Chapter 2
Overview of Virtual Product Development

This chapter provides an overview of product development with a focus on (but not limited to) automotive engineering. After a general definition of mechanical product development processes, the main terms, definitions and a selection of methods of virtual product development are introduced. This includes the history of CAD, CAE and PDM, a classification of fundamental methods of product modeling, and a short description of typical CAD-CAE process chains and product data management tasks in automotive engineering. The chapter closes with a brief introduction to the concepts of collaborative product development.

2.1 Development of Mechanical Products

Product engineering processes cover all operations for the development, manufacturing, use, servicing and disposal of products. Product development manages the creation of the product itself, under the consideration of different boundary conditions. In this way, product development processes include all of the operations necessary to bring a new product to market. This includes the idea generation, the concept phase, product styling and design and detail engineering, all of which are conducted in the context of market research and marketing analysis.

Figure 2.1 shows a typical product life cycle sequence. Product research encompasses both basic research work and product-specific investigations. The product planning stage is often embedded in the concept phase. In this first development phase, the main characteristics of a new product are defined and evaluated. After the concept phase, the series development includes the styling, the design and a detail engineering phase. The extent of the product testing stage depends on the product type. In the case of automotive engineering processes, the testing stage consists of far-reaching test and optimization work. Next, production-related processes are developed and implemented. After the start of production, the product manufacturing phase represents the last stage in the product creation cycle. The product distribution, use and liquidation (eventually recycling) stages take place in the market. During

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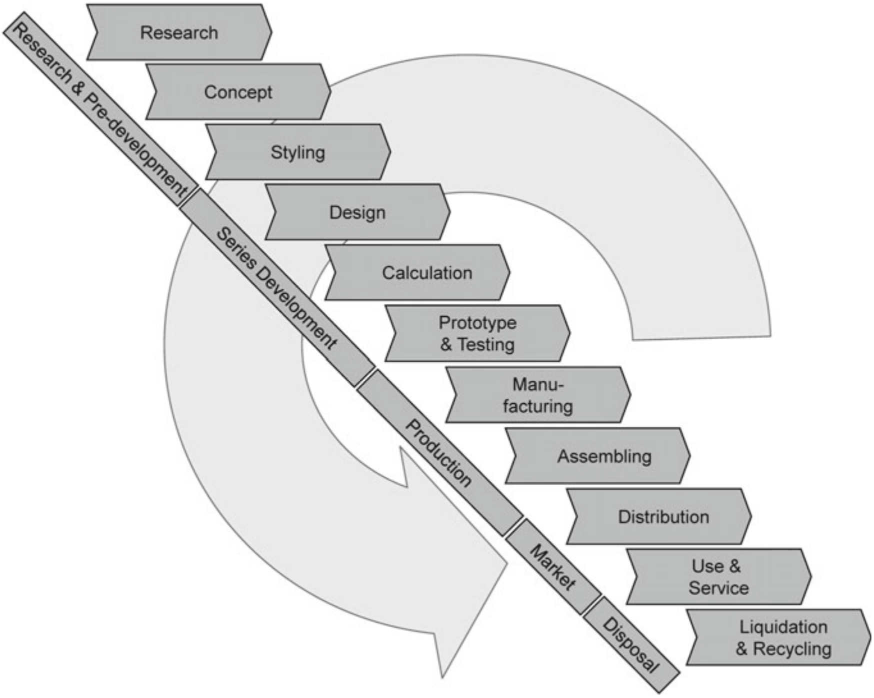

Fig. 2.1 Stages in a typical product life cycle

these phases, marketing-relevant factors, service and customer support have to be considered.

The German VDI 2221 guideline describes the stages in the development of mechanical products [1]. This standard process focuses on product development and does not include the entire life cycle. Regardless of the specific development tools and methods that are applied, the development process for mechanical products can be divided into five main stages (Fig. 2.2). In the first stage, the product requirements and specifications are defined. In the automotive industry, the description of product characteristics is supported by far-reaching market studies, research into constantly changing customer demands and an evaluation of future legislation-based boundary conditions in target markets. The cost-intensive development phase and production planning for a new car require a careful preparation of new automotive technologies or models. Typical car models have a production life time between 6 and 10 years, although some models are sold for more than 20 years. Adding a development time of about 2–4 years, a new automotive product (including new technologies) has to be competitive on the market for more than 10 years from the start of development. For this reason, it is very important to consider market tendencies and legislation-based trends in the very early phase of product development. A miscalculation of product characteristics can have negative effects on the economic success of a product, and

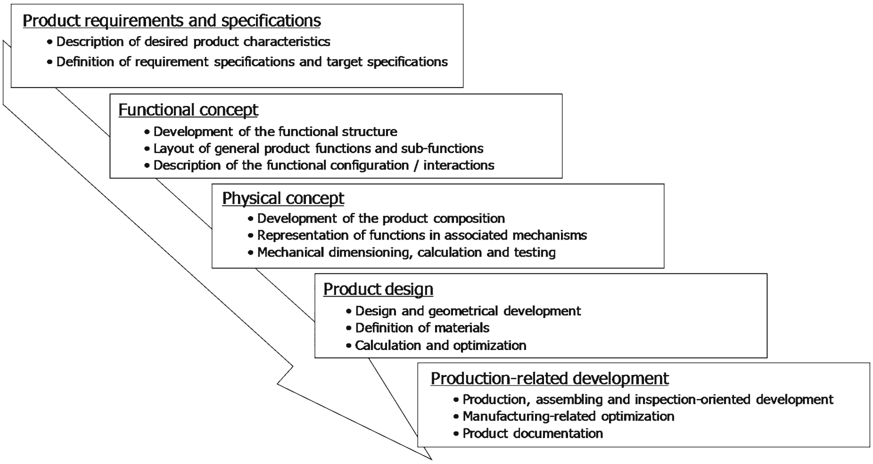

Fig. 2.2 Development process for mechanical products, according to [1]

consequently, due to the immense financial investment, undesirable effects on the car manufacturer.

The description of product characteristics provides the basis for the definition of the requirement specifications and target specifications of a new model. The requirement specifications include a complete description of the new product characteristics. The project initiator is responsible for the requirement specification list. In the case of automobile development projects, this can be the management board that has ordered the development of a new car model. Requirement specifications take into account functional and non-functional specifications. They include detailed information about the requirements of product design and describe the desired behavior of a product in terms of its operation. Supplemental information, such as quality standards and manufacturing-related boundaries, complete the definitions of boundary conditions for development. The target specifications, on the other hand, define detailed approaches for the development process of the product as a function of the requirement specifications. In this way, the target specification list consists of precisely defined solutions and derived working packages for the completion of the tasks that are defined in the requirement specifications.

The second stage of the development process includes the functional concept of the new product. The new technologies implemented are defined and assessed in terms of their functional configurations and interactions. A general product layout describes the definition of functions and sub-functions. All of the interacting requirements of a new product are checked in view of the requirement specifications and other influencing boundary conditions, such as legislation-relevant tasks or production-related influences. In the case of a new car, the packaging concept plays an important role in the functional development. Besides the general layout of a car model, several technological characteristics are defined in this phase, which requires the consideration of a broad variety of influencing factors (e.g. driving performance, vehicle safety, comfort, durability, and legislative/environmental requirements). New technologies in automotive components, such as new safety equipment or environmentally friendly propulsion technologies, are implemented and verified in terms of their general functionalities within the full-vehicle system.

The third stage tackles the physical concept. This stage covers the definition of the product composition. The development of new functions is carried out in associative mechanisms. Besides simulation work, this stage includes the mechanical dimensioning and calculation of components. In automotive development processes, the physical concept defines the vehicle body structure layout in consideration of crash and stiffness requirements. In addition, basic requirements of the new car concept are addressed, such as driving performance, fuel consumption, vehicle mass, and estimated values of driving dynamics. In the case of new drivetrain concepts (e.g. electric driven vehicles), this stage includes an estimation of the performance requirements and energy density, as well as the battery layout and capacity. These factors influence the battery mass and therefore the vehicle mass, center of gravity, driving characteristics and other factors. Together, the functional concept and the physical concept form the concept phase of a new product. In automotive development processes, the concept phase covers complex procedures that take into account a wide variety of influential boundary conditions and factors.

The fourth stage handles the product design phase, which is directly dependent on the product concept phase. The geometrical development of all components has to consider the assembly of the product and the interactions of components, as specified in the concept phase. Based on knowledge from the concept phase, the product components are modeled in detail and optimized. The materials are defined, and the boundaries for the production planning are derived.

Finally, the last stage consists of the production-related development. This phase goes hand in hand with the design process because manufacturing boundaries often influence the design of components. Thus, the production, assembly and inspection-oriented development and the manufacturing-related optimization (including supplier integration) interact with geometry creation and calculation processes. In former times, these sections were performed separately, but nowadays, a close information transfer supports an effective product development. As defined by VDI 2221, the final step is the product documentation, which includes all product-relevant information, as well as manufacturing data (e.g. workshop drawings and assembling guidelines).

The development process of mechanical products stipulated by VDI 2221 does not consider the development tools and methods applied. In principle, the standard is valid for the development of all mechanical products, regardless of the manpower, machines and methods deployed. While standardized processes of product development provide a framework, in the automotive industry, and especially in conceptual development, significant additional specification and development of new models, methods and tools for conceptual design are necessary. Since the late eighties, development processes in the automotive industry have been supported by computational methods and strategies. The trend is definitely going in the direction of integrated virtual development that supports the complete generation of a new car. Taking its cue from early pioneers in aeronautical engineering disciplines, the automotive industry

Fig. 2.3 Design office circa 1900 [2]

has also played a leading role in the development of software tools and methods for improving the virtual generation of new products, new technologies and manufacturing processes. Within the boundaries of a fixed development time and cost reduction, virtual engineering methods play an important role in the optimization of technologies and products through design, simulation, calculation, organization, production, distribution and other important tasks.

Figure 2.3 shows a design office around 1900. At that time, the main development tools were a pencil, a ruler and a lot of paper. Although today's development offices are characterized by the wide-ranging application of computational tools, human beings are naturally still the most important factor in the creation of new products.

2.2 Virtual Product Development

Virtual product development includes all IT-supported, virtual product-model-based processes for the generation of a new product. Virtual product models are used to perform optimization and testing procedures in a virtual environment with the goal of saving development time and costs, while simultaneously increasing the product quality. Depending on the categories of development applied, there are different types of virtual models. They can include market-relevant or business-case-relevant data (economic models), workflow-oriented information (process models), technical characteristics and descriptions (functional models), and geometry information (design models). Depending on the different requirements and characteristics of diverse disciplines, both the virtual models and the results generated can differ significantly. In general, the disciplines of virtual product development can be classified into main groups [3].

CAD ... Computer-aided design
CAS ... Computer-aided styling
CAE ... Computer-aided engineering
DMU ... Digital mock-up
CAM ... Computer-aided manufacturing
CAQ ... Computer-aided quality assurance
CAT ... Computer-aided testing

Depending on the type of product to be developed, several additional disciplines are applied within the main groups mentioned above, such as computer-aided software engineering (CASE), which is used in the development of IT-applications or mechatronic products with implemented IT-supported functionalities.

Efficient virtual product development is based on an effective interaction and integration of the various systems applied to enable a close cooperation with all participating departments and development partners. Virtual product development in the automotive industry uses a wide range of product models, which are connected by global data management systems. Data management is organized in different structures, depending on the requirements of the specific stages in the product development and life cycle. Different terms are used to describe data-management-related processes and functionalities (see Sect. 2.2.3 for an overview of product data management in automotive engineering).

Figure 2.4 shows the historical development of CAD, CAE and process-related management, with a focus on their application in automotive development.

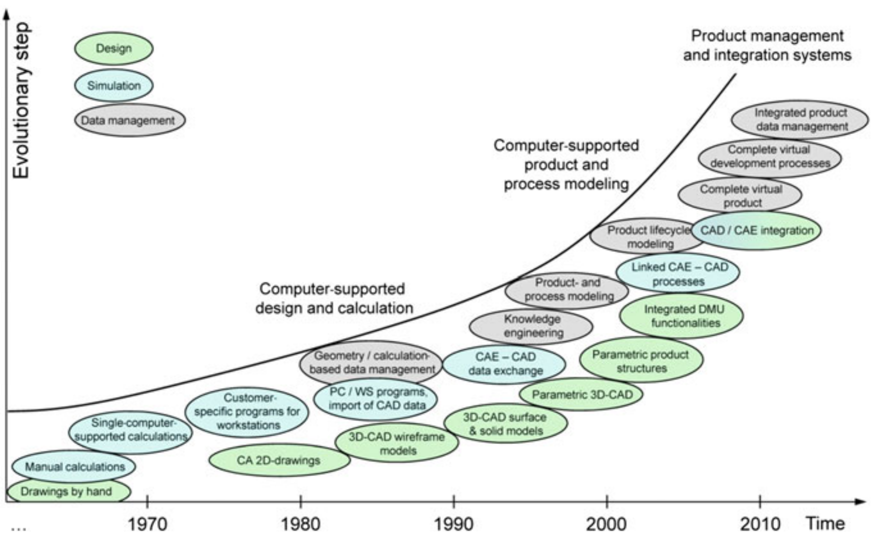

Fig. 2.4 Historical development of CAD, CAE and data management, based on [4–6]

The initial computation-supported functions emerged in the late 1960s. These applications enabled mathematical operations and calculations. The first commercial computer-aided drawing programs were used in the late 70s. These programs used simple functionalities for the generation of two dimensional drawings of technical products. Initial applications defined sketches using lines and circles, while later software included additional functions, such as predefined geometrical figures or the definition of axes, pattern or dimensions. In this way, it was possible to generate 2D product description and manufacturing-related workshop drawings. In the 80s, software suppliers began offering commercial calculation programs for personal computers and work stations. At that time, integrated simulation methods for broad applications were developed. Besides automotive manufacturers, automotive component suppliers also drove the development of product-specific simulation methods for detailed investigations of their products. Geometry-based and simulation-based product data were used in different fields, and this required the implementation of initial geometry-based and physically-based data management strategies.

The transition from 2D drawings to 3D models started in the early 80s, but commercially successful 3D CAD programs were first introduced about 5 years later. 3D CAD design changed the applied design methods significantly. Most importantly, the introduction of 3D surface and solid models resulted in the evolution of design methods from static, two-dimensional drawings in several views and sections to dynamic, three-dimensional virtual geometric product models. Besides a detailed and near-real-life representation of product geometry, these models included a variety of additional information and characteristics. With the help of 3D design, it was possible to integrate production-related knowledge or assembly-related information into the model. Die casting processes and forging procedures found their requirements displayed in 3D geometry models. For example, the design of die-cast parts included all the requirements of moulds and casting process. In this way, 3D geometry models were provided with draft angles and fillets based on the selected draft directions. Design engineers obtained knowledge from cast-model manufacturers that helped them take their requirements into account during the design process. This method enabled a direct derivation of the moulds from virtual 3D CAD models. Similar procedures were applied for the definition of forged components or for the programming of numerically controlled (NC) production machines.

Direct data exchange between design and simulation started in the 90s through the use of standardized neutral data exchange formats. In this way, it was possible to use geometry data defined in design software packages for the definition of product geometries in simulation processes. Imported geometry was used to generate meshes for finite element simulations, the representation of dimensions and inertia characteristics for multibody simulation, or for other types of calculations. At that time, initial modeling strategies supported the implementation of CAD data, material characteristics, load, restraints and other boundary conditions into an integrated simulation process. 3D CAD spurred the development of product-knowledge-related engineering methods. Information from successful projects was stored in CAD models and saved in templates or simplified databases to offer guidelines and basic data for subsequent projects. These methods enabled a direct transfer of virtual product-model-based knowledge and experiences from earlier projects into new tasks.

The parameterization of geometry data represented a significant evolutionary step in 3D CAD processes. Parametric-associative 3D CAD software separated the administration of geometry and its controlling parameters. A logical and precisely defined linkage of parameters and geometry in the geometry-creation process produced fully parameterized geometry models. The parameter-based control of geometrical model characteristics opened up a wide field of application for problem-specific design applications. Parameterized CAD programs offered additional functionalities, such as data interfaces, the integration of catalogue and knowledgeware functions, and the possibility of macro-based procedures. All of these functionalities characterize state-of-the-art CAD packages, which have come into use in automotive development.

The parameterization of geometry models in turn spurred a strong development of data management systems. Initially, product and process modeling, and subsequently product life cycle modeling, were essential for the organization of exploding data volumes. Powerful product data management systems (PDMS) supported the increasing integration of design and simulation processes. The trend in the software industry is definitely going in the direction of integrated packages, which combine parametric design software and simulation software in the same environment. Although this strategy reduces data interface losses, it has been criticized for the resulting reduction in directly compatible program platforms. Nevertheless, future intelligent geometry data exchange formats, which will be able to handle both geometry data and additional characteristic product information, should increase the efficiency of virtual product development processes significantly. In the case of integrated software packages, or in the case of communicating stand-alone solutions, virtual development will be extended to the entire range of product generation, starting from the concept phase, continuing in the different development steps (including manufacturing and production), supporting sales and aftermarket, and ending in the organization of disposal processes.

2.2.1 Product Models

Virtual product development processes are based on product data models, which are able to represent the specific product characteristics. Different applications call for dissimilar product models. In general, the primary methods of product representation can be classified as [3]:

- Geometric modeling
- Feature modeling
- Parametric modeling
- Knowledge-based modeling
- Structure representation
- Technical product documentation

In automotive development, the design engineering of products is performed using CAD. Modern CAD systems offer a wide variety of functionalities for 3-dimensional product creation, 2-dimensional drafting and the creation of components and assemblies. Besides geometry creation, modern CAD systems enable the definition of several additional product characteristics, such as material specifications, process-relevant data (e.g. for production), and product structure. Geometry creation is one important task in vehicle development. Therefore, state-of-the-art automotive development processes are often based on the geometry data of a 3D CAD/DMU master model. During the product definition process, this geometry-based model represents the current state of development and interacts with all of the simultaneously performed processes. This interaction includes geometry data export for the supply of CAE, as well as the import of data for modifications and advancements, which are delivered from simultaneously performed (CAD-external) operations.

The application of 3D CAD provides the basis for a three-dimensional description of the product geometry. Modern CAD systems offer the possibility of parametric geometry control, which can be used for manifold applications of integrated strategies. The geometry is built up through the combination of single components (parts) into an assembling structure. A systematic structure of the assembly in sub-products and main products based on the structures in real life brings the virtual geometry model close to the configuration of a physical product. Structuring tools include bills of material, product configurations, assembling simulation, and others.

In the related literature, the process of virtual product generation is divided into two main sections (Fig. 2.5), [7]. Virtual product development includes all tasks necessary for the creation of product geometry and the implementation of product characteristics. The virtual plant includes the development of all manufacturing-related procedures and simulations. In this phase, the operations of production are simulated and optimized within a virtual environment. In addition, the production development takes into account the implementation of supplier, logistics and controlling mechanisms, as well as financial aspects. Optimized virtual product generation processes are based on integrated virtual product models, which include the entire product description.

Virtual product development itself can be divided into three main phases. The first stage, 3D CAD design, includes the geometry creation based on product-specific features. These features can cover technical functionalities or production-related details, such as draft angles or fillets. The design process also handles the definition of materials and the product structure. The second stage contains the digital mock-up of product components, including tasks related to assembly and packaging. DMUs contain both the product structure and simplified geometric models of individual components or assemblies. DMU procedures calculate clash and assembly procedures and are used to check several geometrical interactions in a product structure, such as clearance or accessibility. In the third stage, the functional DMU (also called VMU - virtual mock-up) considers the functional integration of the product, including all of the features and functionalities necessary for a failure-free operation. These so-called virtual prototypes take functional and physical characteristics into account and enable functional simulations or calculations (e.g. kinematics, masses, center of gravity).

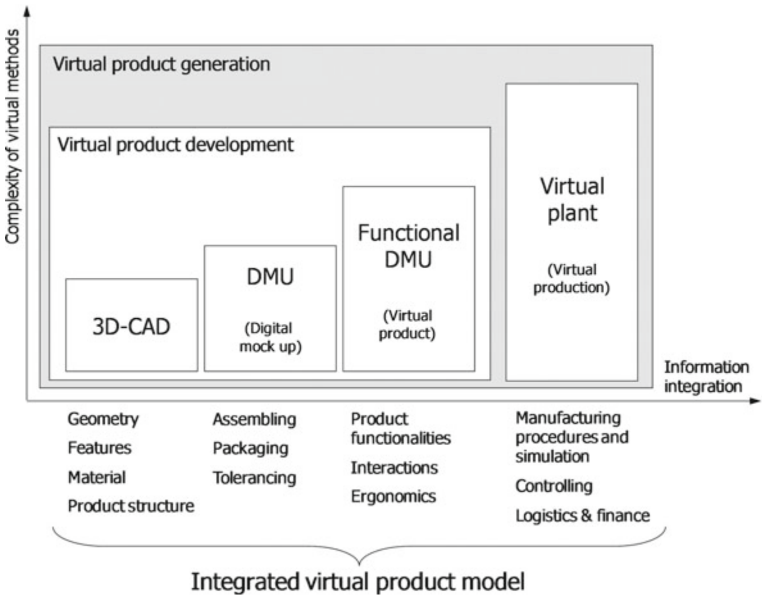

Fig. 2.5 Concepts of virtual product development, based on [7]

In automotive development, the placing of 3D CAD data at the center of virtual product generation is an efficient approach for the creation of an integrated development process. 3D CAD models of vehicle concept, styling, components and packaging serve as display units for each data status during the development project and supply all the other relevant processes with the required information. All geometry-based information is stored in the CAD model. In this way, it is possible to organize the product release updates and project progress steps via a centralized master model. The 3D CAD master model is in turn supported by a data management system, which includes the product structure and other additional information. Of course, the specific data and information required must be generated separately by the departments involved. For example, in crash simulation processes, crash-specific boundaries (e.g. forces, loads, material characteristics) are defined, in addition to the geometry-based information.

2.2.2 CAD-CAE Workflows in Automotive Engineering

CAD is used to create a geometrical product representation within a virtual environment. In automotive development, the product is composed of three-dimensional models in so-called 3D CAD programs. CAE includes a wide range of product calculation, simulation, optimization and planning processes in several disciplines

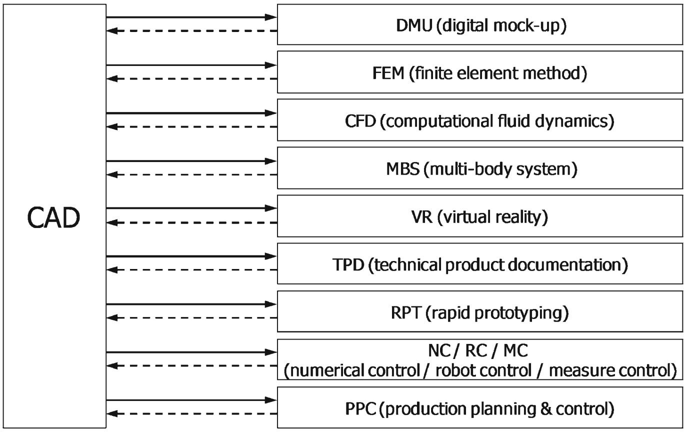

Fig. 2.6 Examples of CAD-CAE workflows in automotive applications [8]

(e.g. mechanics, electrics, electronics, optics), which are performed parallel to the geometry creation. Of course, throughout the virtual development cycle, design always goes hand in hand with computational engineering processes. In some literature, virtual development in general is denoted as CAx (computer aided technologies). The combination of different CAD and CAE processes can be displayed as process chains.

The following sections include a short introduction of typical CAD-CAE workflows. Based on a selection of typical automotive development processes, a short description of the main targets, applied procedures and data formats provides an overview of virtual-development-related tasks (Fig. 2.6). Different CAE applications are based on a 3D CAD master model, which serves as a data source. Depending on the data format and accuracy required, the geometrical product information is converted and transferred into the CAE environment. The black arrows indicate a direct data connection from the CAD system to the corresponding CAE process. The information backflow after the evaluation and verification of simulation results always represents an important task in efficient development cycles (dotted arrows).

Digital Mock-Up (DMU)

Digital mock-ups are digital dummies, which include a simplified geometrical representation of a product. DMUs contain information about the product geometry (volume and/or surface models) and the product structure. DMU processes are used for packaging studies, clash detection, mounting and assembling simulations and other 3D CAD-based analysis steps. Converted (simplified) 3D CAD data from a virtual product model (master model) form the basis for DMU processes. The data transfer can be accomplished using native CAD data or using neutral data formats

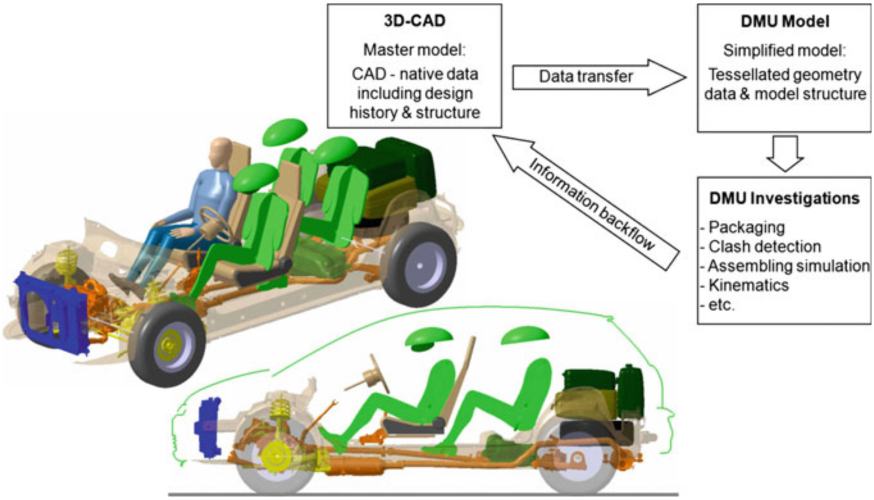

Fig. 2.7 DMU workflow based on a conceptual vehicle packaging study [8]

(e.g. STEP - standard for the exchange of product data [9], IGES - initial graphics exchange specification [10], JT - jupiter tessellation format, VDA (*Verband der Automobilindustrie*, [11]) formats). Due to a certain degree of geometry simplification, the accuracy of DMU models is lower than that of the corresponding 3D CAD master models (i.e. DMU uses tessellated geometries). Direct modification of geometry data is in general not possible within the DMU process. DMU supports simultaneous engineering approaches by handling large data structures throughout the product development, by localizing and eliminating geometrical problems in complex assemblies, and through target-oriented, assembly-based optimizations. DMU methods permit a geometrical freeze in early stages of the development cycle by integrating functional investigations into the DMU process.

In automotive development, DMU investigations cover the creation of assemblies (including components and devices), analysis and simulation (e.g. assembly procedures, movement and space investigations, collision checks, mounting and installation simulation). DMUs are often linked with simulation procedures, such as kinematical simulation processes for the optimization of movable functionalities (e.g. door-opening mechanisms, wheel suspensions, movable components in engines). Figure 2.7 depicts the DMU workflow and shows an example of a conceptual vehicle DMU, which includes initial styling information, carry-over parts from a model platform (drivetrain components, under-carriage and suspension), placeholders for wheels and luggage, and simplified human models and seat geometries. In this example, the DMU process supported the early layout of a new car model and enabled a coordination of vehicle styling proposals with the geometrical requirements of component and ergonomics configurations.

Finite Elements Method (FEM)

The finite elements method is used to calculate stress, deformation, thermal load, structural dynamics or NVH (noise, vibration and harshness). The FEM separates the continuum into finite, simple areas or volumes (finite elements), which are connected at defined nodes (mathematical discretization). FEM calculation processes are based on approximated geometries, derived from a 3D CAD model. Depending on the type of geometry and on the simulation target, different types of approximation are used. The calculation method is based on the creation of a hypothetical continuum, which is divided into simple patches or sub-bodies (*meshing*), which are in turn connected at defined nodes. The deformation of the infinitesimal mass points is approximately described as a function of the node deformation by means of a displacement approach based on an *element type*. This enables the separation of the distributed variables into space and time variables. FEM is suitable for the modeling of geometrically complicated, homogeneous structures in the fields of statics and strength and for the higher-frequency range of the motions [5, 12]. The geometry data transfer from the 3D CAD model into the FE-program is performed by a discretization process. Boundary conditions of loads (e.g. forces, moments), restraints (e.g. bearings, fixed parts), material characteristics, temperatures and other factors are defined directly in the FE-program. Figure 2.8 shows the general data flow in FEM processes using an exemplary application in engine development.

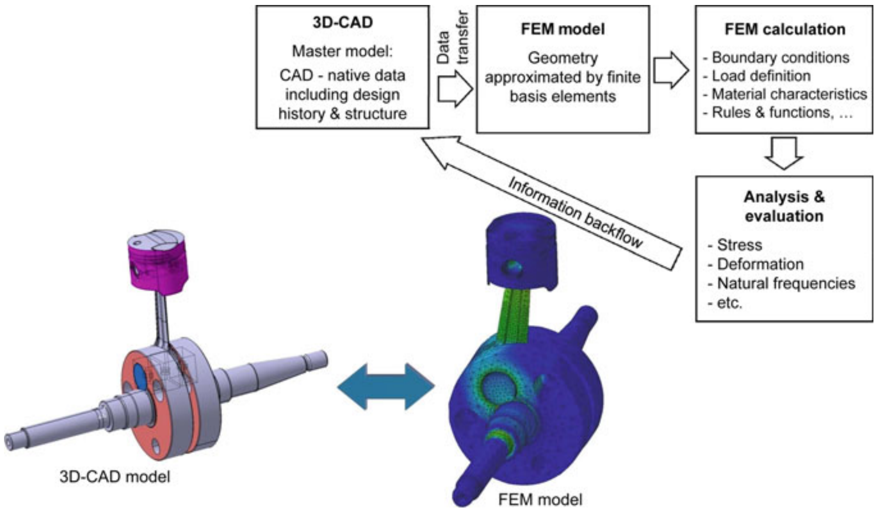

Fig. 2.8 Data flow in FEM processes and exemplary FEM simulation of a 1-cylinder engine crankshaft

Computational Fluid Dynamics (CFD)

Computational fluid dynamics simulation enables the calculation and optimization of gaseous and liquid flow processes. Similar to the FEM calculation process, the CFD model is based on an approximated geometry, the CFD mesh. The treatment of flow problems leads in general to an infinite dimensional differential equation system with space-dependent and time-dependent distributed variables (partial differential equations), which must be dicretized for the practical solution and simplified via idealizations. The idealizations selected depend on the actual interest and task and on the expected accuracy of the results. The discretization (meshing) can be performed at different levels of complexity, depending on the actual tasks and the required accuracy. One-dimensional flow calculation represents the flow characteristics along a streamline (e.g. within a tube). Three-dimensional flow calculations use spatial meshing procedures and are applied for complicated geometries, such as body flow (external aerodynamics), engine compartment flow (internal aerodynamics), and channels in combustion engines. The data transfer from the 3D CAD model into the CFD program is performed by neutral standard data formats (e.g. STEP, IGES), and the boundary conditions for the calculations are defined directly in the CFD program. Figure 2.9 shows the workflow of a CFD simulation and the results of an injection spray and air-fuel ratio simulation of a 1-cylinder motorcycle engine.

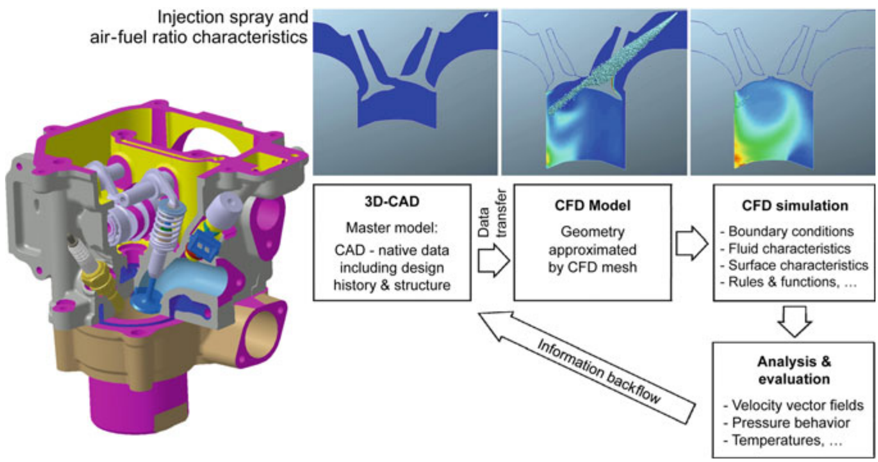

Fig. 2.9 Cylinder head assembly and CFD simulation of a motorcycle engine

Multi-Body Simulation (MBS)

Multi-body simulation is used for the kinematic and dynamic calculation and optimization of assembled (movable) parts. MBS models are based on general geomet-

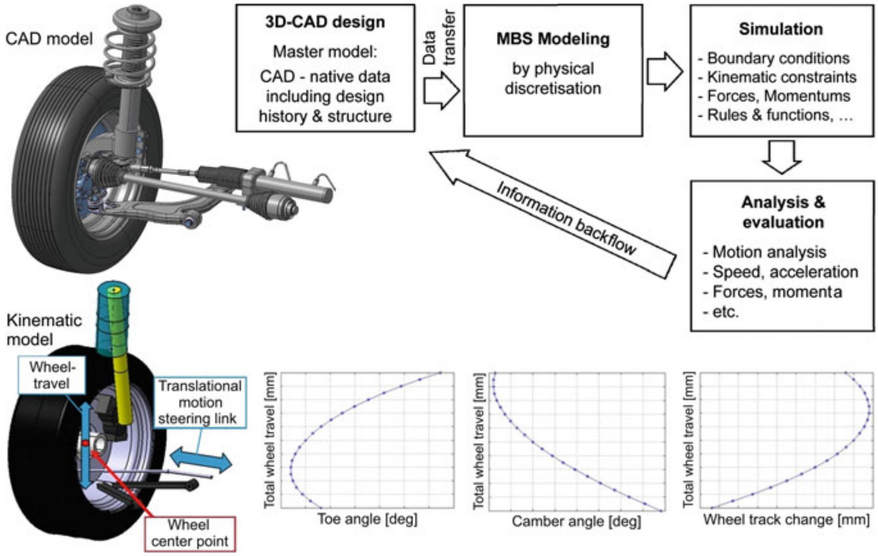

Fig. 2.10 MBS of an automotive suspension

rical definitions in CAD product structures. They consist of stiff bodies or mass points, which are connected with each other or the environment by joints (kinematic constraints) and/or by specific force laws. They are very suitable for modeling complex, inhomogeneous structures, such as full vehicles, and particularly for the low-frequency range of the motions. The boundary conditions (e.g. forces, torsional moments, masses, moments of inertia, degrees of freedom of movement) are defined directly in the MBS program. The separation of the locally distributed parameters into discrete parameters (e.g. mass, inertia, stiffness, damping) leads to a so-called physical discretization of the product model. Besides a rigid consideration of kinematic systems, elastic sub-bodies from FEM-modelings can be imported and integrated on demand (rigid-elastic MBS). Advanced MBS also enables the consideration of non-mechanical couplings (hydraulic, pneumatic and electrical state variables), as well as the modeling of active control units [5, 12]. Figure 2.10 shows the general workflow of an MBS. In addition to the CAD model, the derived MBS model and selected results of the MBS of an automotive suspension are shown.

Virtual Reality (VR)/Augmented Reality (AR)

Virtual reality and augmented reality generate virtual environments as real-time simulations for product representation and product-related investigations. They partially incorporate the user in virtual surroundings and product-related operations. AR functionalities enable the implementation of additional information and data into a VR environment (e.g. look-through functions or the accessibility of (virtual) con-

Fig. 2.11 VR equipment and illustration at a power wall [13]

trol units). The real-time interactions of geometries or functionalities support the assessment of procedures, in-use tests and product evaluation. The ability to manipulate objects gives the virtual product a near-real-life feeling. Besides development-related tasks, VR and AR technologies are used for applications in personnel training, maintenance, marketing and education. One specific data format for these types of applications (VRML - virtual reality modeling language) was designed to display 3D models and to integrate user-based interactions. VRML data, which are generated from a 3D CAD master model, include simplified geometry information without product history or structural data. Figure 2.11 illustrates examples of virtual reality application in automotive development. In the left figure, a realistic representation of exterior surfaces supports the styling evaluation process, while the figure on the right shows a look-through model of a car door module.

Technical Product Documentation (TPD)

Technical product documentation enables the derivation of technical drawings, bills of material, spare-part lists, prospects, and other items directly from the 3D CAD model. In order to enable a TPD generation, the CAD master model has to include all of the required information (e.g. product structure, geometry, tolerances, material, production related data). TPD formats include text-based formats (PDF - portable document format), 2D vector and pixel graphics (DXF - drawing exchange format, TIFF - tagged image file format, GIF - graphics interchange format), hypermedia formats (HTML - hyper text markup language, XML - extensible markup language) or 3D documentation software-based formats (3D PDF, WRL - web rule language) [14, 15]. TPD processes are always linked to standardization regulations and guidelines (e.g. ISO - International Organization for Standardization, DIN - German Institute of Standardization) and company-defined standards. Figure 2.12 shows examples of TPD, namely part lists, workshop drawings and an expanded view of a motorcycle crankshaft.

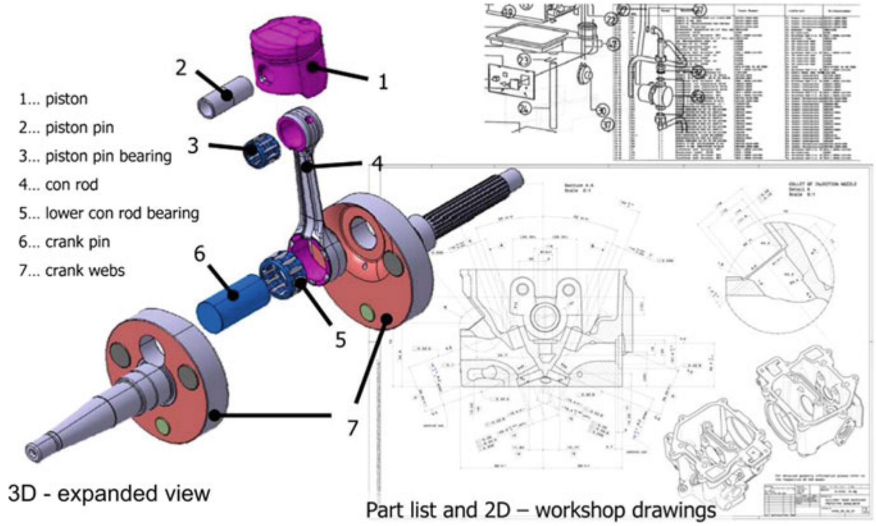

Fig. 2.12 Examples of TPD

Rapid Prototyping (RPT)

Rapid prototyping is used to generate hardware models from virtual geometry data during the product development phase. Such prototypes, which are available at an early stage, enable real-life studies, test bench optimization or customer discussions. RPT is used for concept models, design or ergonomic studies, or functional tests and optimization. Rapid prototypes are generated from tessellated geometries, which are derived from 3D CAD master models. The most common file format is STL (structural triangle language). STL geometries are calculated via triangulated surfaces with no design history or product structure information. RPT production techniques include laser sintering, stereo lithographic, 3D-printing and others. Figure 2.13 depicts the 3D CAD model, rapid prototyping parts and the physical component of an automotive cylinder head.

Numerical Control/Robot Control/Measure Control (NC/RC/MC)

Computer-aided numerical control, robot control and measure control cover manufacturing related process engineering tasks. These tasks are carried out in the course of computer-aided manufacturing (CAM), which addresses IT-supported functionalities for the control and monitoring of manufacturing resources. In NC/RC/MC processes, product geometry data are converted from a 3D CAD master model into a manufacturing-specific environment (language). Besides the geometry information, the master model includes all production-relevant data (e.g. tolerances, surface treatment, material characteristics). An NC data model contains machine-specific

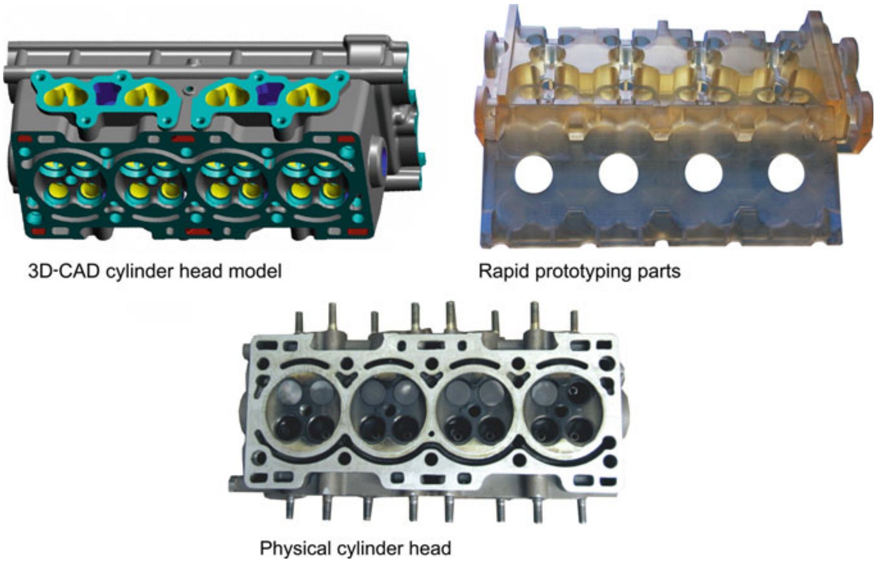

Fig. 2.13 Application of rapid prototyping in cylinder head development [16]

information about the applied tools, model fixation, cutting speed, and other factors. RC data enable the handling of assembly-relevant product information in manufacturing processes. MC data define prescribed measurement procedures for the analysis of the manufacturing process, deviation of tolerances or abrasion parameters. Figure 2.14 shows examples of numerical control machining and robot control simulation within virtual environment.

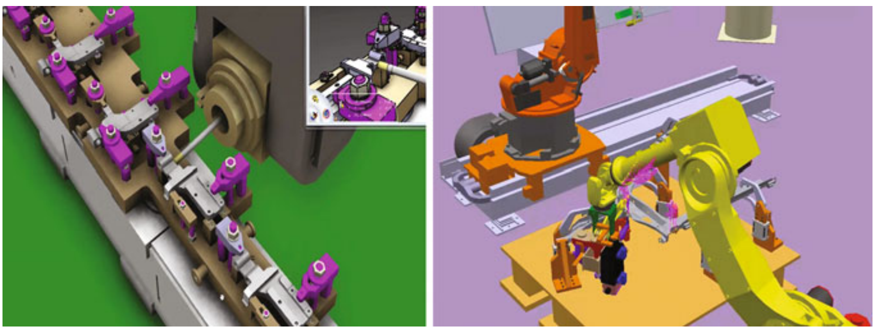

Fig. 2.14 Examples of NC and RC simulation [17]

Production Planning and Control (PPC)

Production planning and control includes the administration and organization of manufacturing-relevant data and procedures. Only released product data are transferred into the production planning process. PPC data are organized in BOM (bill of material) structures and based on 3D CAD geometry, 2D drawings and additional manufacturing-relevant information. Two important influencing factors are the working schedule and manufacturing resources. First, the basic economic and operational functions of PPC include the management of customer orders, the project calculation, the planning of requirements, the material logistics, the production capacity calculation and the order release organization. Second, PPC covers production-control-related tasks, such as production management and control, operating data logging, controlling processes (time, quantity and costs), and shipment management.

Whereas PPC covers the economic and operational tasks of manufacturing, CAD/CAM operations basically handle technical functions. The working fields of CAD/CAM can also be divided into two groups. The first group includes planning processes, such as the product concept development, design and simulation, process planning material logistics and the programming of production machines and resources. The second group includes the control of manufacturing and quality-management-related procedures. This covers the control of NC-machines, transportation control, storage management, assembly control, maintenance management and quality management.

2.2.3 *Management of Product Data*

Product life cycle management (PLM) includes all organizational tasks necessary for the identification, supply and archival storage of product-related data during the product life cycle. The management of all data flow, processes and documents during the development or modification of products across the product life cycle provides the basis for an efficient virtual product generation because complex product structures or product variations create numerous product parameters and a great amount of information. Product data management (PDM) organizes the data and information flow throughout the development process of a product, prevents data redundancy and is an important component in the generation of complex product structures in multi-firm and global collaboration [14].

Product data can be classified into different categories.

- Product-defining data related to technical requirements include all kinds of data for the product specification. In the case of automotive development, this can be driving performance, car weight, fuel consumption, dimensions, targeted vehicle configurations and other factors.
- Product-describing data related to technical product documentation are all of the information that can be found in lists (e.g. BOM).

- Geometry data include CAD model files, styling data, geometry data exchange formats, CAD-based product structures and other design-based data.
- Information concerning the development process itself includes workflow data, management of resources, data for engineering organization and others.
- Product configuration data include information about possible variants. They define the setup of the car in accordance with the customer order, including the type of engine and transmission, safety features, colors and all the possible accessories.
- Metadata describe additional product-related facts, such as production-related information or data for calculation and organization.

Of course, the management of product data includes the maintenance of different types of documents. Besides the main examples of product data, the documents can be classified using characteristic criteria, which address data quality, the age and maturity of data in the project progress, and the status. Further classifications are made based on data formats and the utilization and validity of data.

Due to the introduction of virtual methods in design, simulation and data management, modern IT-supported technologies have emerged in nearly all areas of mechanical industries in recent years. New methods and strategies have been developed to tap the potential of virtual product development processes, which has led to the implementation of new procedures, methods and tools in industry, education and research. IT-supported engineering in design, calculation and documentation characterize virtual product development, whereas specific CAx methods handle the generation of tasks, product models and process models that span multiple disciplines. In the automotive industry, virtual product development processes focus on different fields and disciplines. Depending on the specific tasks, these can address styling, vehicle packaging, component design, assembly, different types of simulation, production development and others. The goal is to integrate individual processes into incorporated virtual development processes supported by efficient data transfer and management.

The integration of virtual product and process models has enabled new approaches in design, simulation and manufacturing, which presents a challenge in the development of new IT methods for data transfer and data organization. Complex development processes require IT support and therefore the generation of PDM systems and other network-based information technologies. In addition, integrated data organization simplifies the documentation across the entire development process. An efficient documentation concept supports process and data standardization and enables network-based development by supplying product information that is available worldwide. Finally, knowledge databases, drawn from successful projects, can be created using an existing PDM network. These databases can be used for the re-integration of knowledge and product data into new project creation process chains and the re-use of experiences for variant studies and product optimization.

The new technologies lead to new possibilities and require new working methods and procedures: from static, theme-related working methods to dynamic, process-related working methods; from individual, hierarchic work to team-based work embedded in multifunctional structures (e.g. matrix structures); from document-based methods to integrated, virtual-product-model-based development. This change calls for the implementation of new networking processes and structures with a high demand for flexibility. Process-oriented working methods require an intensive time schedule with a detailed planning and management of several part-processes and sequences. To tap the full potential of virtual product development, a powerful management system of the entire process structure is needed. Earlier processes, which focused on digital models of the product, were unable to manage the data and information flow efficiently. The increased orientation on virtual products requires an increased implementation of integrated and linked development. Compared to the past, the processes and methods applied are becoming more important, which results in a change in the working procedure and working organization and presents a challenge to the people involved. In Sect. 6.4.1, *product data management* is treated in more detail.

2.2.4 CAD-CAE Data Exchange

The exchange of product data within the same software environment is mainly performed by native data formats. Native data are generated during the development of product-related information within one program. They include product data, information concerning the product development history, and methodological and organizational data. Thus, native data contain much more than purely discipline-specific information (e.g. the product geometry in the case of 3D CAD). Heterogeneous data exchange (e.g. importing product geometry information from a 3D CAD program into FE simulation software) is accomplished with the use of neutral data formats.

Neutral data exchange formats enable the transfer of product data between different software applications. In the case of product design and simulation-related processes, neutral data formats provide product geometry data and limited additional product information for the exchange between different CAD software packages or between CAD and CAE applications. Neutral data formats can be divided in geometrically accurate systems, which transform CAD-native product information into sets of mathematical descriptions of the model geometries. Examples are IGES, STEP or VDA formats. Besides a purely geometrical representation, enhanced neutral data formats are able to include additional facts, such as product structuring information or the configuration of components, modules and sub-assemblies.

The second group of neutral data formats concerns solutions which are able to convert the product geometry into models with approximated (tessellated) geometry. These formats yield geometry information that are less accurate but which also contain significantly lower data volumes. Examples of neutral data formats with tessellated geometries include STL, VRML and WRL. In addition, XML-based (extensible markup language) geometry description also works with tessellation algorithms. These approximated product data are often used in DMU-based investigations or for visualization tasks.

The JT format is a special neutral data format. This type of data exchange language provides a mathematical geometry description by applying BREP-based (boundary representation) algorithms, which rebuild the model geometry with groups of faces, edges and vertices. In addition, the JT format also provides tessellation algorithms for the creation of approximated geometries. Furthermore, product metadata can be transferred using this type of neutral data format [14, 18].

For the application of neutral data formats, specific converters are required to convert CAD-native geometry information into the corresponding format. In the case of data import, neutral data have to be converted or integrated into the corresponding software-specific format, which means that the target program must be able to read the specific type of neutral data format.

Unlike native data formats, neutral data languages cannot contain detailed design-process-related knowledge, such as the design history, product parameterization, implemented algorithms or macros, functionalities, etc. Normally, only the geometrical contour can be transmitted, although in some cases it is possible to transmit some selected additional information. This limits the application of neutral data formats to geometry-based processes and restricts advanced automation or design integration. For this reason, alternative methods and strategies have arisen in recent years. One such method is to manage data exchange by integrating PDM systems. In this method, a PDM system manages the entire product data range, including geometry data, product structure and additional data, such as materials, tolerances, and production-related information. In the case of data exchange (e.g. between automotive companies and suppliers), the required data are provided by the PDM system. This method requires the integration of all corresponding development partners into a comprehensive PDM system and a clear definition of the data models applied.

One trend is moving in the direction of integrated PDM systems, which integrate the corresponding CAD and/or CAE software packages, e.g. [17]. This strategy enables a universal data exchange, depending on the applied workflow. A centralized PDM system provides CAD-native data, as well as neutral geometry data and data for calculation, simulation or testing procedures. Depending on the type of development process, the specific required data are supplied and transferred. The ability to closely integrate CAD and PDM enables direct access by the PDM system to design-related native data (e.g. the product parameterization or specific constraints or links) which have been defined during the design process. In this way, collaborative design methods can be supported directly, without applying neutral data formats (e.g. via internet or intranet-based communication technologies), even in the case of a worldwide distribution of development partners.

The disadvantages of integrated PDM systems with directly integrated tools are relatively rigid structures and stiff data management in terms of the applicable software. The integration of external software (software from other software suppliers) into product development processes requires the application of neutral data formats. In addition, the data exchange performance depends on the data link provided, which can cause problems in the case of the large data amounts characteristic of complex products. Independent of PDM-related strategies, collaborative development methods call for the application of online data exchange and direct product data access across the entire development process chain. In addition, future data exchange formats will facilitate object-oriented methods for the supply of simulation processes and the creation of associative referencing techniques within complex virtual product structures [19].

2.2.5 Concepts of Collaborative Product Development

Industrial development processes have included methods for collaborating strategies for many years. More powerful IT systems and the capabilities of virtual engineering and data management have supported an increase of data exchange and have opened up new ways of collaborating. Modern development strategies, as they occur in automotive development, are only possible with modern networked processes. Although integrated, cross-linked strategies offer a significant potential for the improvement of development efficiency and data quality compared to traditional, sequential development methods, they require a significant re-configuration of established structures and procedures. Two important factors of success are the implementation of knowledge-based workflows in early phases of product generation and the integration of different development disciplines into a comprehensive consideration of product-related parameters. These approaches require extensive planning and preparation phases under consideration of the specific requirements in the relevant organization structures.

The integration of collaborative concepts of product development faces several challenges, including the application of complex communication and data flow structures, as well as the implementation of knowledge management strategies. Besides a resource shift into early project phases, the methods of collaborative development applied are based on the utilization of partially unreleased data and procedures. This requires efficient evaluation and assessment methods to avoid incorrect decisions in the very sensitive phases of product definition. The following short overview introduces three collaborating product development concepts, which have been applied within the current fields of research and development.

Concurrent Design

Concurrent design is a cooperative product development method that is based on the breakdown of complex design tasks into several subtasks. These subtasks are carried out by specialists more or less in parallel sequences. All engineering processes are linked, and the complete development process is supported by a data management system. In concurrent design, an efficient data and information exchange between the subtasks is an important factor. All participating parties (specialists) have to be informed about the sequences of processes, the content of each step and the data exchange procedures.

Synchronization of individual development steps can be performed with the help of DMU methods, in which the product is assembled and checked in the context of geometrical tasks. For example, the design process of a cylinder head is arranged as parallel design steps of the cast part, valve train components, other inner parts and the cylinder head cover (Fig. 4.9, p. 255). One important factor in concurrent design is the definition of design interfaces, such as flanges, adapter geometries or the implementation of skeleton models.

Simultaneous Engineering

Simultaneous engineering covers not only the design process, but the entire product development phase. Instead of working sequentially through stages, simultaneous engineering defines a parallel workflow of development tasks. For example, the tool design might be started before the detailed designs of the product components have been finished. The engineer begins the detailed design of solid models before the concept design surface models have been completed. Although simultaneous engineering does not necessarily reduce the amount of manpower required for a project, it can drastically reduce the development time and thus the time to market entry (Fig. 2.15). Especially in conceptual development, it is important that all responsible departments participate in simultaneous engineering. In automotive engineering, the concept phase has to consider several requirements, including legislative demands, crash and safety, functional aspects, packaging, production-related boundary conditions and many more. The early availability of broad information enables efficient, target-oriented product development.

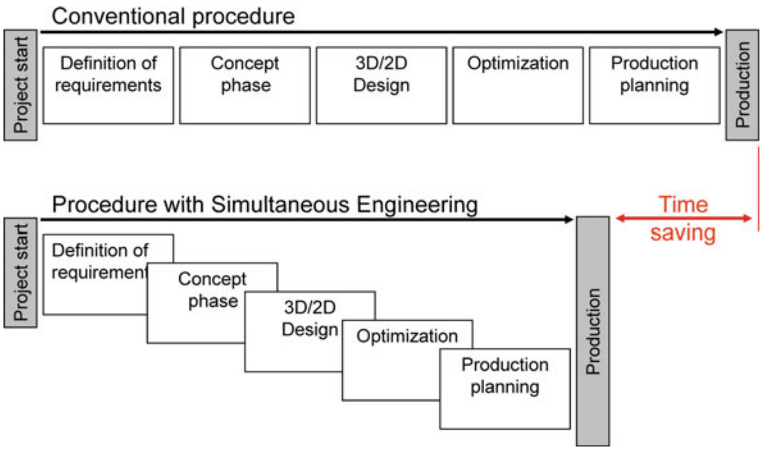

Fig. 2.15 Workflow in simultaneous engineering [12]

Frontloading

Frontloading is used in product feasibility studies, product planning and the early phase of product development. The goal is to define the product specifications as early as possible (as many characteristics and tasks as possible) in the concept phase. To achieve this, it is essential to use knowledge from former projects. Frontloading methods are based on a resources shift into the concept phase, in order to find solutions in the initial phase. This leads to an intensive application of knowledge-based engineering methods in combination with design and simulation steps. This can lead to a reduction in development time through the determination of product characteristics as accurately as possible and the elimination of functional product failure in the early phase, when the degree of freedom for product-related characteristics is high. The foundation is the availability of knowledge from former product development processes, which is supported by the provision of product-related information, the support by expert knowledge in the early phase, the use of simulation methods, and knowledge from former product life cycles (knowledge databases, lessons learned). In this way, frontloading methods are able to reduce the risk of failure in later development steps [2, 20].

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