Abstract:
One of the most challenging tasks in the engineering profession is to develop new products that have the shortest lead-time, highest quality and lowest cost with optimal life-cycle consideration. The issue of product modeling is at the center of various new product development paradigms designed to meet this challenge, and, therefore, has received major attentions from application and research communities. Due to the fast developments of computer and information technologies and the increasing demands of competitiveness and productivity, the scopes and approaches of product modeling have evolved rapidly in recent years. This paper presents an overview of the state-of-the-art and practice of product modeling in terms of product models and process chains, and suggests some important issues for further investigation.

Keywords:
computer-aided design, product development, modeling

1 Introduction
The demand for higher quality and lower cost products with shorter development lead-time for the dynamic global market needs has forced industries to focus on various new product development strategies. For example, the CIM concept emphasizes the interconnection of different technical and management functions within a company by using computer systems from design through manufacture. Lean production strives to minimize the development costs by making organizational and cultural changes with higher employee involvement and optimal exploitation of proprietary knowledge. Simultaneous engineering focuses on integration of complementary engineering expertise, cooperation of multiple competing perspectives, communication of upstream and downstream product life-cycle concerns, and coordination of group problem-solving activities. The product lifecycle concept extends the development considerations from technical aspects to the limited resources of our world, focusing on environmental protection and occupational health issues. Other strategies, such as "Faktale Fabrik" (fractal factory) and virtual manufacturing, are all trying to address the critical issue of product development productivity in order to enhance the industrial competitiveness.

Although each of the above strategies has somewhat different focuses and approaches, they all share one fundamental requirement: that is the need for advanced information technologies to integrate and coordinate various life-cycle considerations during product development activities. A central issue among these needed information technologies is product modeling, which generates an information reservoir of complete product data to support various activities at different product development phases. Therefore, product modeling is the key factor in determining the success of various product development strategies and industrial competitiveness in the future.

Figure 1: Complete Product Life-Cycle Concerns

Product modeling technologies must not only support those new product development strategies described above, but also deal with other manufacturing related models, such as factory models including, resource models, equipment models, machine models, and tool models. This indicates that product modeling, while is a unique subject in itself, is a very broad topic closely related to many other challenging issues in modern manufacturing engineering and complete product life-cycle concerns as indicated in Figure 1. It also shows that the issues of information processing for product modeling is very complex in engineering practice. To take full advantage of the available information technologies and minimize capital investments, it is desirable to adapt to an open system architecture in the implementation of product modeling technologies. As well, it is necessary to broaden engineering education and direct basic research so that the potentials and restrictions of product modeling approaches can be evaluated and realized by future engineers who are responsible for developing new products in industry.

The importance of product modeling has been widely recognized by the research and application communities over the past several years. A clear trend moving toward a wider usage of product models and a strong emphasis on product modeling processes is observed. Although this trend is clear, no definite and commonly agreed product modeling approaches exist to date. There are still major debates on the best approach to this problem, and many open fundamental issues must be addressed in order to fully realize the benefit of product modeling. The aim of this paper is to present the evolution and the current state of the art and practice of this important subject, and to offer some recommendations on its future research, development, education and application directions.

2 Background
2.1 Historical Perspectives
Although product modeling itself is not a completely new subject in some aspects, the fast development of modern information technologies and the increasing demand of product development productivity over the past decades have led to some new meanings and expanded scopes of this topic. It is, therefore, useful to briefly examine the role of product modeling in the evolution of product development activities. The position of product modeling in the historical evolution of product development activities is shown in Figure 2.
Computer-aided design was introduced around 1960 63/6. Up to the nineties, a large variety of geometry-based approaches has been developed, ranging from two-dimensional drawings to three-dimensional representations with connections to NC-programming and other manufacturing applications. During the eighties, some major new possibilities, like knowledge processing and computer simulation, to enhance the capabilities of geometry-based approaches came into view. The demand for integrated, instead of isolated, product development practice during this period led to the concepts of product model and process chain.

The growing software capabilities to support design, planning, and manufacturing tasks made it necessary to change in-house product development strategies and enable close communication with suppliers in industry. Work flows have become a very important consideration for increasing the performance of product development and manufacture. Besides linking different product development tasks by directly connecting software (called the interfacing approach), standardized data formats or common databases have come into use. The disadvantage for their uses is the requirement of specific post- and pre-processors. Some example standardized data formats are IGES, SET, VDAFS, DXF, and VDAIS. These standard formats only allow for the representation of two- and three-dimensional geometrical models for electronic data exchange. A unique and consistent representation as well as data management without too much redundancy is not supported to date. Therefore, the so-called product models which enable a system-independent representation and data management of all relevant product information are still in demand.

In order to introduce the idea of product models into industrial use, a pragmatic approach is necessary to realize the application benefits progressively. For example, a step towards complete product models can be partially achieved by combining the capabilities of geometric models, engineering data management systems (EDMS), and production planning and control systems (PPC). In the past, CAD/CAM and PPC systems had their separate data structures which were difficult to access from different applications. Therefore, an important step towards the integration of product data is to employ EDMS, which allows the physical integration of all product data of existing CAD/CAM and PPC systems.

The information technology that is useful for supporting process chains should be able to support the whole product life cycle concerns. The organizational structure in a company are an important factor in the wide application and full adaptation of product modeling technology. Their skill, engagement, devotion, creativity, and willingness to make use of new ideas and tools determines the degree of acceptance of product modeling and its success. The organizational structure in a company strongly influences the information flow and how decisions are made, which should be carefully considered when developing and adapting new product modeling technology. The product strategy decides the policy and ways under which new products are developed. Product policy contains the decisions to develop a new product and the time to deliver it to the market.

The available information and the technology is one of the most decisive factors in developing product modeling applications. The generation of products is dependent not only on the market and customers, but also the available knowledge and information about the capabilities of the factory and suppliers. With the rapid development of computer and information technologies, it is possible to expect a situation where a set of information, such as factory models including tool or material flow models, order models, usage models or feedback information are all linked together tightly. It is clear that new product modeling approaches have to consider the complexity of product development tasks and their interdependencies. It can be foreseen that, in the future, it will be possible for companies to have all processes in factories supported by information technology, and all relevant information about products will be completely available in digital forms.

3.1 Determining Factors of Product Modeling

A very important aspect is to realize that product development and product modeling activities are a multi-facets subject determined by many complex factors such as human, organization, product strategy, and available information technology. Failure to consider any of these factors will lead to a poor investment return in this area. For example, the employees of a company are an important factor in the wide application and full adaptation of product modeling technology. Their skill, engagement, devotion, creativity, and willingness to make use of new ideas and tools determines the degree of acceptance of product modeling and its success. The organizational structure in a company strongly influences the information flow and how decisions are made, which should be carefully considered when developing and adapting new product modeling technology. The product strategy decides the policy and ways under which new products are developed. Product policy contains the decisions to develop a new product and the time to deliver it to the market.

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3.2 The Role of Process Chains and Product Models in Product Modeling

Product modeling has its central focus on process chains. Process chains should represent all tasks to be performed in a product life cycle. They consist of product development workflows, production workflows, maintenance tasks, and recycling considerations. The challenge is to first generate process chains for specific products, and then manage the cooperation and integration between process chains for different products in a factory. It is also necessary to optimize the efficiency of these process chains to be able to compete with other products on the market. Process chains should be the driving factor in the development of product models to support product modeling application and research efforts.

The information technology that is useful for supporting process chains should have the capability to record intermediate and final results as product model data. In general, a product model data is determined by its structure and content. The structure is dependent on the nature of the product and the tools used to model the information as well as to build the necessary schemes for the database. The content is dependent on the particular product. A product model can be further structured into submodels, creating so called product models 62/ as seen in Figure 3.

![Figure 3: Contents of Product Models and Submodels](image)

**Figure 3:** Contents of Product Models and Submodels

Partial models contain information of specific tasks from process chains. For example, a function model is a partial model of a product model to support the functionality phase of the product strategy. If properly organized, this functional model can be shared by a number of products, although the content will always be individual to each. A clustering of partial models is possible, if needed, for efficiency reasons. There are partial models which are always necessary, and others which are only used in special cases. For example a set of models could contain geometry, topology, and product structure information. These models.
can be clustered in an embodiment model. A technology model consists of material, tolerances and surface roughness. A planning model contains process plans, assembly plans, and inspection plans. Also requirements and failure cases. In this context, a product modeling technology should fulfill three basic requirements: presenting actual data, facilitating product documentation, and offering decision alternatives.

The term actual data has two inter-related meanings in product modeling. First, it is necessary that all activities performed during different phases of a process have the same and identical data available to them about a particular subject. If some information is changed in the design phase, the process planning phase has to know about it. Second, during the use of proper database management technologies, it is possible that several activities can access the same data at the same time. As will be explained further in Section 5.1, concurrent access to actual data will require that changes can be immediately noticed by all parties concerned.

The documentation aspect of product modeling should be structured according to the process and product information. The process or workflow information is necessary because of the need for not only the historical description but also the ability to keep the changes in order to reconstruct the decision processes at a later stage. The product information has to keep the intermediate and final results available, as well as store the product specifications for long-term retrievals.

The schemes of the reference concept represent sequences of activities related to the actual data. This has to be supported by the reference model representing sequences of activities related to intermediate product stages. For structured modeling of product information the development of the reference concept has to be based on fundamental principles of information modeling. These are: enterprise characterization, life cycle view, specification, and management of these large databases.

A key to the successful product development effort is to minimize those unnecessary iterations throughout the process chains. This requires taking into consideration the upstream phase. If there always exist many uncertainties from downstream at early stages, it is necessary to be able to offer and preserve decision alternatives at early stages to account for the future uncertainties. A useful product modeling technology, therefore, should be able to support the representation and exploration of process and product alternatives in order to reduce costly iterations and increase product flexibility. Such decision alternatives can be seen as the “tolerances” of product models as a conceptual level.

In order to meet the above basic requirements, database management systems (DBMS) with a proper architecture are needed to provide data management facilities in an integrated CIM environment. The strategies developed in IMPPACT (Integrated Modeling of Products and Processes using Advanced Computer Technologies) can be generalized to support this point /12/. The key to data integration is to manage the data it describes and to interface it to a data manager without those implementation constraints imposed by other existing DBMS. The manager of the data described by the reference concept does not need to be a new DBMS. Instead, existing physical DBMS should be used to perform the data management operations under the control of the data manager. Figure 3 depicts an overview of the IMPPACT DBMS architecture designed to meet these requirements /29, 32/.

In order to store product model data, a reference concept, which contains all elements of data and their connections, was developed. According to STEP (Standard for the Exchange of Product Model Data), the concept should be written in the formal information modeling language EXPRESS and use the basic principles of object orientation /28, 29, 30/. Other description methods, such as NIAM (Nijssen Analysis Method) /13, 14, 60/, are in use as well. As the main purpose of a reference concept is to enable the integration of process chain modules, it is necessary to perform both software integration and information integration between functions for a manufacturing enterprise. Future process chain modules also need to have the possibility to communicate via this concept which should be independent of implementation solutions. A sufficient consistency with standardization efforts can improve the acceptance of the concept. It is also important to support adjusting general process chain modules to enterprise specific needs. Meeting these requirements, an integrated reference concept can provide an integration framework for product data, production activity data and equipment data.

For process planning purposes, it is necessary to be able to model a product at different stages of its production. This has to be supported by the reference model representing sequences of activities related to intermediate product stages. For structured modeling of product information the development of the reference concept has to be based on fundamental principles of information modeling. These are: enterprise characterization, life cycle view, specification, conception, and representation, as described in Figure 5.

The schemes of the reference concept are stored in the Common Data Dictionary (CDD) which contains data about data and constitutes a conceptual schema for various database operations. It is the link between the logical and physical data models. Since the data in CDD can be treated like any other data, the same interface to DBMS tools can be used to manipulate CDD data. In order to address multiple physical DBMS, Data Location Information has to be added to entity definitions in CDD allowing the distribution of data on a per entity basis. The schemes stored in CDD are used by a Data Manager (DM) to manipulate data. These operations are initiated by the CIM modules using the Data Manager Interface, which is a procedural interface to the DM in the sense of standard data access interface (SDAI) of STEP. The goal of the Data Manager is to support the exchange and sharing of data by multiple CIM modules. The DM can be seen as a general DBMS which stores the necessary semantic content of the reference concept and has access to several storage managers in the form of commercially available databases. The distance between the reference concept and the implemented systems can be seen as a measure of the quality of product models /30/.

**Figure 5:** Example of an Integrated Reference Concept /31/
from the technological point of view, the above three basic requirements lead to several fundamental challenges in terms of information consistency, redundancy, reliability, and security. Consistency is expressed in a system as well as semantic form. Syntactical consistency is easier to maintain because only the conventions of information representations need to be checked against some predefined rules. Semantic consistency is more difficult to achieve, however. Some aspects of the consistency issue can be handled by planners to analyze whether values of parameters are within the prespecified allowance. Other semantic dependencies have to be processed by problem specific programs or methods. No general solutions can be given. Mechanisms for maintaining associativity can also help to perform semantic consistency checking in some ways.

Traditionally, redundancy is often seen as absolutely unnecessary. In the case of product modeling, however, redundancy can be helpful in terms of optimizing processing efficiency and representing decision alternatives. Therefore, the term controlled redundancy is useful here. It makes sense, for example, to have different representations of product shape for different applications, such as FEM models or a drawing. But, instead of regenerating data for each different application, this information should be derived directly from the product model data generated by the design department. Reliability of information is not only important in a single application, but also if the same information is used in different applications. In this way, the data model for each application is more reliable and redundant than if the same data are represented in each application.

Types of Product Models and Some Examples

As an extension of geometry-oriented product models, feature-oriented product models provide the ability to represent often used shape patterns as coherent geometric items, called form features. Form features are application independent because they do not carry any specific non-geometric semantics. Most of the form features represent shape patterns which have a specific semantic meaning concerning the design or manufacturing process [16, 19]. To better support design and manufacturing tasks, it is necessary to extend the concept of form features by the explicit representation of the semantics. As a result, features represent the integration of form features and application-dependent semantics.

In product modeling two main classes of features, design and manufacturing features, can be distinguished.

Design features support the designer to communicate with a design system easily according to their design intent. During conceptual design, features in terms of primitive geometric elements or symbols can be used to describe the properties and functions of the desired product. Using symbols a sketch of the functional representation can be created. Manufacturing features are defined as the interpretation and, most importantly, the combination of form features from the viewpoint of manufacturing, assembly and inspection. Like design features they are constructed by combining shapes depending on their position in the workpiece [64].

As an example, FEAMOS (Feature Modeling System) is a system for defining and using features for design and manufacturing applications (Figure 6) [50, 51]. Using FEAMOS, the product is modeled in terms of features including the processing of the geometric shape. It provides the protocol of the history of the product modeling process. This history, called the part design tree, is more than just a journal of the geometric modeling steps. With the use of feature technology the history assesses only the steps which are important for the product modeling process. The feature model supports the whole product development process beginning with the processing of product requirements models based on QFD (Quality Function Deployment) via detailed design, process and fixture planning to NC-program generation for machining as well as measuring tasks [25, 74].
Another approach to feature-based modeling can be seen by function-oriented models [17]. In this approach, high-level functional features are used to create mechanical parts and product geometry. These functional features are predefined in the Part Definition Language (PDL) and can be easily customized to accommodate various applications. Further examples of feature-based product models can be found [17]. After performing exploratory work for simple models in the domain of extrusion, injection molding, and casting, the origins and definition of features and their subsequent applications in designing and manufacturing preparation have been studied. Tentative taxonomy of features has been developed. Based on these results, a general architecture for a design-with-feature systems is proposed. It consists of design-with-feature library, feature operations library, and primary/secondary representation of products with features. After creating primary representation by design features, it can be converted into various secondary representation for specific applications, such as manufacturability evaluations.

4.1.4 Knowledge-based product models

Knowledge-based product models are characterized by the use of AI techniques like object-oriented programming, rule-based reasoning, constraints, and truth-maintenance systems [54, 73]. Through the employment of these AI techniques, it becomes possible to store human expertise explicitly as well as experience concerning products, processes or factory environments. One important characteristic of knowledge integrated models is the ability to build abstract taxonomies of products or processes as objects and to store knowledge about former designs, possible alternative parts in an assembly or the abilities and validity of processes used for a specific class of products. The use of knowledge-based models enhances the capabilities of information support during the product modeling process, although the automated processing of knowledge in a variety of application systems remains a topic for further research.

An example of the knowledge-based product model is IDEEEA (Intelligent Design Environment for Engineering Applications) [53, 34, 56]. This system integrates frame-based representation, constraint-based language, rule-based reasoning, truth-maintenance systems, and object-oriented composite values, and has interfaces to analysis programs, databases, and solid models (see Figure 7).

Figure 6: Application of a Feature Processing Kernel

Figure 7: IDEEEA as an Example of Knowledge-based Product Models

It can capture both symbolic and numerical knowledge from domain physics and human experts, support hypothetical reasoning from different perspectives, automatically identify conflicting decisions and support their resolutions, and perform multi-directional problem-solving activities driven by different life-cycle concerns. The system has been used by industries for product modeling, process planning, and enterprise integration tasks. It has also been used as the underline software layer for a design process recording system, called PRIME (Providing Reference Concepts for Discrete Part Manufacturing). The goal was to develop and demonstrate a new generation of integrated modeling systems for product design and process planning. In regard to the development methodology for product models, the outcomes have influenced the progress of STEP. The results of IMPPACT were the developments of (1) an information modeling methodology for product models, (2) generic as well as specific reference concepts for discrete part manufacturing, (3) system components for integrated product and process modeling, and (4) an EXPRESS based object-oriented database management system for the integration of distributed database systems. Results of IMPPACT have been demonstrated in the application areas of the sheet metal parts manufacturing for aircraft spaces and complex shaped parts manufacturing for ship propellers.

Another European research project, linked to the STEP activities, is the ESPRIT Project 2165, NEUTRABAS (Neutral Product Definition Database For Large Multifunctional Systems), which aimed at the development of a neutral product definition database for large scale, multifunctional systems /2/. The multifunctional aspect creates special requirements for product information modeling and database design methodologies.

A comprehensive modeling scheme for an integrated-product model was studied in ESPRIT Project CAD* (CAD Interfaces) /6/. The integrated product model in CAD* contains all the information for each phase for design and manufacture. It covers all the technical product information and includes semantic relations. The integrated product model is structured into several logical clusters, i.e. partial models. Distinct partial models have disjoint entity sets, but overlapping sets of relationships. They consist of a function model, a technical shape model, a geometrical model, a technological model, parameter model, a viewing model and production model. Among those models, associativity is defined, where some of the modeling parameters can be derived from other parameters. The result of this project is partially contributing to the development of STEP.

Another example of integrated product models is a HITACHI CAD/CAM System for large scale industrial machine products /36/. This system has been constructed for the purpose of integrating the whole product development and manufacturing preparation activities. Targets products are large-scale products, such as nuclear power plants, water turbines, gas turbines and steel mills. They are produced based on order, and production volumes are very small. and have many variations. For coping with those requirements, a comprehensive engineering database has been developed where general product models can be defined. A product model consists of the following components: core models, such as shape, figures and attributes, product structure specifications, presentation models, such as drawings, manufacturing models, such as process planning, and manufacturing environment models. The system has been used extensively, and a large volume of product data has been accumulated for retrieval usage. The basic idea of this system has been further extended to be more tailored forms /37/.

PACT (Palo Alto Collaborative Texted) is a concurrent engineering infrastructure that encompasses multiple sites, subsystems and disciplines /18/. It aims at integrating existing multiproject systems which have been developed with no anticipation of subsequent integration. PACT is trying to share knowledge among systems that maintain their own specialized knowledge bases or product models by utilizing the standardized knowledge interchange format KIF. KIF is a proposed standard notation and semantics for an extended form of the first-order predicate calculus. Instead of defining integrated shared product models, PACT offers facilitators among systems, and realizes semantically integrated product models in a logical viewpoint. This seems to be a practical approach to meta-level modeling scheme for an integrated product model. As an example, a manipulator design system has been constructed, where a rigid-body dynamics analysis system, electro-mechanical device design system, a digital circuit design system and a control system design system are integrated.
4.1.6 Model Standardization Using STEP

One of the most significant approaches towards the implementation of integrated product models is the development of the ISO Standard 10303 "Standard for the Exchange of Product Model Data" (STEP) which defines a neutral data format for the representation and exchange of product data /59, 78/. The goal is the complete and system-independent representation of all product-related data during the product life cycle. The description of the data format provides a suitable basis for the definition of a neutral file format, the design of a product database and the conceptualization of a procedural interface. With regard to the information scope and possible forms of implementation, STEP goes far beyond the publication potential of previously available interchange formats like IGES, SET or VDAFS which primarily facilitate the exchange of geometric information. STEP was the first approach which introduced the idea of complete product model exchange into standards and is a methodology for the development of application oriented software. STEP development, although, having delivered already some standards, needs more elaboration. In the future, it could work as an information infrastructure for product model representation in order to integrate the whole product development processes.

ISO 10303 can be broken down into a series of partial standards. At the core of the standard, information models for the representation of product data are defined. Among the various information models it is possible to distinguish between integrated resources and application protocols. Application protocols constitute implementable subsets of STEP. They define the specific segment of the entire information structure required for supporting a particular application. The integrated resources are further divided into generic resources and application resources. The generic resource models define application independent basic elements which can be used in several application resources or directly in application protocols. Application-specific resources are tailored to a higher degree to the requirements of particular domains, but serve as a stack of elements for the definition of the application protocols. An example of an application protocol for the automotive industry is shown in Figure 8 /72/.

To represent and develop the STEP information models a variety of tools for information modeling have been used /78/. One of the tools, the data specification language EXPRESS, was developed to support the development of integrated information models /58, 59/. EXPRESS consists of language elements which allow for an ambiguous object definition and specification of constraints on the objects to be defined. Implementation methods define the structure of physical files and the database access using the Standardized Data Access Interface (SDAI). The implementation of a database in the STEP format is based on data structures described in EXPRESS. In contrast to the physical file, the use of the SDAI allows data access independent from the physical representation of STEP data.

![Figure 8: STEP Application Protocol of Automotive Industry](source)

Although the standardization process of STEP is not yet finished, a growing number of companies and organizations, e.g. ProStep, PDES Inc., STEP Tools, Nippon STEP Center, as well as GOSET, are already developing STEP-based applications. These efforts are aimed at the development of the standard itself, especially through the development of application protocols. Another important goal is the development of pre- and post-processors to facilitate a STEP-based communication with existing CAD/CAM systems as early as possible.

4.2 Types of Process Chains and Some Examples

Process chains, another important consideration in product modeling, can be performed manually or supported by computer systems. According to different application needs and technological possibilities, a variety of process chain types can be distinguished. Here, five basic types of process chains and some representative examples are described. Some mixtures of these types may exist in industrial usage.

4.2.1 Process chains without product models

There are two types of process chains (see Figure 9) in this category:

1. A sequence of conventional and computerized tasks is connected to perform the product development processes (Figure 9.a). In this case no product model is used. The computer supported tasks can work on models which can be submodels of product models. These processes are characterized by the difficulties of media incompatibilities, possible loss of information due to manual actions and manual process control.

2. The capabilities of the computerized process chain are faster processing but still there may be redundant data. The interfaces between tasks can be realized by direct communication links with standardized data formats. The process is also manually controlled and no data management mechanism is available (Figure 9.b). Processes of this kind have been created in the past because of the lack of product models.

![Figure 9: Process Chains without Product Models](source)

An example of the second type can be found at AEG /57/. At AEG, process chains were realized to support cutting, punching, bending, and EDM processes for tool and prototype production. Available CAD and NC/DNC systems were integrated using standard as well as system specific data exchange formats. Standardized formats such as IGES and VDAFS have been used for data exchange with suppliers. To reduce the effort for NC-preparation an organizational structure for the representation of CAD data was developed, which allowed for the exchange of NC-relevant data only. Furthermore the efficiency of NC-processes was increased by attaching additional semantic, representing parameterized descriptions of company specific elements to the product shape. The transfer of semantic information between the CAD and NC-System was based on system specific data formats. Machining elements, such as hole patterns, slots or pockets were used for automated tool selection as well as tool path generation. Thus the graphic oriented NC-programming procedure was supported in an efficient way.

For NC-data management and up and down loading to CNC-machine a DNC-system was used. However this led to the problem that the same product component was represented several times in different formats. Furthermore product data belonging to the same product were stored in different data management systems without any reference to each other. This fact caused consistency and redundancy problems because version management was difficult. A solution of this problem is to introduce an overall data management system, supporting the administration of product related data in an object-oriented way. There have been a large number of activities in connecting CAD models with NC /22, 23, 24/.

4.2.2 Process chains with product models

There are also two types of process chains in this category (see Figure 10):

1. Connecting the tasks via product models has the advantage of using actual data for all tasks. Changes can be directly noticed by all tasks, redundancy can be controlled, consistency can be maintained, and the possibility to use the data of the whole process for documentation is available (Figure 10.a). However, the use of product models in this stage still is guided by the developers. The data exchange is performed by standardized interfaces.

2. As the previous structure is controlled by the developers, the demand rises to improve the performance of time control, change control, version control and communication control (Figure 10.b). A control system may be used also for synchronizing with other factory processes and to work on feedback as well as on market and supplier inputs. Therefore additional data, describing the progress and actual status of the product development activities have to be integrated in the product model.
4.2.3 Parallel process chains with integrated product models

Finally, the most advanced type of process chains is (see Figure 11):

(5) When parallel processes are to happen within the product modeling process, simultaneous or concurrent engineering is applied. Simultaneous engineering is also used for the connection of these processes to the outside. These are the already mentioned dynamic influences but also the cooperation with suppliers respectively order giving companies. Some of the most important attributes of simultaneous engineering are: parallel problem solving, team work in a distributed way, availability of adequate databases/product models, and project management systems. The connection of different product development phases which are performed simultaneously is shown in Figure 11. Up- and down stream information has to be controlled because product and project model data have to be integrated.

5 Future Demands for Research, Education, and Industrial Uses

The above examples indicate a clear trend in both the academic and industrial environments to move toward a complete digital representation of all product and process related information to support product modeling activities. Although this ideal situation of having 100% digital descriptions of products cannot be achieved at once and there still exist many debates on what are the most realistic, flexible, and economical ways to arrived at such an ideal state, many major research and application efforts are currently being devoted to advance the product modeling technology. Some of the most important demands from research, education, and industrial points of view are discussed here.

5.1 Research and Education Demands

Due to the limitation of current information technologies and the complexity of required information, it is necessary to segment the product and process information bases into logically related smaller components for easier management and higher efficiency. The concept of Segmented Total Product Model is therefore needed. Using Product Modeling to Support Digital Pre-Assembly

Irrespective of the selected type of process chain it is necessary to specify a methodology for the product modeling process which also has to include a product design logic. A product design logic for an intelligent product modeling system which connects the functional requirement to the geometric and technical information of the designed product was developed. The system represents geometry and technology and designer's thought process which explains the design logic. Another important aspect of process chains is the automatic determination of the optimal product Gestalt (product construction) by giving a complete definition of the design space, design restrictions and design goals such as maximum stiffness or minimal weight. As well, it should be noted that the general process description of design processes was developed over some decades. This approach is used as a guideline in the KALEIT-System, where the connection to a product model is also performed. In order to improve product quality the product modeling process itself has to embody methodologies for designing in quality. Therefore methodologies like QFD, including the definition of customer's functional requirements, competitive bench marking and reverse engineering, robust design and quality loss function should be included.
In practice, it is necessary to adapt a stepwise approach in the development and implementation of the Segmented Total Product Model. At the final stage, the segmented total product model will contain the complete description of products and their components. All information which are relevant to succeeding processes are represented in semantically unequivocal representations; hence, an error free information access can be achieved without new interpretations. The history of each individual product must be documented from the idea to the final waste disposal stage.

Segmented Total Product Models can be structured into internal and external module areas. The internal module consists of all information models, such as requirement model, concept model, function model, process and NC model. It represents the information of a specific product, its variants, costs and data of the occurrence for each manufactured individual product. The external module can be interpreted as the generic portion of the product model. It provides information about constraints, restrictions, newest findings, and other principles about the product and its components defined by the market, environment, users behavior or competitors’ strategies. The internal models have to be created by the user company itself, while the external models are built by gathering information from outside the company, and in some cases, in cooperation with competing companies. An example is the environment model which can be developed between competitors to reduce costs for all. These models often have an impact on standardization. Therefore an early cooperation with standardization organizations is important.

To ensure final acceptance, it is important that users can directly participate in the definition of process chains. It should be noted that the planning of product models and process chains is not just a task of information technology specialists of employees, but must involve all employees with specific process knowledge. The internal cooperation by simultaneous engineering requires that such a task is accomplished in a team setting. Cooperation with external suppliers, as emphasized by the concept of agile manufacturing, has to be considered as well. All these factors indicate that a team approach has to be developed to support the product modeling activities. As a large number of factors influence these activities which require massive amounts of information, the team approach seems to be difficult to perform effectively without the augmentation of some computer-based systems. The development of computer-based virtual teaming technology is, therefore, needed in product modeling research.

One such development effort is currently taking place to extend the knowledge processing technologies (KPT) into the virtual teaming technologies (VTT) to support product modeling activities in a concurrent engineering environment [27]. The project is called SWIFT (System Workbench for Integrating and Facilitating Teams), which integrates the state-of-the-art technologies in computing, reasoning, communication, and coordination. SWIFT provides virtual teaming support by breaking the disciplinary, time, and geographical boundaries between engineers who need to collaboratively work together to develop a complex product. In SWIFT, the word System means a large and complex task (e.g., developing a product) consisting of many inter-related sub-tasks whose solutions require a high degree of interaction among people with diverse expertise. By Workbench, it is refereed to an intelligent, virtual and active "worktable" existing on a networked computing environment that can aid the collaborative process. Workbench Surface for Obtaining Solutions and Workbench Surface for Developing Applications (see Figure 14: The SWIFT Layered Architecture) can directly participate in the environment model.

As indicated in Section 3, the demand for concurrent access to actual data in product modeling creates major challenges in workspace models and transaction management beyond the capabilities of existing database technologies. Distributed databases are needed in simultaneous engineering to permit a manually accessible shared product model for all engineers involved. Everyone should be able to immediately see the result of others work by querying the shared product model, rather than by requesting files or drawings which may be incompatible formats. Explicitly requesting files, however, does have the advantage of enforcing a needed measure of privacy, albeit artificially, by making it difficult to share common product information. The concept of workspace in database management can provide a proper balance between sharing and privacy. Workspaces can be used to partition the database for work groups; subgroups and individuals may have their own, private workspaces as well, organized hierarchically under the group workspace. Ideally, workspaces should be dynamically created, modified, and dissolved during the product development process according to process chains. There still exist many research issues in this area. For example, how does one workspace share information flow between related workspaces, what is the strategy to defer and filter propagation between immediate inter-workspace to support creative, explorative work of individuals.

Transaction management is another research issue in database to support product modeling. The current transaction model does not support required functions of simultaneous engineering. For example, it may be necessary to undo committed transactions if they are based on a decision which has been retracted. In this case, it is important to trace the causal relations of information related to the decision in order to undo its effects in the database. Also, it is often not the case that the database integrity is measured by serializability approaches. The demand for concurrent access to actual data in product modeling requires that database models should be compatible with process chains, the different models which may belong to the Segmented Total Product Model. Using CASE tools to help the specification of process chains in order to drive the development of product models is just one of the possible approaches. There is a strong research demand to develop other approaches that can aid the definition and management of process chains. Different design theories and methodologies, such as the Axiomatic Design approach [26, 27, 79], can possibly offer some solutions to this demand if their scopes can be broadened beyond just product design to cover the whole product development activities.
In fact, the process-chain-driven product modeling concept described in this paper can potentially lead to an interesting scientific foundation for future product modeling research and application efforts.

Finally, the educational demands can be directly derived from the research requirement mentioned above. Product development will be performed with a high degree of computer augmentation. Therefore, future engineers must be knowledgeable about not only product and process knowledge but also information and computer technologies. The term designers may be enlarged by or encompassed with "product engineers" in the future. The responsibility of the designer will be extended to the designing of processes as well. The spectrum of development tasks performed by a single person will be increased. In the future, the difference and division between product and process engineers should diminish and be integrated into product development engineers. Specific knowledge and general knowledge will be necessary to fulfill the demands of future product development tasks.

Combination of design creativity with planning tasks is also needed. Interdisciplinary cooperation at universities and engineering high schools, team work, job rotation, continuous education, and in-job retraining during one's professional career are all necessary to meet the future demands. Product modeling seems to belong to the heart of our engineering education system and a company. Engineering education must take this important role into account in the future.

5.2 Industrial Demands

The competitive pressure in industry concerning low cost, high quality, and short lead-time adds new demands on product development paradigms which can not be fulfilled by traditional approaches. It is essential in present industries to develop strategies which take into account new solutions of information technology. There is a strong tendency to be recognized which leads away from paper drawing as a release and working tool. Instead, digital masters are demanded: To reduce time and costs of physical models, the digital models have to be able to represent different stages from conceptual to detailed. In the case physical models are still needed, it is of high demand to create this model by the direct usage of the digital representation.

One such good example is the Analytical Powertrain (AP) Initiative at the Ford Motor Company (20). The goal of AP is to provide a comprehensive computing infrastructure to support concurrent engineering in automotive powertrain design and manufacturing by developing an integrated CAD/CAM/CAE system built around a central STEP product database (see Figure 15). This central database, an example of the complete product model, will contain all product information with needed consistencies and associativities to support various activities in the powertrain development process chains such as concept definition, design analysis, function evaluation, rapid prototyping, etc. As indicated in Figure 15, these activities are dynamically managed by the Task Coordination and Administrative Processes, guided by the Total Quality Control Processes. This integrated powertrain database will also support other product development activities outside, but related to, the powertrain systems domain.

**ANALYTICAL POWERTRAIN CAPABILITY**

**TASK COORDINATION AND ADMINISTRATIVE PROCESSES**

- CONCEPT DEFINITION
- DESIGN ANALYSES
- POWERTRAIN FUNCTION EVALUATION
- UNDERGOOD PACKAGING
- POWERTRAIN CAD/CAM/CAE SOLID MODEL DATABASE
- POWERTRAIN ANALYSES

**QUALITY CONTROL PROCESSES**

- REVERSE ENGINEERING
- RAPID PROTOTYPING
- DRAFTING
- MANUFACTURING CAE
- BUYERS/SUPPLIER INTERFACING

![Figure 15: The Analytical Powertrain Initiative at Ford Motor Company (20)](source: Ford/AP/DeLorean)

The vision of the AP initiative at Ford is to achieve significant process improvements, hence greatly reducing the lead-time to produce high-quality powertrain designs and enabling the development of the first prototype in less than "World Class Timing" for a vehicle program. Specifically, this integrated product model can store and retrieve all product data from a central integrated database, thereby eliminating duplicate data. It will also simplify the data management task and reduce the potential for using invalid data in powertrain design. Designs are expressed in solid models to support electronic assembly of components and interference checking, direct generation of analysis models, tool and fixture designs, and desk-top prototype creation. Referencing solid models to the master product model can also avoid the recreation and reinterpretation of existing designs. The model utilizes concurrent, rather than serial, process chains for design, analysis and manufacturing engineering with better workflow control and task tracking. The AP effort can also standardize powertrain development processes through the sharing of design and manufacturing guidelines across the whole enterprise, and through the use of standard analysis processes. As well, it can support the creation of new designs through a variant design process that accesses prior design and manufacturing experience as well as analysis and testing results stored in product models. Such a support can facilitate the reuse of component designs and the use of standard parts. The model provides a design decision and configuration audit trail through the integration of configuration management into the product models. Finally, it employs a client/server computing environment with engineering workstations and PCs access to provide electronic collocation and virtual teaming support for large engineering teams.

From many industrial applications, it is clear that process chains have to be able to create and use information handled in the product model database in an evolutionary way. Because of the massive amount of data, it is necessary to think over which raw data really should be kept in product model in advance. To include suppliers as partners into the development activities, it is important to be able to share data with them. For external and internal uses, data security mechanisms have to be provided. Data exchange with suppliers have to be enabled as well. This can be achieved by demanding the native format of the ordering company, or it can be done by using the neutral format of STEP. STEP is also important when deciding on the long-term storage for product legal aspects and for the reuse of parts descriptions as well as spare part manufacturing. The times for long-term storage are different in different industries.

When process chains cover a number of development phases, it is essential to have a release management tool available to the system. This tool not only should take care about different versions, but also must be able to handle different effects. It is necessary to think over which effects have to be kept in the technological planning immediately and reverse. To support this, associativity has to be available between different related objects and also for different phases along the process chain. Possibilities to keep the consistency should be supported by the associativity and related software and not just manually by engineers. During the assembly phase, this mechanism is of special value. Interference, assemblyability, parts lists, kinematics and joint machining of parts as well as disassembling of workpieces have to be supported in an associated and consistent way. Furthermore, in order to have a system functionality in an simultaneous engineering environment available, a multitasking capability has to be available, which also depends on associativity mechanisms.

In order to realize the concept of product modeling systems for industrial use, some preconditions must be established. It is not only necessary to provide the product modeling systems themselves, but, furthermore, to develop methods for the introduction of product modeling into industrial practice. Methods for the introduction of product modeling must take existing data, software and hardware into consideration. The methods must, therefore, allow a step by step introduction of product modeling technology. During this migration process, it is important to involve the end users as early as possible to gain a wide acceptance and to include their specific knowledge and experience. Products, processes and the supporting information technology should be planned concurrently. Concerning the technical demands for product modeling systems from the industrial perspectives, it is necessary to reach a high degree of compatibility with the existing software and hardware environment. Especially, the further usage of existing product data has to be ensured. Furthermore, future product modeling systems must have easy maintenance and extendibility as well as a high degree of hardware independence. This requirement will lead to an open system architecture which can contribute to assure the investment against fast technological changes.

For a successful implementation and usage of process chains, it is necessary to have measures and evaluation methods at hand. These should not only include economic or technical parameters, but also should give a possibility to come to optimal process chains under global conditions. Process cost calculations are one important method which can contribute to this need. As it will be difficult to come up with absolute values, a relative comparison between process chain alternatives should be possible. The evaluation of process chains can give some indication of the process chain quality and is important as well as a high degree of hardware independence. This requirement will lead to an open system architecture which can contribute to assure the investment against the technological changes.

The effective operation of process chains can be strongly enhanced by project management systems which support not only the administrative tasks but also the synchronization of parallel tasks. There is a demand for backward scheduling and the possibility of reorganization of the overlap of different tasks by it. For the acceleration of workpieces, the releases to be made are of high importance. The necessary decisions have to be performed with such an overlap to the task so that it is possible to finalize the task and the decision nearly at the same time.

To come to more systematic and effective ways of defining, developing, implementing and operating process chains and product models the efforts for
standardization have to be enforced. Industry should not only participate in but also drive this standardization process. To avoid unnecessary duplication on an international level after some proposal was already presented, the international community should meet more than in the past to cooperate from the very beginning to shorten the development time of such standards.

The development of user interfaces has to be transformed into a new work style for the process chain /43, 44/. The combination of working on the basis of these product models, the browsing through others work on design and technological planning tasks has to be provided. Figure 16 proposes a possible layout of a future engineering workbench allowing the use of a large variety of design tools for calculating, embodiment and process modeling in parallel /76/.

![Figure 16: Future Engineering Workbench](image)

Besides the integration of product development processes, product planning related information flows, including scheduling tasks, should also be considered. The usage of database management systems with additionally developed software is one solution for this type of tasks. Another possibility is the usage of EDMS, but they need further development as discussed before. Future development will lead to integrated Product Data Management Systems (PDMS), which will realize the idea of product models /2/ (Figure 17).

![Figure 17: Transition of EDMS to PDMS](image)

This development will be strongly influenced by product model related standards like STEP, standardized data access interfaces, as well as object oriented database systems. Since further developments of CAD/CAM and PPC systems will also take the product model related standards into consideration, the development as well as the utilization will be promoted. The industrial demands are processed in different ways.

Many companies which see a need for product modeling have taken action and they create their proprietary system. Others try to cooperate on a national or international basis. There major examples will be briefly described. The German Ministry of Research and Technology is supporting a project which was initialized by the association for computer science (GI, Gesellschaft für Informatik). The project goal is to develop a description of a new CAD system architecture which can be a basis for future CAD system developments. It is recognized that there is a need for open systems. The demands of industry are taken into account for generating this architecture. The approach concerning product models is related to the STEP activities which is seen to be an essential for envisaged process chains /2/. Based on an initiative of Daimler-Benz the European Community is creating a program for Advanced Information Technology (AIT) in Design and Manufacturing. This program is shared by all major European automotive and aerospace companies as well as by component suppliers. It is aimed at articulating the future information technology requirements in product development and manufacturing as well as in their integration from the user's point of view. Process chains and product models are essential parts of these efforts. This will be the basis for the cooperative development of the needed software with IT industry. The consensus also should be an enabler for defacto standards.

Intelligent Manufacturing Systems (IMS) is a program which was initiated by MITI in Japan and is now a worldwide activity /79/. The feasibility study which is performed has the goal to exercise this type of research and development cooperation on a global scale. Six subjects have been chosen for elaboration. At least two of the projects are affected by process chains and product models. These are GLOBEMAIN 21 and GLOBAL CONCURRENT ENGINEERING. It can be expected that in the case of full IMS, the topics of product modeling will have an even stronger impact.

6 Conclusion

Product modeling is the heart of product development activities that determine the engineering productivity and industrial competitiveness. The subject is still a fast evolving one, and is at its entrance phase from basic research to industrial applications. No common theoretical foundations and agreed implementation strategies exist to date, which poses many interesting challenges and opportunities to researchers and practitioners in this field. The rapid changing information technology and the competitive nature of global market also make the research and application efforts in product modeling a fast moving target. Notwithstanding these difficulties and uncertainties, the potential benefits of computer-aided product modeling is very significant as evident by those initial attempts in companies as described in this paper. In the future, industry, university, and government at the national and international levels must devise collaborative efforts to jointly investigate the scientific bases and practical issues of this important technology.

Even without a common theoretical framework, several key product modeling concepts are clear at this stage based on important lessons learned from many R&D and application efforts around the world. For example, process chains should be used as the bases to create complete product models in order to support various product life-cycle considerations. This process-chain-driven approach to product modeling not only points out important future research demands in database and related information technologies, but also opens new opportunities for the exploration of more comprehensive design methodologies that can support the definition of process chains for the whole product development activities. Some general research goals are the optimization of processes and product data capabilities as well as planning tools for generating the information environmental preconditions for the usage and connection with a holistic view of the factory. Users of new product modeling approaches and suppliers of advanced information technologies must joint their efforts in these development efforts so that needs and demands are met in the future. Some examples of these needed joint efforts can be seen from those current standardization and open system architecture initiatives, which are all very critical to the product modeling.

The needed skills in industry to adapt to new product modeling approaches can only be generated by improved and continuous education. Education of the higher level management in a company is also of high importance to the success of this technology in practice. Top managers have to make clear decisions and commitments to go for this technology. The understanding of basic principles behind the technology and its surrounding environment is important to the transformation of general ideas to specific solutions. Education in design, manufacturing and product development has to take this into account more than it has in the past. Product development has to be based on the application of the new tools which often change the way of doing business and the types of results. The mentality as well as the knowledge of product developers and managers have to be trained even further to sustain the development of information technology for these important tasks in the factories. The effective usage of these technologies is largely dependent on people who will determine the future of the company, and, ultimately, the whole economy as well as the common welfare of the society.

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