to install a new application module.

Often special application modules are required that cannot be integrated seamlessly into the CAD system. Therefore, various automobile manufacturers, such as Ford, General Motors, Nissan, VW, Audi, and Skoda, have implemented special surface modelers besides their standard CAD systems to enable free-form surface designs to be carried out.

4.3. Shared System Architectures

The scope and time restrictions of most design projects demand the collaboration of many designers. The implementation of shared CAD systems significantly simplifies this teamwork. Here it is possible for several designers to work on the same CIR (computer internal representation). It is not necessary to copy the CIR to various computers in order to work on it and then manually integrate the changes afterwards. The management of this process is taken over by the CAD system. These tasks, however, remain widely concealed from the user. Before this work is begun, only the design area of the respective designer must be defined in order to avoid overlapping.

Such shared CAD systems use a common database. This is usually accessible from the individual CAD stations through a client–server architecture (Figure 26). Usually an Engineering Data Management System (EDMS), implemented in conjunction with a CAD system, is used.

This technique is often found applied in local area networks (LANs), but new problems emerge when a changeover is made to wide area networks (WANs):

- The bandwidth available in a WAN is significantly lower than in a LAN and is often too small for existing shared systems.
- The data security must be absolutely ensured. Therefore, six aspects must be considered:
  - *Access control:* exclusive retrieval of data by authorized personnel
  - *Confidentiality:* prevention of data interception during transmission

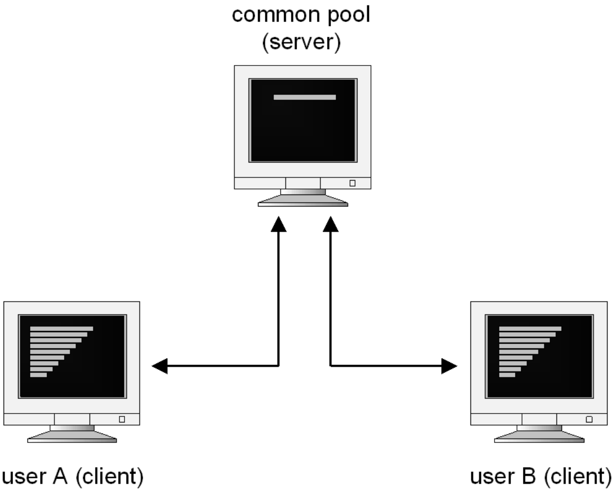


Figure 26 Shared CAD System with a Common Database and a Client-server Architecture.

- *Authentication:* the origin of the data transferred can be reliably identified
- *Integrity:* data cannot be modified during transmission
- *Nonrepudiation:* the sending of data cannot be refused or denied
- *Availability:* the data must always be available to authorized users

Newer implementations of shared systems rely on software architectures for the exchange of objects. Here, not only data is exchanged but, according to the object, also the data methods.

5. KNOWLEDGE MANAGEMENT

5.1. Origin and Background

The concept of knowledge management has been used in different disciplines, mostly in knowledge engineering (De Hoog 1997; Schreiber et al. 2000) and artificial intelligence (Göbler 1992; Forkel 1994). AI research often reduces the concept of knowledge management to the description of the development and use of expert systems (Gödicke 1992) and decision support systems. However, Davenport et al. (1996) found only one expert system application within 30 knowledge work improvement projects. Analysis of approximately 100 case studies published before February 1998 shows that IT-based approaches towards knowledge management are dominant. IT-based knowledge management approaches focus mainly on the storage (databases, DMS) and distribution (intranet and Internet applications, push and/or pull) of explicit, electronically documented knowledge, thus ignoring the tacit dimension of knowledge (Mertins 2001).

The improvements in data processing and network technologies have enabled access to data and information via the Internet at every time and every place in the world. Increasing market demands for reduction in time-to-market, more flexibility, and higher quality at lowest costs have contributed to a new discussion of the concept of knowledge management. These approaches differ from the above-mentioned ones in giving more emphasis to critical success factors such as culture and motivation of the employees and aiming to combine human-based and IT-based methods and tools for knowledge management (Davenport and Prusak 1998; Probst et al. 1998; Skyrme and Amidon 1997; Wiig 1995, 1997; Willke 1998).

5.2. Knowledge

What is knowledge? That is the question most frequently asked by people interested in knowledge management. The discussion about knowledge has a very long tradition. More than 2 thousand years ago, Socrates asked his students, “Why do we have to know what knowledge is? How can we know what knowledge is? What do we know about knowledge?” (see Plato, *Theaetetus*). Today there are numerous descriptions and definitions of knowledge. Romhardt (1998) finds 40 dichotomies of knowledge, such as explicit vs. implicit or tacit and individual vs. collective. Von Krogh and Venzin (1995) create seven categories of knowledge to be used in management and organization theory: tacit, embodied, encoded, embrained, embedded, event and procedural. Holsapple and Whinston (1992) discuss six types of knowledge that are important for knowledge management and decision support systems: descriptive, procedural, reasoning, linguistic, assimilative, and presentation. Moreover, Schreiber et al. (2000) ask the question, ‘‘Why bother?’’ because even physicists will often have difficulty giving an exact definition of energy. This does not prevent them, however, producing energy and other products.

The concepts most often mentioned by authors in the context of knowledge management are data, information, and knowledge. Some even add wisdom. This classification, if not properly understood and used, could lead to a philosophical discussion of the ‘‘right’’ distinction between the categories. The transition from one to the other is not always clear-cut. Instead of a hierarchy, a continuum ranging from data via information to knowledge has proved to be the most practical scheme for knowledge management (Probst et al. 1998; Heisig 2000).

Data means the individual facts that are found everywhere in a company. These facts can be easily processed electronically, and gathering of large amounts of data is not problematic today. However, this process alone does not lead to appropriate, precise, and objective decisions. Data alone are meaningless. Data become information when they are relevant and fulfill a goal. Relevant information is extracted as a response to a flood of data.

However, deciding which knowledge is sensible and useful is a subjective matter. The receiver of information decides whether it is really information or just noise. In order to give data meaning and thus change it into information, it is necessary to condense, contextualize, calculate, categorize, and correct (Tiwana 2000). When data are shared in a company, their value is increased by different people contributing to their meaning.

As opposed to data, knowledge has a value that can be anywhere between true and false. Knowledge can be based on assumption, preconception, or belief. Knowledge-management tools must be able to deal with such imprecision (e.g., documentation of experiences).

> Knowledge is simply actionable information. Actionable refers to the notion of *relevant, and nothing but the relevant* information being available in the right place at the right time, in the right context, and in the right way so anyone (not just the producer) can bring it to bear on decisions being made every minute. Knowledge is the key resource in intelligent decision making, forecasting, design, planning, diagnosis, analysis, evaluation, and intuitive judgment making. It is formed in and shared between individual and collective minds. It does *not* grow out of databases but evolves with experience, successes, failures, and learning over time.” (Tiwana 2000, p. 57)

Taking all these aspects into consideration, knowledge is the result of the interaction between information and personal experience. Typical questions for data and information are Who? What? Where? and When? Typical questions for knowledge are How? and Why? (Eck 1997).

One important differentiation is often made between tacit and explicit knowledge. Tacit knowledge is stored in the minds of employees and is difficult to formalize (Polanyi 1962; Nonaka and Takeuchi 1995). Explicit knowledge is the kind that can be codified and transferred. Tacit knowledge becomes explicit by means of externalization. With the introduction of CNC machines in mechanical workshops, experienced and highly skilled workers often felt insecure about their ability to control the process. They missed the ‘‘right sound’’ of the metal and the ‘‘good vibrations’’ of the machine. These signals were absorbed by the new CNC machines and hence workers were not able to activate their tacit knowledge in order to produce high-quality products (Martin 1995; Carbon and Heisig 1993). Similar problems have been observed with the introduction of other CIM technologies, such as CAD/CAM in the design and process-planning department and MRP systems for order management. The information supply chain could not fully substitute the informal knowledge transfer chain between the different departments (Mertins et al. 1993; Fleig and Schneider 1995). A similar observation is quoted from a worker at a paper manufacturing plant: ‘‘We know the paper is right when it smells right’’ (Victor and Boynton 1998, p. 43) However, this kind of knowledge is not found only in craftwork or industrial settings. It can be found in high-tech chip production environments (Luhn 1999) as well as social settings. From the noise of the pupils, experienced teachers can distinguish what they have to do in order to progress (Bromme 1999).

5.3. Knowledge Management Is Business and Process Oriented

Nearly all approaches to knowledge management emphasize the process character of interlinked tasks or activities. The wording and number of knowledge-management tasks given by each approach differ markedly. Probst (1998) proposes eight building blocks: the identification, acquisition, development, sharing, utilization, retention, and assessment of knowledge and the definition of knowledge goals. Another difference is the emphasis given by authors to the steps of the process- or knowledge-management tasks. Nonaka and Takeuchi (1995) describe processes for the creation of knowledge, while Bach et al. (1999) focus on the identification and distribution of the explicit, electronically documented objects of knowledge.

5.3.1. The Core Process of Knowledge Management

The analysis of different knowledge-management approaches (Probst et al. 1998; Davenport and Prusak 1998; Nonaka and Takeuchi 1995; Bach et al. 1999; Bukowitz 1999; Weggemann 1998) and the empirical results (Heisig and Vorbeck 2001) lead to the design of an integrated core process in which all activities are supported by organizational, motivational, and technical aspects. The core process can be further broken down into the core activities "define the goals of knowledge," "identify knowledge," "create (new) knowledge," "store knowledge," "distribute knowledge," and "apply knowledge." The quality of these stages is guaranteed by certain design fields for knowledge management. These fields include a company's process organization, available information technology, management systems, corporate culture, management of human resources, and control.

- *Create (new) knowledge:* Measures and instruments that promote the creation of knowledge include the acquisition of external knowledge (mergers, consultants, recruiting, patent acquisition), the setting up of interdisciplinary project teams that include the customers, and the application of lessons learned and methods to elicit tacit knowledge.
- *Store knowledge:* The stored knowledge in manuals, databases, case studies, reports, and even corporate processes and rules of thumb makes up one column of the other core activities. The other column consists of the knowledge stored in the brains of thousands of employees who leave their respective organizations at the end of each working day.
- *Distribute knowledge:* Provision of the right knowledge to the right person at the right time is the aim of the core task of distribution of knowledge. The methods and tools are dominated by IT applications such as the Internet or intranet. However, these tools provide added value only if trust and mutual understanding pervade the atmosphere of the entire company as well as project teams. The development of a common language is an important task. Other aspects of the distribution of knowledge are the transfer of experiences to new employees by training on the job, mentoring, or coaching techniques.
- *Apply knowledge:* According to our survey, the application of knowledge is the most essential task of knowledge management. Knowledge management mainly provides methods to overcome the barriers of the "not invented here" syndrome: the one-sided thinking and the development of preferred solution by existing information pathologies.

The close relationship between process and knowledge management is underscored by the critical success factors named by companies in the Europe-wide survey. Nearly one out of four companies (24%) mentioned aspects of the design of structures and processes as a critical factor in the success of knowledge management. Knowledge management is understood by practitioners from manufacturing and the service industry mainly as part of corporate culture and a business-oriented method: "The sum of procedures to generate, store, distribute and apply knowledge to achieve organizational goals" (Heisig and Vorbeck 2001).

Furthermore, the survey results indicate that companies focus on specific business processes to implement knowledge management. One out of every two companies starts its KM initiatives in the R&D area, two out of five focus on the process "Understanding Markets and Customers," and more than one out of every three of the companies begins in the area "Production and Delivery of Products and/or Services." The process "Manage Information" is ranked fourth in our overall sample and second in the service industry sample (Heisig and Vorbeck 2001). The companies locate their core competencies in these business processes too (Figure 27). Knowledge-management activities are started mainly within the areas identified as core competencies.

5.3.2. Design Fields of Knowledge Management

The second important step is to set up the link between knowledge management and the general organizational design areas, such as business processes, information systems, leadership, corporate culture, human resource management, and control (Figure 28).

- The business processes are the application areas for the core process of knowledge management. Existing knowledge has to be applied and new knowledge has to be generated to fulfill the needs of internal and external customers. The core activities have to be permanently aligned with the operating and value-creating business processes. Furthermore, knowledge-management activities could be linked with existing process-documentation programs (e.g., ISO certification) and integrated into business process reengineering approaches.
- Information technology is currently the main driving factor in knowledge management. This is due to considerable technological improvements in the field of worldwide data networking through Internet/intranet technologies. IT builds the infrastructure to support the core activities of storing and distributing knowledge. Data warehouses and data mining approaches will enable

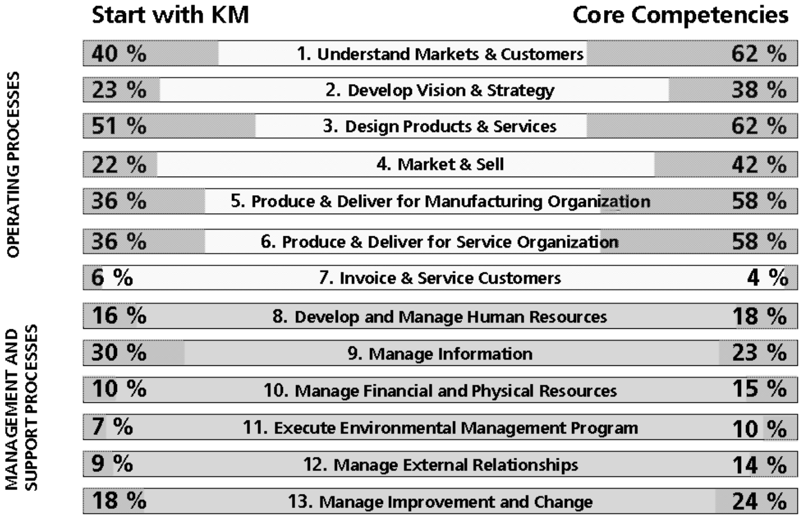


Figure 27 Where Companies Start with Knowledge Management and Where They Locate Their Core Competencies.

companies to analyze massive databases and therefore contribute to the generation of new knowledge.

- The success of knowledge-management strategies is to a large degree determined by the support through top and mid-level managers. Therefore, leadership is a critical success factor. Each manager has to promote and personify the exchange of knowledge. He has to act as a multiplier and catalyst within day-to-day business activities. Special leadership training and change programs have to be applied to achieve the required leadership style.
- If the knowledge-management diagnosis indicates that the current corporate culture will not sustain knowledge management, wider change-management measures have to be implemented.

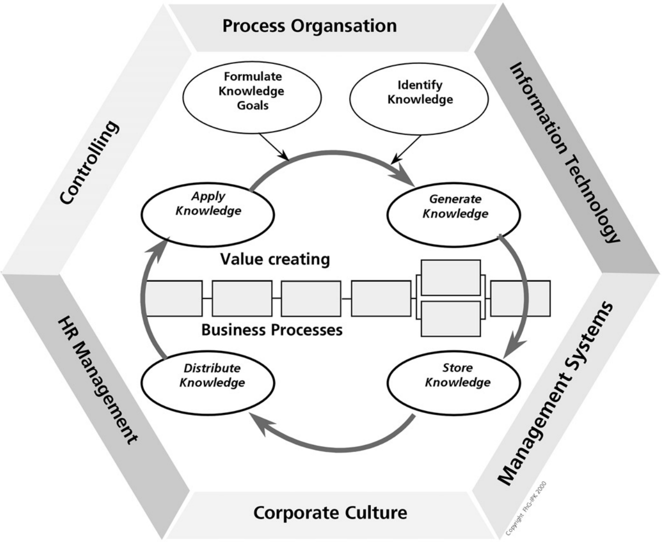


Figure 28 Core Process and Design Fields of Knowledge Management.

The required company culture could be characterized by openness, mutual trust, and tolerance of mistakes, which would then be considered necessary costs of learning.

- Personnel-management measures have to be undertaken to develop specific knowledge-management skills such as the ability to develop and apply research and retrieval strategies as well as adequately structure and present knowledge and information. Furthermore, incentives for employees to document and share their knowledge have to be developed. Career plans have to be redesigned incorporating aspects of knowledge acquisition of employees. Performance-evaluation schemes have to be expanded towards the employees' contribution to knowledge generation, sharing, and transfer.
- Each management program has to demonstrate its effectiveness. Therefore, knowledge-controlling techniques have to be developed to support the goal-oriented control of knowledge creation and application with suitable control indicators. While strategic knowledge control supports the determination of knowledge goals, operative knowledge control contributes to the control of short-term knowledge activities.

Empirical results confirmed the great potential for savings and improvements that knowledge management offers (Figure 29). Over 70% of the companies questioned had already attained noticeable improvements through the use of knowledge management. Almost half of these companies had thus saved time and money or improved productivity. About 20% of these companies had either improved their processes, significantly clarified their structures and processes, increased the level of customer satisfaction, or facilitated decisions and forecasts through the use of knowledge management (Heisig and Vorbeck 2001).

However, some differences were apparent between the answers provided by service and by manufacturing companies. Twenty-eight percent of the service firms indicated an improvement in customer satisfaction due to knowledge management, as compared with only 16% of the manufacturing companies. Twenty-three percent of manufacturing companies stressed improvements in quality, as compared to only 15% of the service companies. Answers to questions about the clarity of structures and processes showed yet another difference. Twenty-six percent of the service companies indicated improvement with the use of knowledge management, as opposed to only 14% of manufacturing companies.

5.4. Approaches to the Design of Business Process and Knowledge Management

One primary design object in private and public organizations are the business processes that structure work for internal and external clients. Known as business process reengineering (BPR) (Hammer 1993), the design of business processes became the focus of management attention in the 1990s. Various methods and tools for BPR have been developed by research institutes, universities, and consulting companies. Despite these developments, a comparative study of methods for business process redesign conducted by the University of St. Gallen (Switzerland) concludes: "To sum up,

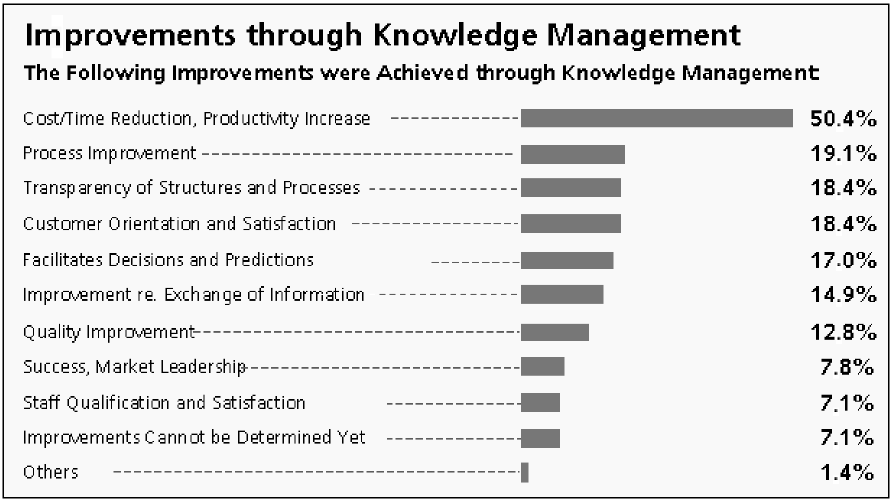


Figure 29 Improvements through Knowledge Management.

we have to state: hidden behind a more or less standard concept, there is a multitude of the most diverse methods. A standardized design theory for processes has still not emerged'' (Hess and Brecht 1995, p. 114).

> BPR's focus is typically on studying and changing a variety of factors, including work flows and processes, information flows and uses, management and business practices, and staffing and other resources. However, most BPR efforts have not focused much on knowledge, if at all. This is indeed amazing considering that knowledge is a principal success factor—or in many judgment, the major driving force behind success. Knowledge-related perspectives need to be part of BPR. (Wiig 1995, p. 257)

Nearly all approaches to knowledge management aim at improving the results of the organization. These results are achieved by delivering a product and/or service to a client. This again is done by fulfilling certain tasks, which are linked to each other, thereby forming processes. These processes have been described as business processes. Often knowledge is understood as a resource used in these processes. Nevertheless, very few approaches to knowledge management have explicitly acknowledged this relation. And even fewer approaches have tried to develop a systematic method to integrate knowledge-management activities into the business processes. The following approaches aim to support the analysis and design of knowledge within business processes:

- CommonKADS methodology (Schreiber et al. 2000)
- The business knowledge management approach (Bach et al. 1999)
- The knowledge value chain approach (Weggemann 1998)
- The building block approach (Probst et al. 1998)
- The model-based knowledge-management approach (Allweyer 1998)
- The reference model for knowledge management (Warnecke et al. 1998).

None of the approaches presented to knowledge management has been developed from scratch. Their origins range from KBS development and information systems design to intranet development and business process reengineering. Depending on their original focus, the approaches still show their current strengths within these particular areas. However, detailed criteria for the analysis and design of knowledge management are generally missing.

Due to their strong link to information system design, all approaches focus almost exclusively on explicit and documented knowledge as unstructured information. Their design scope is mainly limited to technology-driven solutions. This is surprising because the analysis of 30 knowledge work-improvement projects suggests a modified use of traditional business process design approaches and methods including nontechnical design strategies (Davenport et al. 1996). Only the business knowledge management approach (Bach et al. 1999) covers aspects such as roles and measurements.

5.5. A Method for Business Process-Oriented Knowledge Management

Since the late 1980s, the division of Corporate Management at the Fraunhofer Institute for Production Systems and Design Technology (Fraunhofer IPK) has developed the method of integrated enterprise modeling (IEM) to describe, analyze, and design processes in organizations (Figure 30) (Spur et al. 1993). Besides traditional business process design projects, this method has been used and customized for other planning tasks such as quality management (Mertins and Jochem 1999) (Web and process-based quality manuals for ISO certification) for the design and introduction of process-based controlling in hospitals and benchmarking. The IEM method is supported by the software tool MO^{2}GO (Methode zur objektorientierten Geschäftsprozessoptimierung—method for object-oriented business process optimization).

The method of integrated enterprise modeling (IEM) distinguishes between the three object classes ''product,'' ''order,'' and ''resource.'' These object classes are combined by the construct ''Action'' within a generic activity model. Five elements are provided to link the objects to the actions (Figure 31). The IEM approach offers the possibility of describing knowledge as an object within the process model. According to the overall modeling task, knowledge can be modeled as a subclass of the superordinated class ''resource'' and broken down into different sub-subclasses in the form of knowledge domains. The subclass ''knowledge'' can be linked to other ''resource'' subclasses such as ''staff,'' ''EDP-Systems,'' ''Databases,'' ''Documents,'' and so on that are relevant for the analysis and improvement of the business process. The final objective of every business process consists of the fulfillment of the internal and/or external customer demand with a product and/or service. Knowledge is required to produce and/or deliver this service or/and product and thus becomes implemented in the object ''product.'' This implemented knowledge could be divided into subclasses as well. The object ''order'' that triggers the actions could be translated into knowledge goals if appropriate.

The business-oriented knowledge-management approach starts with the selection of the business process to be improved. Davenport (1996) characterizes knowledge work processes as possessing a

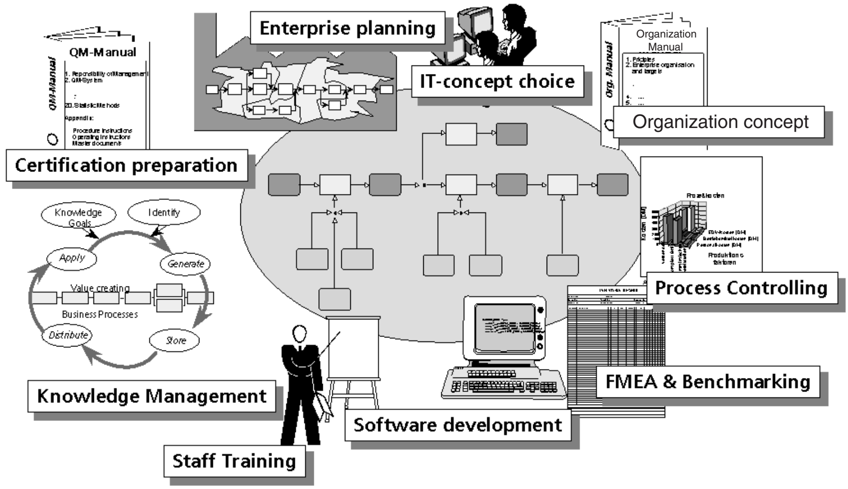


Figure 30 Application Fields of the IEM Business Process Models.

high degree of variety and exception rather than routine and requiring a high level of skills and expertise. The description of the real-world business process is carried out with the modeling constructs of the IEM method. After the description of the real-world business process, the analysis starts with the evaluation of each business task. The result is a knowledge activity profile that shows the level and quality of support provided by the current operational task towards the individual core

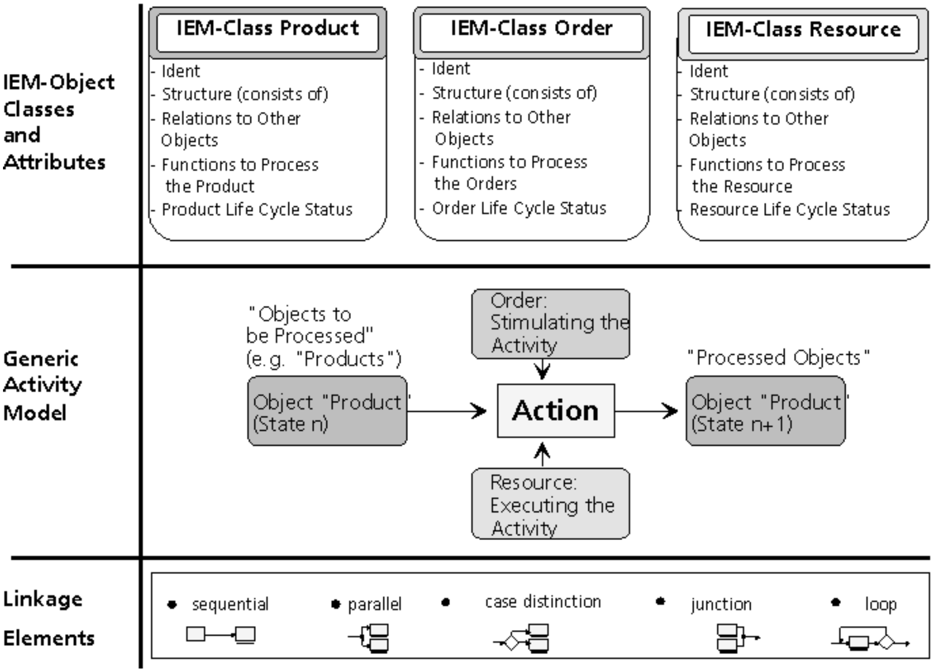


Figure 31 The Object Classes, Generic Activity Model, and Linking Elements of IEM.

tasks of knowledge management. The scope is then extended towards the analysis of the relations between the knowledge-processing tasks within the business process. This step contains the evaluation of the degree of connectivity inherent in the core process activities of knowledge management within the selected business process. The result shows whether the business processes supporting knowledge management are connected in a coherent manner. The optimization and new design of business processes aim at closing the identified gaps within the underlying core processes and sequencing the core tasks of knowledge management. One design principle is to use available procedures, methods, tools, and results from the process to design the solution. In the last step of the analysis, the focus shifts from the actions towards the resources used and the results produced within the process. The results of the analysis not only demonstrate which kind of knowledge is applied, generated, stored, and distributed but also the other resources, such as employees, databases, and documents. Due to the project aim of the improvement, the user will be able to evaluate whether the required knowledge is explicitly available or available only via the internal expert using the expert's implicit or tacit knowledge. The identified weaknesses and shortcomings in the business process will be addressed by knowledge-management building blocks consisting of process structures. The improvement measures have to integrate not only actions directed to a better handling of explicit knowledge but elements to improve the exchange of implicit knowledge.

5.6. Knowledge-Management Tools

Information technology has been identified as one important enabler of knowledge management. Nevertheless, transfer of information and knowledge occurs primarily through verbal communication. Empirical results show that between 50% and 95% of information and knowledge exchange is verbal (Bair 1998). Computer-based tools for knowledge management improve only a part of the exchange of knowledge in a company. The richness and effectiveness of face-to-face communication should not be underestimated. Computer tools promote knowledge management. The access to knowledge they enable is not subject to time or place. A report can be read in another office a second or a week later.

Therefore, a broad definition of knowledge-management tools would include paper, pencils, and techniques such as brainstorming. According to Ruggles (1997, p. 3), "knowledge management tools are technologies, which automate, enhance and enable knowledge generation, codification and transfer. We do not look at the question if tools are augmenting or automating the knowledge work."

E-mail and computer videoconference systems can also be understood as tools for knowledge management. However, we consider this kind of software to be the basic technology, that is, the building blocks for a knowledge-management system. Initially, groupware and intranets are only systems for the management of information. They become knowledge-management tools when a structure, defined processes, and technical additions are included, such as a means of evaluation by users.

This is not the place for a discussion about whether software can generate, codify, and transfer knowledge alone or can only aid humans in these activities. For the success of knowledge management, the social aspects of its practical use are very important. For example, a sophisticated search engine alone does not guarantee success as long as the user is not able to search effectively. It is not important for this study whether employees are supported in their knowledge management or whether the tool generates knowledge automatically on its own. This is an important point in the artificial intelligence discussion, but we do not need to go into detail here.

Syed (1998) adopts a classification from Hoffmann and Patton (1996) that classifies knowledge techniques, tools, and technologies along the axes complexity–sophistication and intensity along the human–machine continuum, indicating whether certain tools can handle the complexity of the knowledge in question and what kind of workload this means for the user (Figure 32).

5.6.1. Technologies for Knowledge Management

The following is an overview of the basic technologies used in every knowledge-management solution. The following explanation of the basic technologies helps to examine and classify tools more precisely. These are the technologies that we find today in knowledge management (Bottomley 1998). Different knowledge management tasks can be processed using these basic technologies.

Intranet technology: Intranets and extranets are technologies that can be used to build a knowledge-management system. The unified surface and access to various sources of information make this technology perfect for the distribution of knowledge throughout a company.

Groupware: Groupware is a further substantial technology that is used for knowledge-management systems (Tiwana 2000). Groupware offers a platform for communication within a firm and cooperation between employees.

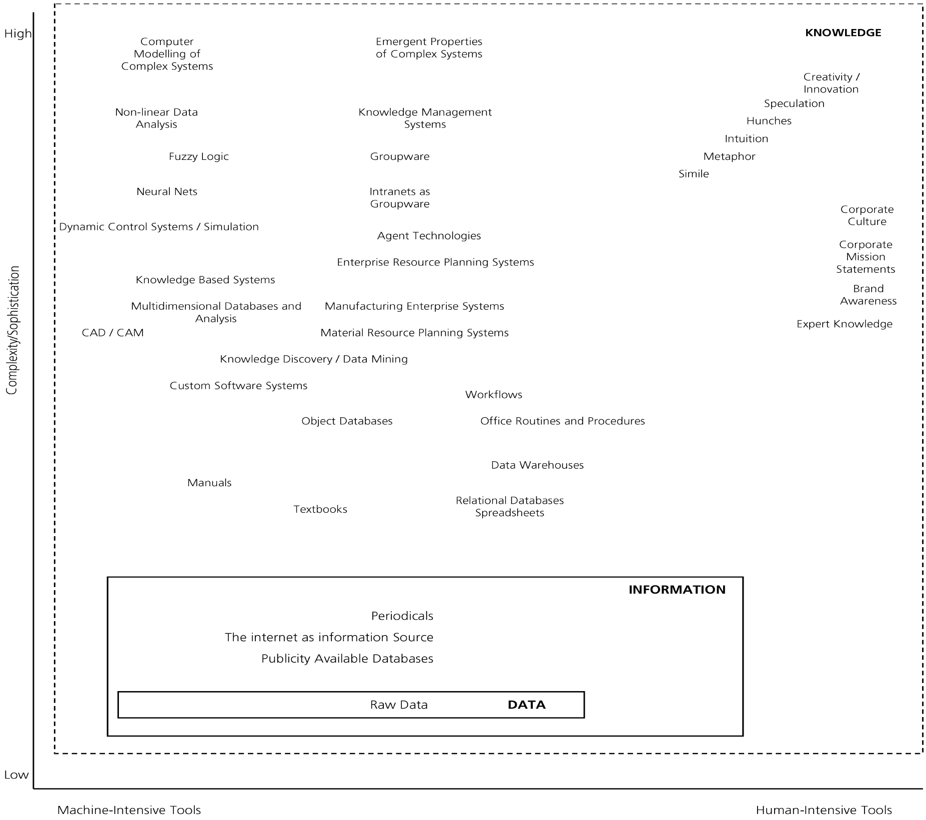


Figure 32 Knowledge Techniques, Tools, and Technologies. (From Syed 1998, p. 65, adapted from Hoffmann and Patton 1996 © 1996 by SRI Consulting, Business Intelligence Program. Reprinted by permission of SRI Consulting Business Intelligence.)

Electronic document management: Documents are a central means of storing and spreading knowledge. Procedures for using and maintaining such documents, such as a check whether an update is overdue, can be easily implemented for knowledge management systems.

Information-retrieval tools: Information retrieval offers a solution to tasks from text searches to the automatic categorization and summation of documents. Advanced search algorithms use thesauri and text mining to discover contexts that could not be found with simple queries. Semantic text analyses can also be implemented.

Workflow-management system: The business processes of a company contains a large part of knowledge. In addition, the integration of knowledge management into business processes is an important factor for success.

Data analysis: Pattern recognition and classification and forecasting are the techniques used for data analysis. Data analysis is a possible method for generating new knowledge.

Data warehousing: A modern database is where data and information are stored. Connections that are not readily apparent can be uncovered with the use of data mining and OLAP. These techniques are part of data analysis.

Agent technology: Software agents based on the essentials of artificial intelligence enable the user to search independently for information according to a personal profile and use various sources and other agents.

Help desks: Help desks are an important application area for case-based reasoning technology based on individual cases. Case knowledge can be quickly put into use in this way.

Machine learning: This technology from the field of artificial intelligence allows new knowledge to be generated automatically. In addition, processes can be automatically optimized with time with little necessity for human intervention.

Computer-based training: This technology is used to pass on knowledge to colleagues. The spread of implicit knowledge is possible with multimedia applications.

5.6.2. Architecture for Knowledge Management

Historical classification explains the special use of a certain product or how the manufacturer understands its use. The following historical roots are relevant (Bair and O'Connor 1998):

- Tools that are further developments of classical information archives or the retrieval of information.
- Solutions from the field of communication and reactivated concepts from the field of artificial intelligence come into play in the analysis of documents and in automated searches.
- Approaches to saving and visualizing knowledge also come from classical information archives.
- Tools for modeling business processes.
- Software that attempts to combine several techniques and support different tasks in knowledge management equally.

The Ovum (Woods and Sheina 1998) approach is an example of a well-structured architectural model. The initial level of the model consists of information and knowledge sources (Figure 33). These are delivered to the upper levels through the infrastructure. Next comes the administration level for the knowledge base where the access control is handled, for example. The corporate taxonomy defines important knowledge categories within the company. The next layer makes services available for the application of knowledge, such as through visualizing tools, and for collaboration, such as through collaborative filtering. The user interface is described as a portal through which the user can access the knowledge to use it in an application.

A further possibility is categorization according to the basic technology from which knowledge-management systems are constructed.

Most knowledge-management tools use existing technologies to provide a collaborative framework for knowledge sharing and dissemination. They are implemented using e-mail and groupware, intranets, and information-retrieval and document-management systems. Applications from data warehousing to help desks can be used to improve the quality of knowledge management (Woods and Sheina 1998).

5.7. Future Trends

Knowledge management is currently a buzzword on the agenda of top management and marketing and sales departments of software providers and consulting companies. Nevertheless, decision maker's awareness is increasing. Knowledge is regarded as one or even the main factor for private and public organizations to gain competitive advantage. First experience from knowledge-management projects show that a win-win situation for companies and employees is possible. By reducing double work, the company saves costs. Moreover, employees increase their experience through continuous learning and their satisfaction through solving new problems and not reinventing the wheel.

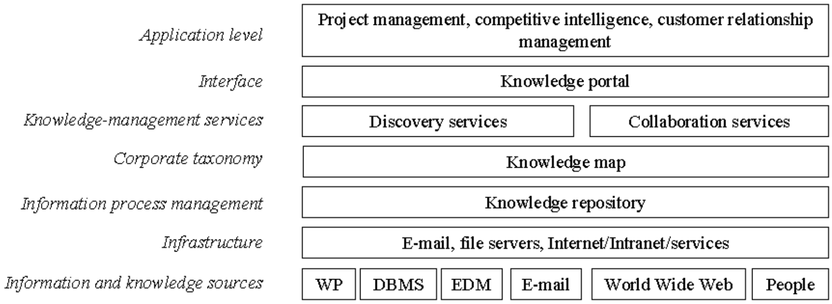


Figure 33 Ovum Knowledge-Management Tools Architectural Model. (From Woods and Sheina 1998, p. 8)

Even if knowledge management goes out of fashion as a buzzword, the essence of the idea of knowledge management—the systematic management of knowledge and experiences of the employees, suppliers, and clients—will definitely never be superfluous. Even in the dynamic new economy, experience and knowhow are still extremely important, as the example of retired experts who are very happy to pass their knowledge as "senior experts" on to young start-up companies shows.

With business process engineering, companies have focused their attention on eliminating non-value-adding process steps in order to improve their competitiveness by means of value-adding process steps. In the future, companies will regard their business processes as knowledge processing processes and enhance their ability to improve their use of their one and only competitive advantage—the knowhow of the people.

In the future, the basic technologies will be standard and increasingly integrated. This will require the integration of knowledge management in everyday business as well as a sense of responsibility from each individual. This will result in knowledge management becoming less discussed and more and more taken for granted.

For the exchange of knowledge to continue to improve, meta-knowledge will become increasingly important. Meta-knowledge helps to describe knowledge and specify its meaning. This form of description will have to be standardized due to the growing need for a global exchange of knowledge. This is apparent in the increased importance of Internet markets, which require a globally accepted description of products and thus knowledge.

In the IT industry, the dominant trend is toward takeovers of small, innovative companies. The market leader can then integrate new technologies into its standard product and advance that product.

Another future trend is toward knowledge management being practiced not only within companies, but between them. The Internet will reinforce the trend toward small companies being able to benefit more from the exchange of knowledge with other companies. However, some companies are becoming disillusioned regarding the use of new technologies. For example, intranet technology is taken for granted as a medium nowadays, although there is still uncertainty about what kinds of information it should be used to transfer to yield the maximum benefits. Despite continuing technological improvements in the future, people will still remain the definitive force.

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