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Holistic Integration of Product, Process and Resources Integration in the Automotive Industry using the Example of Car Body Design and Production

Product Design, Process Modeling, IT Implementation and Potential Benefits

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Holistic Integration of Product, Process, and Resources in the Automotive Industry Using the Example of Car Body Design and Production

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A Doctoral Thesis to obtain the Degree of

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DISSERTATION

By

Dipl.-Ing. Mbang Sama

Day of oral examination:	29.06.2007
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Preface of the publisher

The automotive companies are facing a rapidly changing operating environment. Optimizations of production efficiency and costs, technological advances as well as production automation remain a challenge for this industry. Furthermore, competition has intensified on a worldwide scale. Especially in emerging markets, it is important for the automotive industry to be able to adapt to the challenge of mass motorization. Therefore, the key challenge is the ability of deliver excellent products in shorter times, by empowering the worldwide distinctive qualities.

To tackle theses challenges, some main questions have been focusing on: how best to design and innovate, how to understand constantly shifting customer needs, how to produce the products that meet those needs including advanced tasks, process planning and manufacturing within tight budget and time constraints and, how to manage complexity.

Furthermore, to increase competitiveness and sustainability in the current situation, automotive companies have to formulate business strategies that improve the intelligence, flexibility and re-configurability of product development, production systems and processes through continuously integrated engineering services along the entire product lifecycle.

One efficient way to address these problems is adopting an integrated approach for product innovation and process reorganization as well as a new comprehensive engineering methodology and new technology solutions.

The overall goal to identify best practices and to capture and process the relevant requirements of a product is of critical importance for the whole product life cycle. The intelligent features and intelligent templates approach presented in this work are the chosen strategy for manage complexity and considerer the main stages of product lifecycle in terms of an integrated product development, process planning and resource allocation in production.

This work is concerned with the description of new methods for product design and process modeling as well as with their technical implementation. Based on requirements from industrial practice, it proposes a concept for the integration of product, process, and resources using the example of car body development and manufacturing. The proposed approach serves as a backbone for a new intelligent and knowledge driven design-for-X.

Karlsruhe, June 2008 Jivka Ovtcharova

Acknowledgements

This thesis represents the result of my post-graduate research work in the Research and Technology Division of DaimlerChrysler. The dissertation topic, “*Holistic Integration of Product, Process and Resources in the Automotive Industry, using the Example of Car Body Design and Production* , relates to several research projects undertaken within the Lab IT for Engineering and Processes.

This task in addition to my daily work was ambitious. I spent most of my weekends and evenings working on the dissertation. Yet the fact that this topic was presented with the highly competitive DaimlerChrysler Research Award 2002 demonstrates not only the value of these results, but also the pivotal importance of modeling integrated process chains in the automotive industry today and, of course, the keen interest on the part of DaimlerChrysler. It was also a notable achievement that these results were put into practice much sooner than expected for the development and production of new cars at DaimlerChrysler.

Over the course of this work, I led two major research projects which were closely related to this topic: “Feature-based Process Chain Car Body” and “Advanced Stamping Die and Tooling Manufacturing Process from Body Part to Finished Die”. These and other projects, such as “Tolerance Analysis and Synthesis and ’Feature-based Analysis’”, helped to refine my ideas and to extend the application of the results of this work.

In addition, I am pleased that these efforts have also generated further strategic projects for the development department of Mercedes Benz and have brought about some cooperatives project with software vendors.

I particularly wish to express my deep gratitude to Dr. Siegmar Haasis, since the research work at hand would not have been possible without him: Thank you for putting your confidence in me and for providing me with the opportunity to accomplish this research work.

No less gratitude is due to Prof. Dr.-Dr. Ing. Jivka Ovtcharova, Prof. Gustav Olling, and Prof. Roller, who supervised the work on behalf of the university with a great amount of interest. Their valuable expertise and analytical thinking have always helped me to critically examine the concepts I have developed and have guided me in the right direction.

Special thanks go to colleagues at the research center in Ulm and at the Technical Computer Center (TCC) in Auburn Hills, USA, for the inspiration they gave me and valued discussions undertaken. The concept of FAD is mainly based on this intensive collaboration. Thank you.

I would also like to mention the graduate students doing internships and engaged in diploma theses related to the research work. They addressed important aspects of this work

Finally, I owe much more than merely my gratitude to my family -- my wife Muhau Salay, my daughter Malaïka and my son Amani -- for supporting me above and beyond what I had expected or could ever have hoped for.

Karlsruhe, June 2007 Mbang Sama

Summary

Today's automotive market is highly competitive. Minimization of development time, increase of productivity, increase in product quality, and reduction of manufacturing costs remain crucial factors for success in the automotive industry. As a result, car makers are being forced to offer newer, better, and cheaper cars in a shorter period of time to stay competitive in the global market. One way to achieve this goal is to introduce platforms in which each part is produced in a highly integrated and cost-efficient process. This call for cost efficiency in manufacturing drives change to upstream processes. During the design phase, parts – in addition to the optimization of their function -- have to be optimized with respect to their manufacturing process. Design, engineering, and production planning of a part interact to a high degree and often take place at the same time (concurrent engineering).

To meet these requirements, a concept that provides procedures to assist engineers in designing components and assemblies and linking them with process planning, while taking the tools and resources into account at the same time, is essential, thus supplying the foundation necessary to automate the engineering process. Current trends in car body development and production such as feature-based engineering and knowledge integration offer particularly high potentials.

This thesis is concerned with the description of methods for product design and process modeling as well as with the technical implementation of the associated information. Based on requirements from industrial practice, it proposes a concept for the integration of product, process, and resources using the example of car body development and manufacturing. The proposed approach serves as a backbone for a new intelligent and knowledge driven design-for-X.

The thesis is divided into five main parts:

- Introduction, objectives and approach
- The framework (state of the art in research and practice as well as the theoretical foundation)
- The concept of Intelligent features and solution patterns
- The realization concepts in dedicated process steps of the vehicle creation process
- The implementation in an application called Feature-Knowledge Assembly Design (FAD)

The introduction describes the problems in current product creation processes in the automotive industry and the identification of requirements for improvement, followed by the presentation of the method introduced in this thesis for solving these problems. A short explanation is given as to why the current state of feature technology is not sufficient, stating the need for an advanced or intelligent feature technology which is characterized by enhanced dynamics, adaptivity and flexibility. It ends with a brief description of the objects of investigation and with the structure of the work.

The state-of-the-art in practice and theory is analyzed in the second part of the work. Basic methods necessary for the holistic integration of product, process, and resources are discussed, starting with the parametrics and associativity. As the method deployed requires greater intelligence and a focus on the associative linking and the automation of processes, and since design is often reflected in problem solving which implies decisions, an in-depth look at knowledge mechanisms and the underlying theory in designing products and modeling integrated processes is provided. Thus, a framework for designing design objects is discussed. This framework allows designers and process planners to more quickly understand the relationship between the intended functions of an object and the means by which they are achieved, thus enabling identification of the potentials for reducing design time and complexity. In addition, possible consequences can be determined in advance and tracked during the design process, which may save money and time. The section concludes with the requirements for new concepts and tools for the holistic integration of product, process, and resources.

The third part presents the underlying approach employed in this thesis: the notion of intelligent features and solution patterns. The elaborated Intelligent Feature concept enables not only the earlier consideration of requirements (in the sense of functional modeling) but also the integration of a kind of feature-based decision-making during the design process, resulting in an automatic and knowledge driven derivation of a detailed specification of a product or process. To support the designers and process planners, a library of intelligent features has been developed and methods for their processing for the car body development and production have been derived.

Based on these concepts, the holistic description of key sub-processes in car body development and production is provided in part four: styling features in the area of aesthetic design are introduced, the CAD/CAQ process is modeled, the first approach to feature-based modeling in stamping die manufacturing is described, and finally a new concept for feature-based welding is discussed.

The fifth part sets out the implementation of this concept for future CAD/CAM systems: Feature-Knowledge Assembly Design (FAD). Additionally, its application as a vehicle conceptual engineering framework is illustrated, leading to an advanced vehicle conceptual design and process synthesis tool. The guiding idea is to provide a backbone throughout the design process, maintaining design and process consistency and keeping links between the necessary views and aspects of the component or assembly to be manufactured. A second key principle is to support designers and process planners in their decision-making process, while observing design methodologies and reusing design intents and automating design and engineering tasks.

To sum up, the purpose of this thesis is to overcome the drawbacks of insufficient support of both the design and process engineers and to elaborate and prototypically implement a concept for integrated vehicle creation. This integration allows design decisions to be based on well-known patterns, right and the right time.

The thesis ends with the conclusions drawn and a look at future works.

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Diagrams

List of Abbreviations

Abbreviation	Term Definition
AD	Axiomatic Design
AI	Artificial Intelligence
API	Application Programmer Interface
ASCII	American Standard Code for Information Interchange
AVE	Advanced Vehicle Engineer
BiW	Body in White
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CAM	Computer Aided Manufacturing
CAPP	Computer Aided Process Planning
CAQ	Computer Aided Quality
CAS	Computer Aided Styling
CAx	Common term for Computer Aided technologies
CATIA	CAD system of Dassaut Systèmes
CMM	Computer Measurement Machine
CN	Customer Needs
CNC	Computer Numerical Control
CTR	Collaborative Team Room
DIN	Deutsche Internationale Norm
DMIS	Dimensional Measurement
DMU	Digital Mock-Up
DNA	Deoxyribonucleic Acid
DP	Design Parameters
DR	Design Rationale
EC	External Conditions
EDM	Electronic Data Management
EGDT	Extensions to General Design Theory
ERP	Enterprise Resources Planning
EU	European Union
EUCAR	European Council for Automotive R&D
FAD	Feature Knowledge Assembly Design
FEMEX	Feature Modeling Experts
FR	Functional Requirements
GDT	General Design Theory
ICT	Information and Communication Technology
IP	Intellectual Property
ISO	International Standardization Organization
IT	Information Technology
KR	Knowledge Representation
LoP	Level of Practice

NC	Numerical Control
NURBS	Non-Uniform Rational Basis Splines
OEM	Original Equipment Manufacturer
PDD	Property Driven Design
PDM	Product Data Management
PLI	Priority Level Index
PLM	Product Lifecycle Management
PPR	Product Process Resources
PV	Process variables
QFD	Quality Function Deployment
QG	Quality Gate
R&D	Research and Development
STEP	Standard for the Exchange of Product model data
TRL	Technology Readiness Level
US	United States of America
VE	Virtual Engineering
VDI	Verein Deutscher Ingenieure
VDS	Vehicle Development System
VR	Virtual Reality
XML	Extended Markup Language

PART I

INTRODUCTION, CURRENT WEAK POINTS AND OBJECTIVES

Chapter 1

1 Introduction:

A look at the product creation process in the automobile industry quickly yields a significant conclusion: there has been a substantial change in the last few decades. Nowadays, the pressure to be innovative in the automobile industry is higher than in any other industry. The vehicles born in recent years are ultramodern products which are characterized by the integration and interplay of complex mechanical, electronic, and software components. Moreover, within the industry, carmakers are increasingly subjected to aggravating competitive conditions and trends [Ovtcharova 04]:

- ***Individualization*:** Customer demands are rising for functions, quality, safety, comfort, and variety (the call for the multifunctional car that incorporates the greatest number of functions into one and the same vehicle, e.g., minivan for the family, convertible function in good weather, etc.). At the same time, car models, variants, and options are growing in complexity and diversity. The resulting market changes necessitate ever shorter response times and wider product ranges.
- ***Socialization and legislation*:** Consumers and governments are demanding ever stricter rules regarding safety, mobility, fuel economy, and ecological compatibility (e.g., concerning pollution-free materials and manufacturing technologies). All these require an early and flexible adjustment of product as well as production development.
- ***Globalization*:** Automobile manufacturers are undertaking global development with multicultural, cross-functional teams in multiple geographic locations and time zones. Furthermore, global takeovers and consolidations are more and more leading to changed competition constellations and new procurement, development, and production groups.
- ***Virtualization*:** Virtual engineering is providing all the related groups of users and workers with models to observe, handle, and assess future vehicles intuitively, close to reality, early in development process.

Thus, the actual competitive scenario that manufacturers are facing is a rapid evolution of technologies in a global, ever-changing and demanding market. New market demands are forcing companies to adopt rapid innovation, shorter development times for new products, and expanded product offerings. At the same time, they must balance costs that satisfy consumers with a ratio of value to price that gives reasonable profits to stakeholders

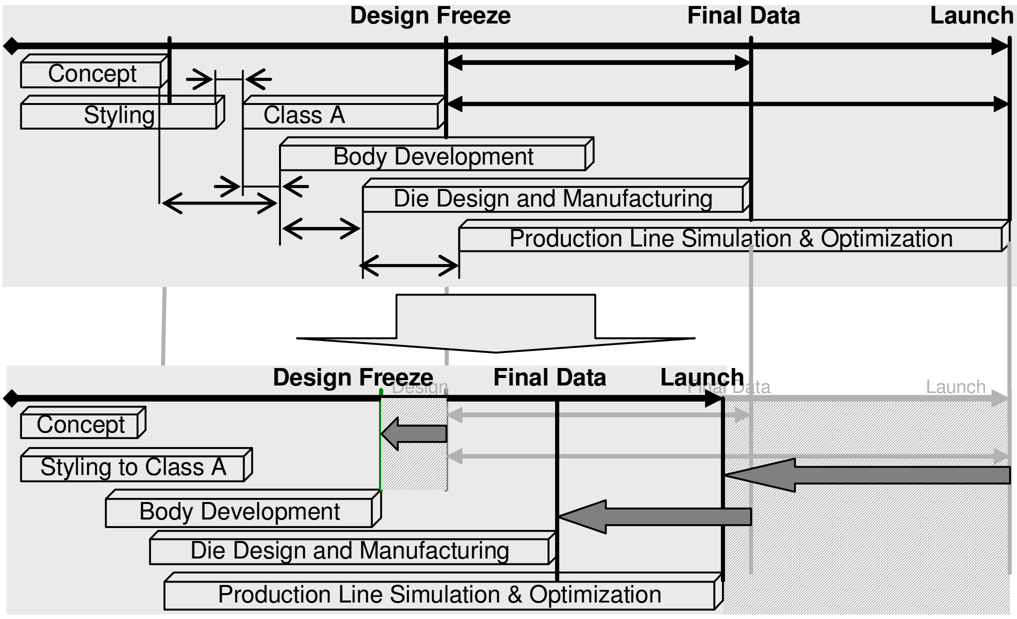


Figure 1-1: Shortening the product creation process
as a key issue in the automotive industry.

Recent surveys show that compared to the United States, Europe gives product innovation a marginal role, and less than 10% of innovative products represent an effective breakthrough. This situation becomes even more serious because of the inefficiency of the entire product creation process, especially where development and marketing costs are very high and it is not possible to establish clear relationships among research investments and the degree of commercial success of the new product.

A possible explanation of this circumstance is that product innovation is not sufficient alone to guarantee success, but it is necessary to support new products generated by a higher innovation in methodologies and tools to support processes and organization. This innovative infrastructure is required to act faster, develop more product alternatives, evaluate scenarios, and capture in time and before the competitors new customer needs.

Furthermore, to increase competitiveness and sustainability in the current situation, automotive companies have to formulate business strategies that improve the intelligence, flexibility and reconfigurability of product development, production systems and processes through continuously integrated engineering services along the entire product lifecycle.

The only way to address these problems is adopting an **integrated approach to product innovation and process reorganization as well as a new comprehensive engineering methodology and new technology solutions.**

Chapter 2

2 The product creation process today in the automobile industry

2.1 Overview

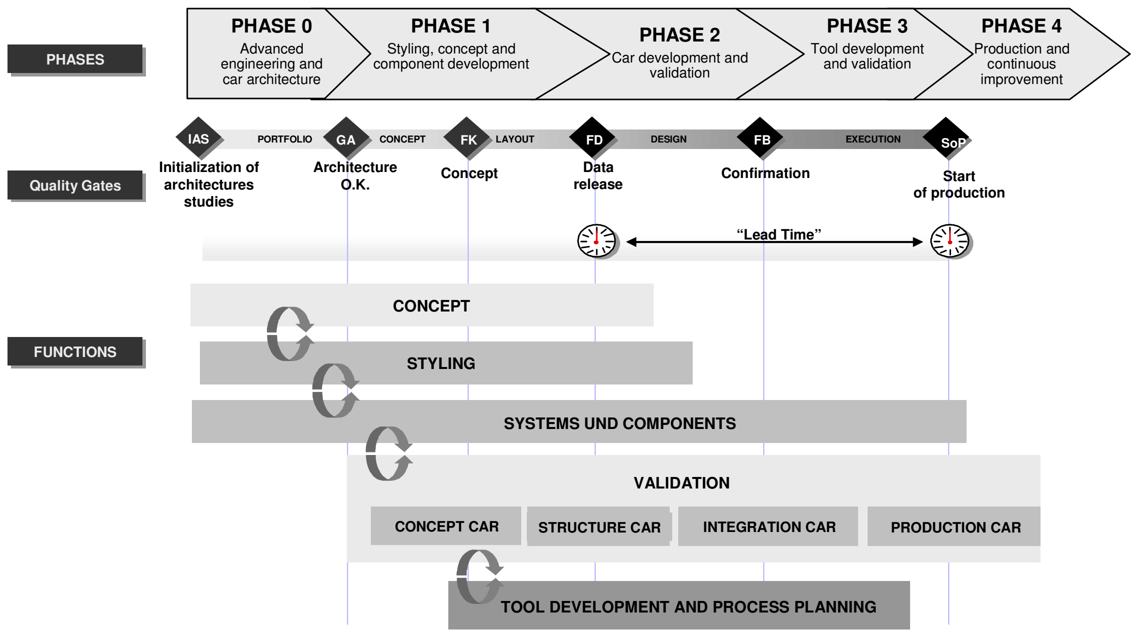


Figure 2-1: The product creation process in the automotive industry [Ovtcharova 04].

The product creation process is divided in four main phases (figure 2-1):

- **The strategy phase (Phase 0):** New models are designed from promising product concepts and modified car variants in "project houses" (all cross-functional business units taking part at a car project). The bases for the strategy are new market requirements and customer's requests.
- **The phase of technology development (Phase 1):** Innovative components of engine, transmission, axle and impulse are purposefully selected and brought to the production stage, and are fitted into a close-knit overall. The development of these components is methodically closely interlocked with the vehicle process. Thus the smooth integration of all aggregate processes is secured.
- **The phase of product development (Phase 2):** All vehicle parts are optimized between simulation and test, and are integrated into the total vehicle. Computer simulations inform engineers promptly about possible problems and their solutions. Investigations into test results ensure that both total vehicle and smallest construction units are sufficient for highest requirements. The gained experiences are use to optimize the production process. The result is the fully developed product.

- **The phase of serie (Phase 3 & 4):** Production checks are performed on series conditions in start-up plants and process-safe production conditions. A goal is the efficient interaction of humans, plant, and product. An increasing load of vehicles under material production conditions is built from test to test. After each test, the volume is stopped, the produced load analyzed and documented, and each detected error eliminated. Afterwards series production can start.

The phases are usually networked. The expected advantages of this cross-linking are that efficient processes accelerate product development, increase maturity, lower development costs, and promote innovations

The quality of the processes is governed by "quality gate" in which the integrity of products and processes are checked at fixed points to ensure the accurate evaluation of dimensions, function, material, and other factors. Hence, one can be sure from the outset that the finished product will fulfill claims of quality without restrictions.

2.2 Weak points in current vehicle creation process and business issues

Despite the progress in information technology penetration observed recently, the state-of-the-art in vehicle process chains are still characterized by many breaks between sub-processes.

Weak point 1: No associative process network

In the transition from one process step to another, expensive recognition technologies of design objects or geometric elements are applied.

Normally, the planning of appropriate manufacturing, assembly, and inspection processes are performed on the basis of information about the function, structure, and shape of vehicle body parts.

Currently this information is insufficiently represented in the CAD model, and so process planning is conducted in an unstructured fashion. The Shape is very well represented, but only on a very basic level. Especially “high-level” geometric entities, which have certain meanings in “high-level” contexts, are not well represented. “Structure” is also well represented, but only in the form of a bill of materials. In engineering reality, there are many more structures that are not represented -- e.g., the “function structure” (a term used in a very broad sense here, not as formalized as in design methodology), manufacturing structures, and assembly structures.

Issue 1: Multidomain and multistructure computer-aided data representation

There is a great need of multi-structures representations in future computer-aided systems. These representations could then include the so called functional views.

In Particular, CAD models cannot pass the existing interfaces between design and process planning without serious information losses. Figure 2-4 below documents the key weaknesses of current process chains in body development and production [Mbang 02b]. The interfaces between design and stamping die manufacturing process engineering behave similarly, largely due to a lack of sufficient bi-directionality.

As a concrete example, a great deal of information pertaining to design operations such as tolerances, welding or draw tip are generated by the designer, whereas the actual requirements come, usually late, from downstream sub-processes such as manufacturing, assembly or inspection planning. However, the component itself was already released by design. This information was generated and evaluated only in the context of individual components and units; yet it has many relationships to neighboring parts and assemblies, which, until now, could not be captured properly in the information model, despite the fact that the people involved had the whole picture in their mind. The information related to the inspection or welding process, for example, has thus far been recognized or re-modeled in the late process phase. This implies that such information is no longer linked associatively to the component geometry. The consequence is a high degree of complexity in change management.

Furthermore, during the product life-cycle many different users e.g., in the areas of vehicle safety evaluation, robot simulation, quality assurance, production planning, and die and tooling modeling must have access to the component information in digital form, which places substantial requirements on the information technology systems.

Today's IT systems are not able to capture and provide component-spanning information. When the processes were "local" and not divided into several teams and companies this was no problem. But today it is becoming a problem.

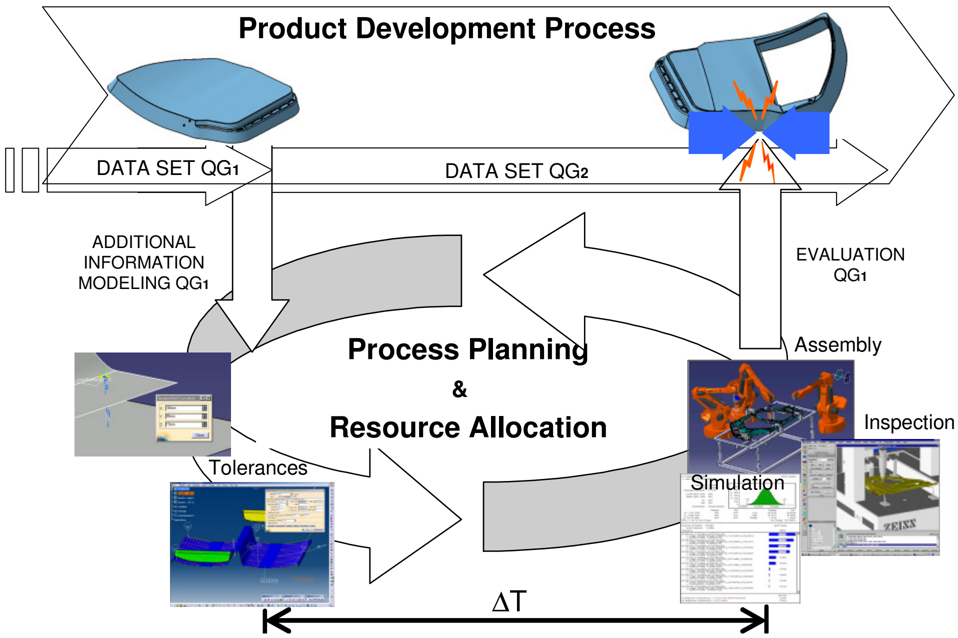


Figure 2-2: An example for problems in current product development processes.

Weak point 2: Many iteration loops

In addition, the vehicle body process chain is characterized by many iteration loops, resulting in major challenges regarding development time, production costs, and product quality, all of which strongly affect competitiveness. And it is here that change management plays a main role.

Figure 2-2 illustrates these major problems in current product development: the status of information at QG1, which was used during product development for process planning and resource modeling became outdated after a short time and needs to be adjusted to the new status of information at QG2. Otherwise, an inconsistent database could result, making efficient change management considerably more difficult [Mbang et al 03a].

Issue 2: Design for production

Efforts aimed at cost-cutting have become more stringent. Thus, reduction of manufacturing costs is paramount in automotive development:

A major concern is the elimination of inadequate production issues already in the product development process [Mbang et al 03b]. Figure 2-3 depicts the process of error emergence and troubleshooting as performed during the different steps in the product development process. As the figure clearly illustrates, roughly three quarters of all errors which occur during production have their sources in development. At the same time, development also incurs the majority of the manufacturing costs. A goal in this thesis is to shift the efforts of troubleshooting from production to design in order to minimize error emergence in the design phase

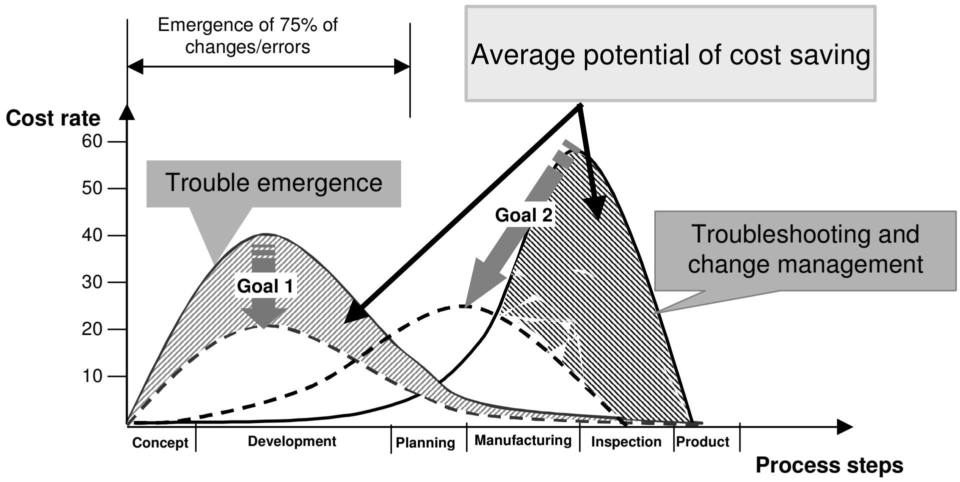


Figure 2-3: Process of change management and its relation to costs.

Issue 3: Concurrent engineering in a common CAx platform

In addition, an improvement in data management, interfaces, function, and communication seems necessary.

These iterative processes need to be transferred into a concurrent engineering environment, with the individual process-oriented and specialized divisions acting in parallel and considering interdisciplinary aspects. A prerequisite for concurrent engineering, however, is a suitable CAx platform. Such an integrated CAx platform enables the close cross-linking of the sub-processes along the car body process chain, thus accelerating product development, product analysis, production planning, and resource allocation.

Further business issues are summarized in the following:

Creating innovative products	The vehicle manufacturing market place suffers from considerable over capacity and saturation. In future, consumers will be attracted to “fresh” innovative products that suit their rapidly changing tastes and lifestyles. Product innovation and freshness will be critical to expanding market share.
Strong legal and ethical constraints	For both legal and ethical reasons, manufacturing companies want to produce vehicles that are safe and environmentally friendly. Safety regulations dictate items like air bags, seat belts, bumpers, lighting, and overall crashworthiness. Environmental concerns include emissions, fuel economy, recycle-ability of materials, and waste products from manufacturing plants leading to the need of a total lifecycle consideration and process optimization during product creation.
Product quality	Product quality is a continual concern. Firstly, companies want to minimize warranty costs. In addition, given the improved access to quality data, excellent service and repair records are important to continued sales.
Faster and flexible vehicle development process	The vehicle development process must be fast and flexible, so that new vehicles can better match rapidly changing consumer tastes. Also, R&D must be brought to market quickly in order to gain competitive advantage from innovation.
Managing product variation and complexity	To satisfy the wide variety of consumer wishes and social and geographic niches, vehicle manufacturers must find efficient ways to produce enormous variety of different vehicles in relatively small numbers. To address this problem, many companies are trying to establish portfolio of basic platforms that can be used as the foundation for a wide range of different vehicles. Modular design techniques also provide ways to handle variation and product line complexity without increasing capital investment. However, this advantage must be weighed against the impact on assembly plant configuration, and the loss of integration, performance and innovation that is likely to occur.
Supplier relationships	Suppliers are playing an increasingly important role in the vehicle development and production process. Vehicles are typically developed and produced by an extended enterprise consisting of dozens of companies, and the OEMs must coordinate the activities and integrate the results of these companies. Close collaboration with supplier companies raises difficult is-

	sues regarding communication, exchange of information, security, and protection of intellectual property. Some large automotive companies (i.e. General Motors and Ford) have both launched major e-commerce efforts in this area.
Global collaboration	The partnerships and supplier relationships often involve companies in different countries around Europe and the world. Also, adhering to local wishes, requirements, and regulations encourages globally distributed vehicle development. Furthermore, regulations about local content force globally distributed production. Thus, the development and production of vehicles is becoming a global operation, which makes it significantly harder to manage.

Table 2-1: Business issues in the automotive industry.

Summary of current deficiencies:

The existing interfaces between the individual systems demonstrate substantial flaws:

- The digital car body process chain is still not closed. It has missing links.
- Effort required for downstream and upstream changes is great and expensive.
- There is a lack of support during the concept phase, particularly in the handling of incomplete and inconsistent data.
- Design methods are insufficiently digitally documented, and best practices are insufficiently captured.
- A process-specific validation of the product, its function, and manufacturing requirements under design-method criteria is missing.
- The data exchange among application systems over standardized interfaces is substantially limited to geometric information.

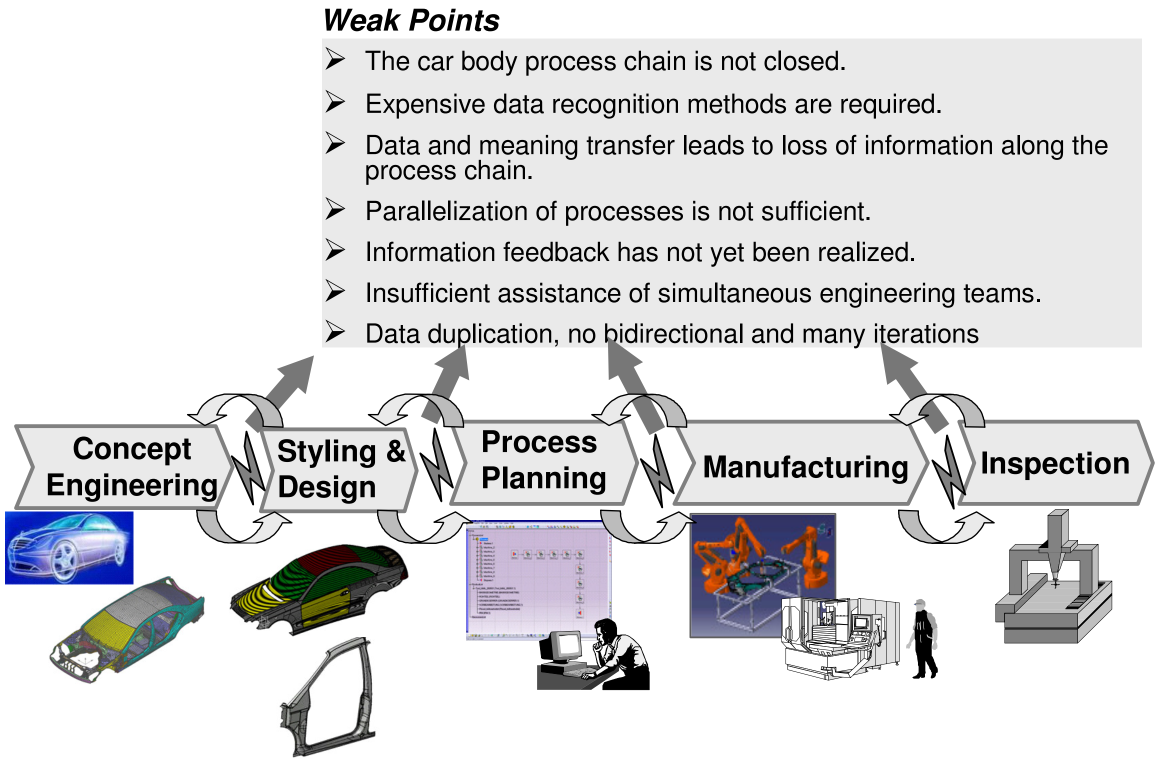


Figure 2-4: Weak points in the process chains used today.

2.3 Psychological impacts

The rapid evolution of IT methods has a deep psychological impact on the organization and the way engineers work. Technological restrictions and cultural aspects cause barriers in knowledge exchange [Schulze et al 03]. A further key aspect is the fact that Experts along the product creation process have different views of the process chain and use different terms. The methods developed by IT vendors or IT departments does not always fit the way users work, as their experience is not intently captured

2.4 Requirements and improvements request

The call for cut-to-the-bone development times, better cost constellations, and enhanced marketability has led to a uniform view of the overall product lifecycle. Thus efficiency in industrial value added – in the sense of maximization of the key success factors time, costs, and quality – can generally only be achieved through realization of the maxim “Get It Right the First Time”. This prospect implies optimal product development, validation, production, and usage of the current digital – but in the future more virtual – product engineering in the context of the today’s digital – but tomorrow’s virtual – factory and enterprise.

Overall requirements

In this regard, business processes in all automotive markets have common overall issues:

- Products must be offered, designed, and computed very quickly and *flexibly* in accordance with the customers' requirements, which presupposes a correspondingly *flexible product creation process.*
- Enterprises must exhibit a high degree of *standardization* and *automation* internally, so that the offer and job execution are accelerated and costs and time are reduced.
- External partners must be smoothly integrated into the enterprise processes relating to digital product development and production organization, since in the automobile industry, and particularly in Europe, 70 % of all development activities are outsourced to development and design engineering offices located world-wide.

Furthermore accelerating globalization in the production area requires consideration of what have, in the meantime, become very different production conditions.

New paradigms

The automotive industry is introducing many paradigms, procedures and tools, such as

- Modularization and standardization of products / product components
- Modularization and standardization of processes with (more or less) clear process elements and (more or less clear) interfaces between them
- Specialization, including the integrating of external specialist partners for development as well as production
- In information technology acceleration of processes the wish to become "physical" as late as possible and the wish to better re-use existing information (and make it independent from people).

Prerequisites

However, all these new paradigms are facing many problems in practices: Standards are defined mostly only on paper or intranet portals. When defining standards, there is a restricted view of processes and CAx systems to be used.

A fundamental prerequisite for all these aspects (standardization of processes, globalization, digitalization and virtualization) is a global cooperation based on a work platform, which acts as an information, communication, and cooperation network. *In this context, an* ***associative, flexible and adaptive integration*** *of product development, process organization, and resource allocation is indispensable*. The functionality is extended through the information technology support of upstream phases up to the complete coupling of all the systems in engineering and logistics involved in the product creation process.

Essential for this is the development of intelligent design and production CAx-objects which are understood by all those involved and which serve as a backbone within the product creation process.

Summary

To summarize, the issues identified (preservation of information and meaning throughout the product creation process, data availability, cost factors, quality of products data, time to market, etc.) call for a holistic integration of product modeling, process engineering, and resource allocation which requires the following:

- An integrated product model structure that represents and stores the necessary product and process related information in a computer-internal structure.
- Continuity of information technology support and links between the different product creation phases.
- Support of concurrent engineering and decision-making.
- Linking and exchange of high-order information between the individual software systems deployed in the product creation process.
- Capture, reusability and automation of design intent.
- Consideration and satisfaction of functional (product) and manufacturing (production) as well as customer requirements
- A lean business process flow improving the **intelligence, flexibility and reconfigurability** of product development, manufacturing systems and processes through continuously **integrated engineering** services along the entire product lifecycle.

A great deal of research has been done on all of these topics, as well as on integrated product models, specification-driven processes, and knowledge integration. These have been largely isolated efforts, and thus far have not really found application in an industrial context such as the automotive industry.

Chapter 3

„The significant problems we face cannot be solved at the same level of thinking we were at when we created them"

Albert Einstein

3 Motivation, objectives, approach, and structure

3.1 Motivation

The performance characteristics of common industrial processes can be visualized by a process-performance curve, which is almost always "S"-shaped as shown in figure 3-1. When a process is initially implemented, performance improves slowly first, since there is an inertia (confusion, resistance, and a learning curve to surmount). Performance then accelerates rapidly as the new process gains momentum, generates irrefutable results, wins converts, and becomes widely adopted. The new quantum change will then create an entirely new process performance curve that is discontinuous from the current one. It will use a process with an entirely different business approach and entirely different management.

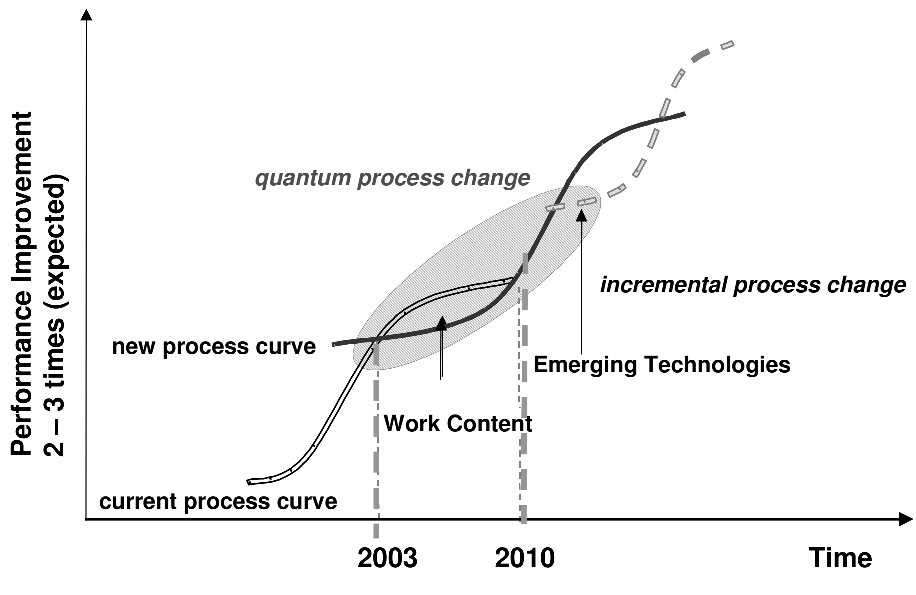


Figure 3-1: Quantum Process Change [Ovtcharova 04].

The automotive industry is by now on the verge of a similar process curve. It is time for a radical "quantum" change. Therefore manufacturing organizations must design new vehicles that create value-added "experiences" tailored to each customer.

The objective of this thesis is to discuss requirements, principles, and perspectives for the realization of an information technology environment which can support design and downstream process planning activities in an integrated manner, improve process reliability, product quality, and change management, and reduce time and cost of the product development process in the area of car body engineering.

Definition 3.1: Product

A "product" is used in this work to mean a tangible output that is engineered as result of a process and that is intended for delivery to a customer or end user.

Product Design in generally is defined as the idea generation, concept development, testing and manufacturing of a physical object. Thus, Product Designers conceptualize and evaluate ideas, making them tangible through products. The idea for the design of a product arises from a need and has a use (for example function or behavior). It follows certain method and can sometimes be attributed to more complex factors such as association.

Definition 3.2: Process

A "process" consists of activities, a sequence of operations that are planned and executed in accordance with policy; employing skilled people having adequate resources, which lead or should lead to the production of a product.

A process; involves relevant stakeholders; is monitored, controlled, and reviewed; and is evaluated for adherence to its process description

Definition 3.3: Resources

A "resource" in the sense of this work is a tool or device, i.e. is a piece of equipment that provides a mechanical advantage in accomplishing a physical task (i.e. in production).

Definition 3.4: Integration

Integration, in the most general sense, is a process of combining or accumulating.

In computer science, integration allows data from one device or software to be read or manipulated by another, resulting in ease of use.

Definition 3.5: Product, Process and resources Integration

Therefore, the "product, process and resources integration" (PPR Integration) is a systematic approach that achieves a timely collaboration of relevant stakeholders throughout the life cycle of the product to better satisfy functional expectations, production requirements and customer needs.

A customer in this sense is a department or organization responsible for accepting the product and is a subset of stakeholders, i.e. groups or individuals (product and production engineers, suppliers, customers, and others) that are affected by or in some way accountable for the outcome of the industrial undertaking.

The PPR Integration approach requires specific technologies and an organizational structure to perform it. Its performance is subject to verification and validation. While verification confirms that products and processes properly reflect the (production) requirements specified for them, validation confirms the product will fulfill its intended use. In other words, while verification ensures that "you built it right", validation ensures that "you built the right thing."

This work will not focus on verification and validation, rather on enabling factors to build the right product the right time. Following objectives will be pursued in this work.

3.2 Main objectives

Objective 1: *The first objective of this thesis is to discuss requirements of a holistic information flow method, the so-called digital compute-aided information backbone to enable efficient information processing and change management throughout the car body creation process.*

To react quickly and flexibly to market and customer requirements within the product creation process, the prevailing divisions and sequential operations must be parallelized and automated to a greater degree as far as possible. The foundation for this is a constant information flow and digitalization of data which integrates all the process divisions in the body development process.

The chief purpose for the optimization of the car body process chain is to develop the structure of a digital backbone for the connection of product design, process modeling, and resource modeling. Key emphasis is therefore placed on a holistic and integrated digital information data model used to describe the individual process steps and facilitate the communication between them. Moreover, this model has to be accessible to all users in order to extract and feed in relevant data throughout the complete product creation process.

Objective 2: *The second objective is the systematization of product functional characteristics (features) according to their downstream process requirements, thus enabling earlier evaluation of product design and the management of product and process complexity.*

The main point here is to develop a concept, how products can be described in an object-oriented way and intelligently and adaptively link them to downstream requirements (front loading). Furthermore, the objective is to lead to an increase in productivity, allowing development teams to reuse both designs, process solutions and know-how and manufacturing guidelines. To achieve this objective, the requirement to share the same information and knowledge to all people involved in the vehicle creation process is to be fulfilled, leading to less iterations.

Objective 3*: Finally, the feasibility of the theoretical principles and system concepts is to be piloted in such a way as to provide practical guidance for both product designers, process planners, and consider wide company-wide structures*

The difficulty is not really to develop a methodology. Rather, the crucial issue is to implement a new paradigm in existing business processes, taking into account the organization structure and philosophy as well as intercultural aspects and education of users. In this context, this thesis aims to provide solutions that are accepted by end users. Furthermore, it presents a concept how the organizational structure can be developed.

Benefits

Expected benefits are:

- Management of complexity of product and process.
- Flexible and transparent descriptions of product design, process engineering, and resources modeling.
- Effective management of design changes and variants due to parametric associativity between product development, manufacturing processes, and auxiliary tooling.
- Management and availability of company product, process, and resource know-how.
- Support of modularization and standardization.
- Partial automation of the information flow along the process chain.

Research needs

To reach these objectives, several subordinate tasks must first be addressed:

- Describing and structuring car body components using object-oriented methods and functional structuring approaches

- Capturing and preserving the product design intent as well as process engineering activities at different levels of abstraction.
- Preserving functional or behavioral correctness of models, thus enabling a linking between different application contexts along the process chain.
- Supporting a bi-directional information feedback and associative and adaptive propagation of product, process and resource model changes.
- Integrating with other engineering disciplines such as mechatronics.

Technical goals

The technical goals can be divided into several points:

Methodology

- Capturing, structuring and processing overall lifecycle-oriented requirements and available human and enterprise knowledge on design and manufacturing.

Systematization

- Structuring the product functions in the form of an intelligent semantic, ontology-based framework that integrates multi-disciplinary product views, etc.

Implementation

- Service-oriented integration of products and processes

Product, Process and Resource Validation and Feedback

- Managing the product design and manufacturing complexity through engineering methods for product validation and manufacturing process assessment keeping the focus on re-use and sustainability of the contents of the products

3.3 Approach

The description of semantics in computer processing form is a precondition for the integration and automation of the product creation process while serving as a basis for designing interfaces between process steps and between the systems deployed. In this context, many research activities have been carried out in the area of capturing and structuring knowledge on product and engineering processes and making it generally available. In addition, such work has targeted formalization of the product model structure.

3.3.1 Basics and current feature concepts

Over the last twenty years, feature technology has emerged as a recognized factor to improve of the product creation process [Shah 89], [Haasis 95], [Krause et al 92], [Weber 96], [Ovtcharova 96].

Its main potential lies in its ability to link different information between different processes. Further characteristics of the current feature activities are:

- Product description using high-grade functional objects.
- Consideration of shape, function, and tolerances.
- Intuitive product and process modeling.
- Support of different views of a product within different process steps.
- Bi-directional experience feedback along the process chain.

Although the initial goal of feature technology was motivated to automate the creation of NC (numerical control) programs, the widespread use of feature technology, so far, has contributed to the consistency of several engineering and manufacturing processes [Haasis et al 99].

Depending on the area of application, specific feature contexts were considered: design features, inspection features, manufacturing features, assembly features, welding features, analysis features, tooling features, etc.

- Thus, ***design feature***s consist of a particular topology or of geometric elements with a common functional meaning employed by the designer to model product components and to facilitate the communication with downstream processes. The functional meaning of the design feature is defined both by its geometric form and by technological elements such as dimensions, and tolerances.
- **A*ssembly features*** define functional or hierarchical structural relationships among different product parts or subassemblies in an assembly context. They may carry various types of information -- for example, kinematics, fastening, or organization for manufacture. An assembly feature connects several design features from different parts and specifies assembly conditions and processes.
- ***Inspection features*** logically contain all the necessary information to inspect the geometric correctness of a design feature (design verification) or an assembly feature (assembly verification) or a manufacturing feature (verification of the manufacturing process).
- ***Manufacturing features*** connect a design feature with any manufacturing processes and contain information about resources. Its concept is similar to that of inspection features.
- **T*echnological features*** are used either to specify material information (in which case, it is called a material feature) or to apply tolerance information (tolerance feature) to define allowable deviations from the nominal shape or its ideal dimension (straightness, flatness, cylindricity, and shape roundness). Nevertheless, this term is still not clear at all.

- ***Analysis features*** contain information associated with finite-element models (nodes, type of elements, boundary conditions). This term is used more in the field of finite element analysis.

In practices, these different feature models did not have common backbone. Almost every step between the design and downstream processes encountered vexing issues of data exchange, incompatible formats, lack of interoperability, and pre- as well as post-processing. Product design features as represented in design geometry must be identified correctly and linked with the appropriate planning and manufacturing strategy. Recently, enormous efforts have been expended on finding ways to automate these interpretive steps (figure 3-2).

Step 1: Feature recognition

Initially, to link different sub-processes, extensive feature recognition was developed in order to identify the design feature geometry and other design elements that can be automatically processed. The major goal of feature recognition was the manual or automatic identification of shape characteristics and the subsequent generation of a set of geometric elements for manufacturing or inspection process planning. While manual feature recognition is easy to put into practice, it presents numerous disadvantages because it strictly depends on the way the user selects the geometric or technological items.

In automatic feature recognition, an algorithm attempts to find geometric items that correspond to predefined geometric shape representations.

The chief advantage here is the unique identification of features. However, this method shows some weak points as well. Often these algorithms recognize only the assigned class of features. However, their capability can be extended when using neural networks, for example. Most work in the area of feature recognition focuses on recognizing machining features for process planning [Anderson 98]. Other important contributions on feature recognition can be found in [Kyprianou 80], [Henderson 84], and [Falcidieno/Giannini 90]. At this point, the author must observe that feature recognition becomes obsolete if features are defined in an intelligent way from the beginning.

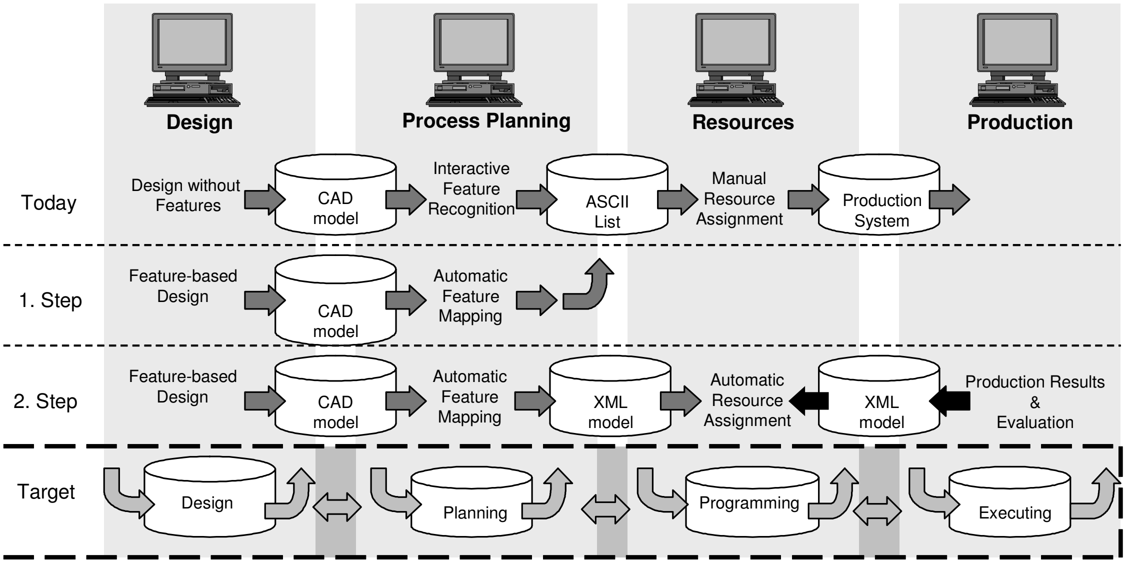


Figure 3-2: Current efforts in designing interfaces applied today
to link product, process, and resources with different CAD/CAM systems.

Step2: Feature mapping

The second attempt to automate the processes was the introduction of feature mapping. Feature mapping was essential to automate Inspection routines for computer-driven coordinate measuring machines or to generate NC programs. Analysis and fastening processes likewise benefited. However, so far, its purpose has been seen in the transformation from one feature class into another, i.e. a mapping of design features into manufacturing or inspection features. In fact, the mapping was a remodeling of missing design elements needed to perform a specific task in process planning. There is a duplication of geometry to fit the related process view. In inspection, for example, planes, points, and circles were re-generated in order to inspect a design feature. In the second step, extensive mapping tables or databases were developed to describe the relationship between design and manufacturing or inspection features. Much work has been done in the area of solids where it was simpler to describe this kind of application-oriented features which largely consists of rule geometries. This is not the case in the area of the car body.

In the past, the application of feature technology in specific steps within the process chain, yielded local benefits only. First, it made reproduction of repetitive features easier. Second, it contained information that allowed modifying the original part design or simply facilitating the realization of coming production steps. Yet, only the continuous application of feature technology throughout the overall process chain can offer global benefits.

Today, research activities show more far-reaching potential for feature technology pointing toward extended process chains and functionality -- the possibility to evaluate mapped feature information for example from production back to design.

The deployment of advanced feature technology as a uniform and constant information medium is essential for the product creation process. The goal is the complete digital cross-linking of the product creation process. Thus, not only is the consistency of process data improved but there is also an enormous potential for its use in the simulation of process cycles and early recognition of bottlenecks and critical resources [Haasis/Schulze 97].

3.3.2 New approach: Intelligent features and solution patterns (intelligent templates)

The basic prerequisite for the efficient rationalization of the product creation process is the extension of feature technology to upstream phases of product development, i.e. the smooth integration of the specification and concept phase to the process chain. The early integration of analysis-, manufacturing-, and assembly-related aspects into the design makes it possible to ensure the advantages of information-technical consistency. Up to now, features have only been considered in individual processes and their semantics have therefore been described solely in particular process areas. Moreover, the functional requirements of the overall component as well as the individual features (feature interaction) were not sufficiently considered. Since these requirements drive the design, the features should, of course, be linked automatically to the overall requirements of the process.

Feature recognition is a difficult issue and extremely time-consuming because the complexity of the component often requires the remodeling of missing design information. These drawbacks can be avoided by implementing advanced (intelligent) features concepts, thus enabling an automatic mapping, not between application-specific features, but directly with process tasks. In this new mapping process, an inspection feature, for example, is no longer the inspection view of a design feature, but an inspection object used to inspect a design feature, according to different inspection strategies.

Thus the information about the product is made available at the time of its generation for the downstream processes so that restrictions and dependencies e.g., between body part and stamping die, are considered and defined at the earliest possible time.

A new generation of engineering system and IT methods is therefore needed to enable users to automate the links to the different process steps and to generate different process views. Here, the function of the component and its production requirement are essential. One of the key methods which pertains to the statements above is so-called functional modeling, or requirement engineering. However, these methods, not explained in this work, are to be viewed within a technological or engineering object context. This leads to further consideration of constraint-based methods, object-oriented methods, and behavioral modeling, for the geometry as a functional object. It is important that these methods take into account the entire set of constraints that can appear at any time in the product life cycle.

Hence, further consideration of knowledge-processing methods is paramount. Furthermore, design activity implies a certain degree of problem solving and decision-making, and these decisions further imply subsequent consequences in downstream processes. Thus, there is a need to extend the current feature approach more intelligently and adaptively to enable the direct impact of a specific feature behavior, allowing support of the decision-making process and tracking of the related consequences in both design and process planning as well as production.

It is the *intelligent feature and solution pattern concept (template)* introduced that automates or streamlines this process and is the new concept that is the basis of this work.

3.4 Structure

Since the goal of this thesis is to provide practical guidance for the development of an integrated and holistic product creation process, the work is organized as follows (figure 3-3).

First**, *chapter* 4** examines the state of the art in practice and science followed by a discussion of the weak points found. Next, the status of the scientific discussion and current trends in IT-based methods and systems are reviewed.

Chapter 5 forms the theoretical part of this thesis, providing a background of the basic methodologies and procedures. First, fundamental methods of designing and describing products are illustrated. Second, an excursus in design and process planning theory is presented to provide the necessary comprehension of the underlying principles of the design process which are the foundation of this work.

Chapter 6 discusses the notion of intelligent features in product design and process engineering, with their key characteristics adaptivity and flexible interaction. The approach employed here is based on object-orientation as a common basis and integration component. A further innovative approach is its extension to solution patterns (part, product and process templates). Based on this approach, a concept for a holistic processing of these intelligent and functional objects is given. Furthermore, a systematization of an integrated information model for feature-based engineering is proposed. An analysis of the product and process model in car body engineering then leads to a detailed systematization of features, and, finally, the underlying information model in an interpretable language is described.

Chapter 7 describes the main process steps on the basis of intelligent features and solution patterns in order to allow holistic processing of data. This starts with the styling process, followed by the CAD/CAQ process chain, with the stamping die process and finally, the fastening concepts concluding the section. Great importance is devoted to tolerance information, because it provides the necessary technological and functional information for the downstream processes and is a key source for determining quality and costs.

The application part makes up ***chapter 8***. Here, the main goal is to demonstrate the feasibility of these concepts. Thus, a prototype called Feature-knowledge Assembly Design (FAD), a vehicle conceptual engineering framework, is introduced: it employs the previously proposed methods as a foundation for the integration of product, process, and resources and represents the next generation of component engineering.

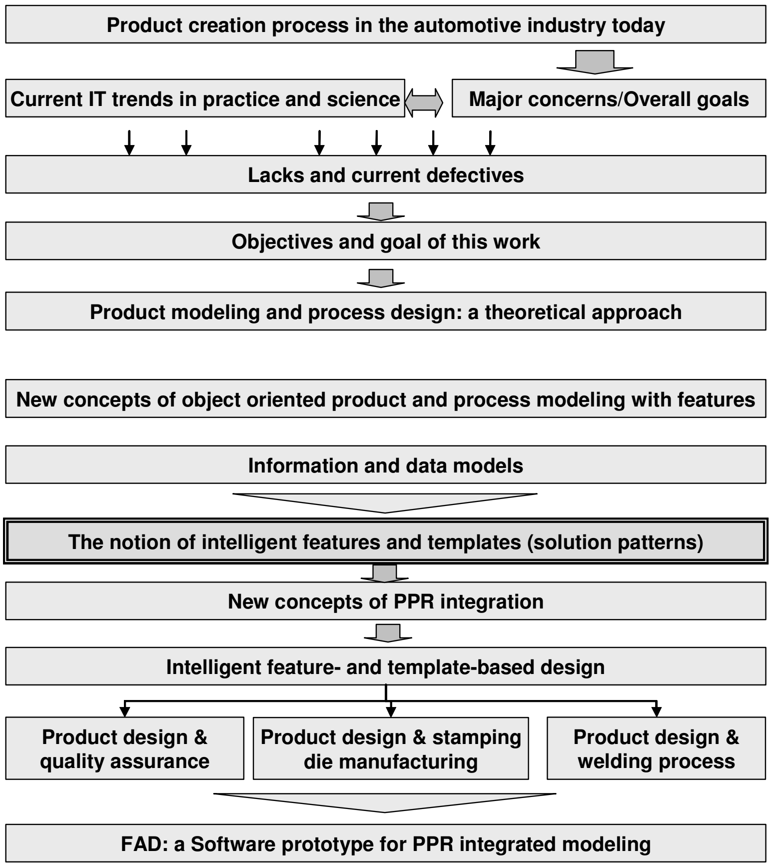


Figure 3-3: Progression of the work.

Finally, ***chapter 9*** reviews the results and explores opportunities for future research.

3.5 Object of investigation and raison d'être

Most of the research activities and prototypes related to feature technology in the product creation process in the automotive industry have been developed in the area of the powertrain (solid) or in the field of aesthetic design or styling. The integration of product process and resource have been so far considered for coupling design and NC manufacturing in the area of powertrain.

Some of approaches described in this thesis are not really new, but it is surprising to find that most of them have not really found application in an actual industry context. Hence, the purpose of this work is to extend these approaches into an integrated framework and to set out a pragmatic concept that not only has scientific relevance but can also be applied in a practical context.

Accordingly, this work is introduces **a new work environment** based on a comprehensive engineering methodology and technology using **the concept of intelligent features and solution patterns (feature-based templates),** in comparison with traditional geometry-related associativity.

The extension of feature technology to advanced feature technology or, better said, from (simple) features to intelligent features is realized by omitting the transformation of a feature class to another and by the intelligent description of its behavior in the product creation process. Furthermore, this work sets out the foundation for the next step towards a vehicle template trough intelligent solution patterns (product and process templates), using the same concept of intelligent features by capturing best practices. The concept introduced and the prototype presented at the end of the work, is not a new CAD/CAM system. It is a concept that extends the capability of existing systems and provides a broad framework dedicated to conceptual engineering in the automotive industry, automating design and process engineering tasks by integrating different technological approaches. The verification of these concepts has also been proven, as these concepts are now applied in practices at some automotive manufacturers.

The objects of investigation are:

Product design

Here a concept for product modeling with intelligent features and solution patterns is underlined. Two main aspects are considered: the styling process and the product development. A first step is to describe how the styling process can be improved by mean of intelligent features, then how the styling and the design can link in order to improve the change management. The second step is to describe the new design methodology for components

Quality planning

After describing the key issues of this process, the challenge here is to specify standardized quality requirements for body components by means of function specification. The second step is to automate inspection planning just by analyzing integrated information from product design.

Assembly or welding process:

The main challenge here is to define common feature specifications in the design for all related fastening concepts and to allow flexibility to adapt the fastening concept according to the underlying specification. Thus, the key issue is to enable earlier evaluation of different fastening concepts, change assembly sequence and update product design.

Die process and stamping die manufacturing

In this section, a broad view is considered from the component (product development) down to the finished stamping die. The section shows how the intelligent solution patterns (features and templates) are systematized in this area and how these elements are used to integrate the process chain.

All these objects are seen in the context of integration of design with the related process step -- design for X. Figure 3.4 shows a simplified graphic of the car body process chain and the emphasis of this work (represented by shaded blocks).

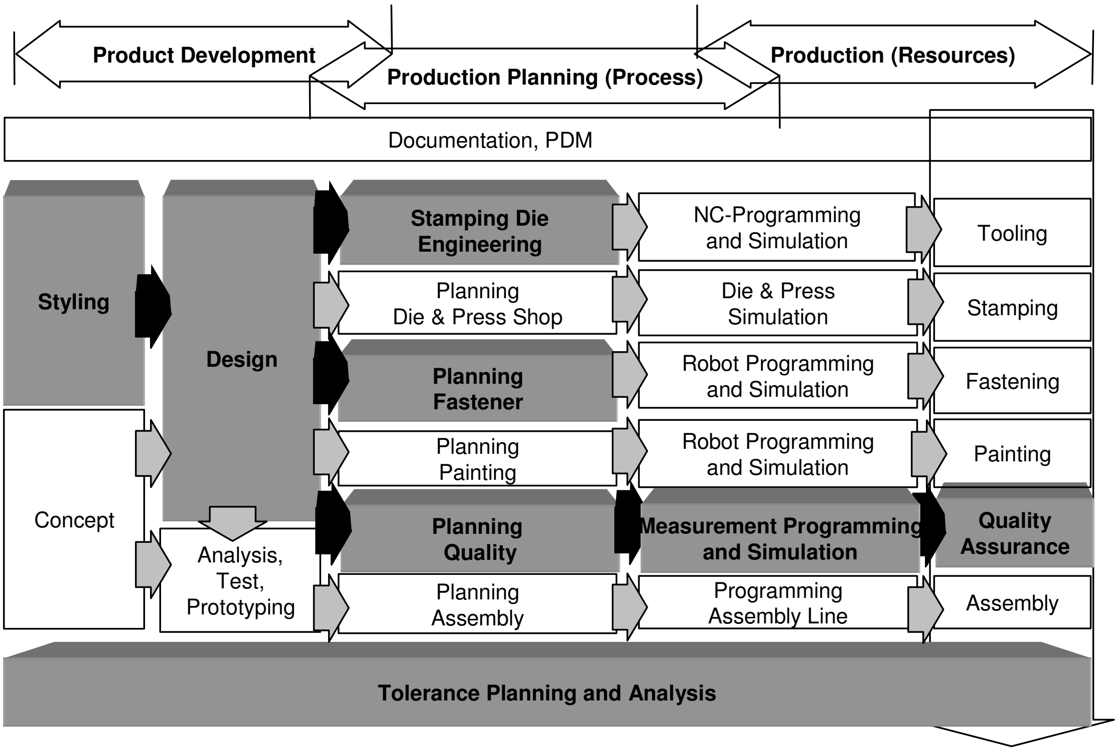


Figure 3-4: A simplified car body process chain and the scope of the work.

PART II

FRAMEWORK: THE STATE OF THE ART AND THEORETICAL BASICS

Chapter 4

4 The state-of-the-art in practice and science

The goal of this chapter is to review existing concepts and current systems as well as IT-based trends.

A recent survey at EUCAR made in September 2006 is summarized in table 4.1. It reflects the current needs of the European automotive industry in the areas of development environment, manufacturing integration, and virtual engineering. The task here for manufacturers was to express their interest (1 = low, 3 = high) in the different topics. Furthermore, each car manufacturer evaluated research level and the readiness for practice. Three topics in particular capture our interest:

- Lean engineering and ICT for integrated product and manufacturing
- ICT for seamless integration of process execution and process planning
- Integrated modeling for virtual design and manufacturing process

			AVERAGE				INTEREST									
Area	RESEARCH TOPICS	Topic	TRL	LOP	PLI	Count	CRF (v3)	DC (v3)	FORD (v2)	GME (v3)	PSA	PORSCHE (v3)	RENAULT (v3)	VOLVO (v3)	VW (v2)	Count
DEVELOPMENT ENVIRONMENTS	Holistic evolutive product modelling	E1	1	1	7.5	2	3			2		2		2	1	5
	Complete multidomain CAx interoperability approach	E2	2.33	3.33	8.33	3	3			1		3	2	2	1	6
	Complete CAx data sharing	E3	4.6	4.4	7.6	5	3	3		3		3	2	1	2	7
	ICT for efficient distributed, simultaneous engineering	E4	3.5	4.25	7.25	4	3		2	3		3	2	2		6
	Neutral format that can be understood by all CAD and FE	E5	1.67	1	7	3	3		1	2		1	2	1	1	7
	Dynamic synchronous development process management	E6	3.33	3.5	6.67	3	3	3		1		2	1	1		6
MFG INTEGRATION	Concepts, methods and ICT for integrated product and manufacturing	M1	4.5	3.5	7.5	2	3			1		1	2	3		5
	"Lean" engineering and massively parallel development process	**M2**	**3**	**3.33**	**6.67**	**3**	3			1		3	1	1	1	**6**
	Data Model to map PDev with Mproc	M3	3.75	3	6.75	4	3		2	1		2	2	2		6
	Model to measure level of Flexible production	M4	3	1.33	6	3	3		2	1		1	2	2		6
	Direct utilization of Bill of Material	M5	3.33	2.33	6.33	3	3		2	1		1	2	2		6
	ICT for seamless Integration of Process Execution and Process Planning	**M6**	**3.33**	**2**	**6**	**3**	3		2	1		1	2	2		**6**
	Data model for visualization of relevant and manufacturable vehicle representations	M7	3.5	3	6.25	4	3		2	1		2	2	2		6
	Integrated PPR modelling for a virtual design and manufacturing process	**M8**	**2.5**	**2.5**	**6.5**	**4**	2	3		1		3	2	2	3	**7**
VR	VR and VE for the creativity process	V1	4	3.75	4.75	4	3		1	1		2	1	1		6
	High resolution CAVE.	V2	3	3	4.5	2	2			1		1	2	2		5
	CAx methods for Reality-based Virtual Engineering	V3	4.67	3	5	3	2	3		2		2	2	3		6

Table 4-1: Current research needs of the automotive industry.

The survey shows that these topics have a great relevance in the automotive industry: three automotive manufacturers have mentioned a high interest and three others a medium interest:

- The *Technology Readiness Level* (TRL), indicating the state of the technological maturity, is still seen in the research stage. Here, the automotive industry states that only proof of concepts have been demonstrated on critical aspects of methods or that methods and prototypes are validated only on simple representative test cases.
- The *Level of Practice* (LOP), giving a measure of industrial maturity, is quite low: First approaches exist, but these concepts are only occasionally used in practice.
- The *Priority Level Index* (PLI), giving the relevance for industry, is classified as important.

Two considerations have been derived from this view: First to extend existing research topics and, second, to demonstrate their application on real use cases and to develop enabling factors for their introduction.

Diagram 4-1 depicts the relationship of the topics in a diagram and gives (arrows) the emphasis specified by the automotive industry. From these trends, we conclude that the industry is interested on tools validated on real-world analysis problems with good performance.

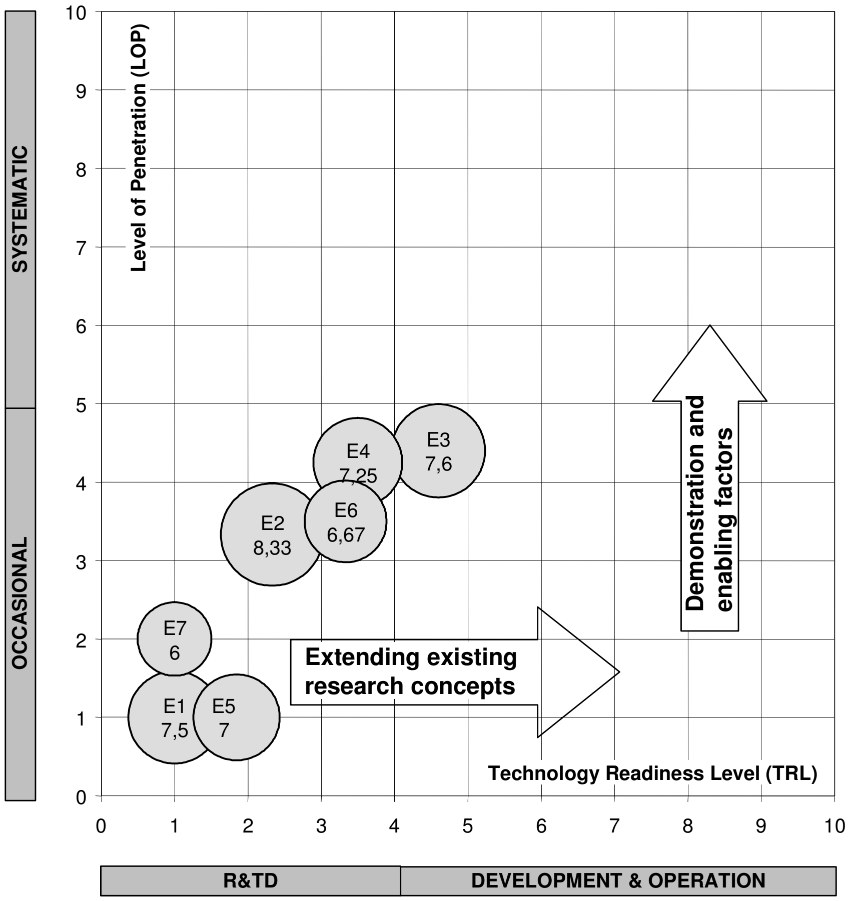


Diagram 4-1: Level of Practice – Technology Readiness Level Diagram [Autosim].

4.1 IT trends

The needs of the automotive industry and the demand for a completely digital product description necessitate specific methods which, apart from the pure geometry definition, allow the additive representation of semantic information and the consideration of product lifecycle. Currently, CAD-CAM systems are focused on the following topics in modeling processes [Mbang et al. 02b]:

- Parametric associative modeling.
- Knowledge integration through rules, formulas, constraints, and references to sources of knowledge.
- Integration of digital product development and the digital factory.
- Use of feature technology.

At present, vehicle manufacturing practice shows that progress in using advanced information technologies for rapid product creation is still insufficient to reach a real quantum change in industrial performance improvement. The main reasons lie mostly in the inability to associate the intuition, knowledge and expertise from different engineering teams, as well as to integrate sufficiently mechanical, electrical and electronic parts in a common technology platform. Furthermore, OEMs and suppliers are currently using IT solutions based upon their specific needs, which results in compatibility problems when tight collaboration is needed to address new market opportunities. Thus, the methodology and technology for supporting fast and flexible manufacturing enterprises within different product creation stages is not there at all. In the following, the current state of the art in the main IT areas related to this work is briefly outlined (Table 4-2):

Area	Description
CAx	The 21st-century CAD systems have evolved enormously. However, even the most advanced CAD systems of today (i.e., CATIA, UG) base their core functionality on 3D geometric representation, taking advantage of surface and solid modeling and incorporating parametric, features and geometric tolerance analysis. Functionality for representing engineering knowledge and efficiently supporting product variants and part re-use based on total product creation requirements and specifications are not sufficiently available. This is even more apparent in the manufacturing environment and CNC machining processes: CAD/CAPP systems are capable of generating process plans, mostly based on geometric characteristics of the parts only, while CAD/CAM systems are capable of generating CNC tool paths, but the planning of the machining process, including decisions regarding roughing and finishing, number of passes and sequence of paths, still relies on the programmer’s knowledge [Yeung 03]. Integrated CAD and Computer-Aided Quality (CAQ) systems

	are also based on the exchange of geometrical data, which, however, is implemented in an unsatisfactory way, so that important topological information is lost at the direct interfaces. Current CAD/CAM systems also offer basic functionality to capture the designer's intent. Despite this fact, substantial efforts have to be made by CAD/CAM developers in order to: • Support functional and manufacturing-oriented design, where only a set of functions and their relationship are used to specify the behavior of the design object for which features and feature-based templates are defined. • Support the conceptual phase, where specifications of features and feature-based templates will meet the functional and manufacturing requirements. • Preserve the semantic correctness of models along the product life-cycle. • Support feature and part template interaction in design and manufacturing. • Support consistent feature conversion methods between different applications. • Support the configuration of user interfaces to help minimize confusion over the complex functionality of a specific system. • Promote open architecture system development. Summarizing, although available CAx systems offer a mechanism to represent, model and incorporate engineering knowledge, they do not provide a fully functional working environment for engineering, especially in the vehicle creation area, where different engineering disciplines and processes are interrelated so deeply.
PLM, PPR, and VE	Current scientific discussion reflects the general trend toward integration and meshed processes. In place of pure product data management, the notion of PLM (product life-cycle management) has become increasingly prevalent. Here, digital engineering methods are paramount for the handling of the vehicle life-cycle [Kimura 00]. PLM requires that all knowledge associated with the product be designed, handled and managed wherein the integration of individual process sections is such that product developers are able to evaluate product requirements as early as possible and, under consideration of resource optimization, efficiently carry out

changes to the product and process throughout the product creation process [Mbang/Haasis 03].

Product Lifecycle Management is a collaborative product creation environment that enables manufacturers to manage a product from its early concepts to its recycling. PLM systems aim at totally integrating product lifecycle information, allowing product engineering, manufacturing, marketing and suppliers to better coordinate their activities.

In contrast to the case with CAD/CAM systems, large enterprises have already recognized the benefits of PLM technologies and have introduced PLM systems under substantial expenditure, some of them already in the second generation. In order to remain competitive, medium-size enterprises must pull tight [Ovtcharova 06]

Today's state-of-the-art PPR-Integration concepts are already oriented around the feature technology and solution patterns (templates) concept. For example, part of IBM Corporation's product line aims to reduce design cycle time on some facets of automotive development processes by enabling simultaneous engineering and relatively fast design change from early styling to final manufacture. However, existing systems have not succeeded completely modeling both engineering knowledge and capturing product requirements and specifications from the entire product lifecycle and thus improving the entire costly process. Fruitful cooperation in multidisciplinary teams should make it possible to succeed in the creation of solution patterns methodology to allow design teams to work with the great flexibility and efficiency, leaving more time for creative engineering design.

In the most cases in practice, VE is seen in the context of VR. VR refers to the interaction of a system with its environment through its 3D visualization and with an immersion capability i.e., the optical embedding in a virtual world in a real time.

Its practical application still remains in the area of the evaluation of product performance in the earlier phases of the product development and the simulation of resources in the factory (virtual factory). On the other hand, VR technology and the Internet now allow engineers to use Virtual Collaboration Environments for product design and evaluation [Shyamsundar 02]. Using collaborative virtual engineering, industry aims at building a fully integrated virtual product based on a collaborative product definition, an integrated e-business platform, and multidisciplinary teamwork [Ovtcharova 03]. However, the VR/AR based environments presented in the scientific literature seem to be either preliminary academic research work without well focused and justified results for quantitative and unambiguous measurements of process characteristics, or industrial demonstrations

	that do not provide an integrated and operation-independent simulation environment. Today in research, VE is used in the context of an **integrated virtual product development process,** which clarifies, for example, the product development process in respect to virtual engineering and uses the following [Ovtcharova 05]: • **Validation systems** allowing the construction of the product in regards to static, dynamics, safety, and feasibility to be tested. • **Virtual Reality-Systems** allowing the corresponding models to be visualized in, from single parts up through a complete assembly. • **Virtual prototypes** combining CAD data as well as information about the remaining characteristics of the components and assembly groups for intense visualization, functional tests, and functional validations in the VR/AR/MR environment.
Feature Technology and Templates	Software developers have been working on feature-based engineering for almost a decade. In the past, most of this effort has been in academic circles. What has promoted commercial applications of feature technology in the last few years is the development of parametric and associative 3-D modeling and its widespread adoption by CAx users mainly in the automotive industry. With this concept, the CAD file now has information about what is between or around its computer representation. This new level of information is the enabler that makes product modeling the precursor to feature technology. Furthermore, substantial efforts have been made toward a semantic product development description based on feature technology over the past years. The first generation of feature oriented CAD/CAM systems (not "feature-based" because the semantics are not sufficiently embedded in the feature model) such as CATIA V5, Unigraphics, and Pro/Engineer, to name only a few, have had a significant impact on the automotive industry. The conventional CAD/CAM systems of today already implement initial feature processing approaches. In the past, complex enterprise-specific macros were programmed requiring complex maintenance support. One of the requirements nowadays is internal support of the generic and user-oriented definition and usage of features by the system, without requiring the additional generation of source code by a programmer. One proven solution is the deployment of user-defined features, which provide methods both for the feature definition and for handling of features over a dedicated user interface. It is thus possible to describe a product in an object-oriented way, assign operations and tools to a feature, and

	allocate them to resources utilizing and combining new functionalities presented.
Application trends in vehicle creation process in practice	In the automobile industry, a paradigm shift has taken place. The new philosophy targets the storage of all relevant product and process information inside or alongside the 3-D model and its virtualization. The underlying notion is to do away with the cost-intensive and time-consuming creation of drawings and to reduce expensive design of the interfaces needed to link the different process steps. Some available CAD systems support this paradigm change. Apart from being able to define the geometry, the functional product description is moving gradually into the foreground. On the other hand, more and more information that in the past was exclusively captured on the drawing (e.g., tolerances, master data) can be represented in the 3-D model. In this sense, CAD systems offer innovative and, at the same time, complex methods for the management of engineering tasks. Three-dimensional tolerance modeling is also part of the new paradigm and one of the complex subtasks during product design. Some CAD/CAM systems offer functions for standard and functional 3-D tolerance of components and assemblies. Software tools for tolerance analysis are chiefly employed during the development process, promoting the realization of an integrated flow between tolerance definition, tolerance analysis, and the downstream production processes. The integration is supported on the organizational side by interdisciplinary working groups and on the technical side by interfaces for passing on of tolerances throughout the CAx process chain. In the end, measured data feedback should lead to the introduction of large automatic control loops for tolerance definition between product development and production. The holistic digital linkage of product modeling, process organization, and resource planning is a focus of present IT activities in the automobile industry. Here, the transition from digital product development to digital process planning in the context of the digital factory plays a pivotal role. Digital factory aims at digitally representing the real world in order to enable simulation and evaluation. A number of so-called best-in-class systems are available and provide extensive functionality. In these systems, however, information exchange is unsatisfactory: many customized interfaces have to be designed in order to link information, and it is at these interfaces that important topological and historical information is lost. Integrated system platforms, utilizing a common and associative data structure, enable these deficiencies to be solved and product, process, and resources to be linked. Since process planning and numerical control programming systems use

	the CAD model as a starting point, their process plans and NC programs are associatively linked with the product description, facilitating necessary changes to the product. Therefore, in the context of the digital factory, most of process planning can be accomplished before production start-up with high-quality planning and verified feasibility secured by simulation methods (figure 4-1).

Table 4-2: State of the art in information technology in the automotive industry.

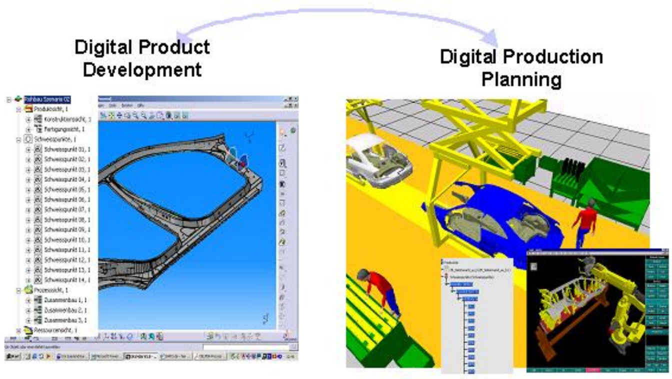


Figure 4-1: Integration of CAD and simulation tools in the context of the digital factory.

4.2 Discussion and future trends

Despite the fact that research institutions, CAx vendors, and industrial users are continually trying to find ways to integrate their individual contributions, some divergences in approaching a common definition and understanding in implementing the concept of features are to be noted. Here, the role of the automotive industry, as a user, is to provide some practical aspects to help both research institutes and CAD/CAM vendors to understand the different engineering approaches when deploying object-oriented techniques in the industrial context.

Statement 4.1: Broadering of engineering scope

In the future, design engineers will be able to consider the different topics which are important in the life-cycle of a product while designing the product i.e., they will consider requirements analysis, development (functional aspects, strength, and durability), planning (costs, material), manufacturing, configuration and assembly, and recycling at the same time.

This, in the end, enables the development of products straight to target [Katzenbach et al. 00]. The starting point is the digital 3D master model as mentioned earlier, in which all process-relevant information is stored. Such digital models are directly employed for validation and verification of the product using digital mock-up (DMU). The digital mock-up prevails only in the packaging area, however; it is still limited to geometry clearance and collision investigation.

Statement 4.2: Expansion of engineering roles

The logical consequence of this evolution is that designers of the future will be more frequently taking the role of product developers. They will also address additional analysis and simulation tasks, such as the early preliminary verification and validation of their own component design before release.

All these methods are possible because they utilize a common database. The resulting operational sequences and processes, however, must be mastered. Here, PLM has become a strategic tool for automotive manufacturers, to collaboratively manage the digital mockup configuration with process knowledge and resource information. Furthermore, PLM can be coupled with enterprise resource planning (ERP) in order to capture and report resources in the form of data from all parts of the organization that can be reused in process planning. All these lead to the following thesis [Mbang et al. 02c]:

Statement 4.3: New ways of creating products in the future

"Engineers of the feature will not be creating products from scratch. In the future, they will rarely start with a clean sheet of paper for new designs. Using a proven design starting with a conceptual or study template, they will transform, adjust, and adapt it with product morphing, using captured product, process, and production knowledge to meet the new (customer and manufacturing) requirement...."

Morphing enables engineers to create new products by quickly and efficiently reuse all the experience in design that has been gained in the past, thus shortening cycle time and market responsiveness and maximizing the benefit. Product morphing involves the combination of data generated from previous development programs and templates with new program specifications, resulting in the transformation of this combined information into a new, valid design for the required program environment. These will be completed in so-called relational design. In advanced form, relational design is able to propagate changes automatically from one definition object to another -- and also process definitions and resources. The user then can evaluate impact of a change. Using a common information model for product, process, and resource definition, users can trigger automated processes to update design or manufacturing aspects.

Shortening the product creation process requires new IT concepts as well as new business processes (lean process thinking). Thus, IT systems have to fulfill a wealth of requirements, such as associativity between data contents, intuitive and context-sensitive user interfaces, system independence, and consistent availability of data. In addition, one of the crucial demands aside from performance and stability is the requirement for high data security and flexible communication with other engineering processes. In order to promote integration and interplay of the individual the process steps, a new generation of IT methods and tools is necessary.

To summarize, the state of the art in industrial practice shows a high demand for radical savings of time and costs. However, there is still a lot of work to be done before the practical use of advanced methodologies and technologies can satisfy the industrial needs. The ability to develop comprehensive engineering solutions using advanced IT methods and tools based upon individual needs and addressing new market opportunities in a flexible way is not evident today.

Chapter 5

5 Basic methods and procedures for product design and process modeling

This chapter will focus on the fundamentals of this work, discussing the terms, technological and theoretical concepts used in this thesis.

In the design process, a product component is generated to meet certain functional requirements. This design intent affects not only the overall shape of the component but also its functional meaning and production requirements. Usually, the designer thinks in terms of objects or functional elements i.e., feature such as locating beads, flanges, or holes. Traditionally, the information passed from design to process planning is a representation of the finished part. Here, the process planner has to specify how the part is to be manufactured by examining the functional aspects of the components and assigning manufacturing task sequences. Manufacturing itself calls for specification of strategies for removing material or shaping the component to meet the specified functional aspects. Then, it remains the domain of the inspection process, for example, to ensure that the component is within the required tolerances.

The need to embed functional and technological information as well as a large variety of knowledge has led to the specification of features mainly based on the concept of object orientation. The underlying benefit expected is that feature-based engineering should support all the information about a product, allowing design, analysis, process planning, manufacturing, and inspection tasks to be captured without loss of information at any stage the product creation.

5.1 Basic methods for product modeling

Products are getting better in terms of performance, reliability, and economy. Yet, crucial concerns remain as to the growing complexity of products and processes, the trends toward globalization, and the increasing reliance on IT.

According to the operation-oriented, design-methodical proceeding (e.g. after [Roth 95], [Pahl/Beitz 97], an allocation of the design is divided into the phases of requirement modeling, function modeling, principle modeling, and shape modeling:

- The ***requirement-modeling*** phase (specification-driven) comprises the intrinsic computer representation of design defaults (design order), the description of task structures, and the definition of product requirements for future products.
- The **function-modeling** phase (functional verification) is concerned with the definition of functions, their organization into sub-functions, and the description of functional de-

pendencies between the sub-functions. The result of this phase is the function structure.

- The **principle-modeling** phase (effect principles) is the definition of the physical principle of the design solution. This covers the definition of the physical effects with equations describing it and the associated effect carriers in the form of effect areas and effective areas.
- The **shape modeling** phase (detail design) describes the geometric arrangement of the effect areas in individual parts, which are combined into an assembly structure.

Based on these models, the design process presents a gradual definition of technical object, whereby, in principle, iteration cycles and jumps are necessary both within a design phase and across phases. The information required in all these phases, as is the case in many areas of automotive development, is linked with the shape of an object. The decisions made during the design process define the product to be manufactured and influence all subsequent stages. Therefore, the primary interest in design processes today is the geometry.

The following sections focus on the key methods for product modeling and their relevance for the application of the concept proposed in this thesis.

5.1.1 Parametric, associative, and constraints product design

While parametric-associative methods are provided by all current CAD systems, their adoption by users still remains an issue in practice.

The concept of parameterization in design

Two types of parameterization can be distinguished: geometric and topological or structural parameterization. In geometric parameterization, only the geometry, or the position and dimensions, of an object can vary, but not its structure, as is valid for topological parameterization.

In general, parametric models may be adapted by linking geometric and non-geometric elements in the product model, and relations between the elements may be linked automatically to changed inputs. In contrast to rule geometry, whose usage makes the parameters such as the length and diameter of a drilled hole obvious, parameterization of free-form surfaces cannot be considered trivial. Here, parameters must possess a strong, meaningful technical association for the designer in order to make an intuitive change of the geometry possible, since the variation of a guidance curve or a change of individual process parameters (e.g., bead radius or flange width) subsequently have an effect on the geometric development of a free-form element.

The problem is magnified for the outer skin of a vehicle, since subjective perceptions such as aesthetics play a greater role by far here. The parameterization of free-form surfaces thus calls for substantial expertise and experience during the definition of suitable parameters, since the usage of the parameter does not consist exclusively of reducing the cost of change but also of assuring design consistency and making key parameters available to the downstream processes.

The concept of associativity in design

Associativity is described by means of characteristics and specifies different representations of an object. In design, associativity is also called relation. This kind of associativity is based on the principle of parent-children relation, expresses by “is part of” or “is kind of”.

In this work, the term associativity has an extended meaning. Here, it denotes continuous information retrieval and processing along the entire process chain e.g., when measuring programs or tools adapt automatically to changes made in the product shape.

Associative modeling necessitates expenditure of a great deal of effort for structuring the model (input/output principle). In the case of a possible subsequent change, the update process runs associatively, which means, in this context automatically. Associative modeling requires an additional step compared to parametric: It is essential to first structure and to describe behavior of the parametric-associative model with consideration of the additional complexity of the model carefully with the demands of the respective development process.

For this reason, an analysis phase of the requirements and boundary conditions, in which fundamental dependencies and internal connections of the component are specified, is needed before the design can be started. This type of concept work has so far been done outside computer-aided systems by the stylist and the designer e.g., on paper. The system now supports the designer by means of associative modeling. This completely new way of modeling components offers a great benefit: stable behavior when confronted with changes, enhanced transparency, and reusability.

A key characteristic of parametric-associative modeling is that all the modeling steps together with all their operations can be captured as history (design record). The results of these operations, which cover not only topological and all the geometry production functions but also operations for change of position and for the representation of the associativity, can then be reused in other operations.

The concept of constraints in design

The underlying concept of parametric-associative modeling is identical to the principle of constraint-based modeling. Constraints in design consist of storing relations in the model under consideration of the desired behavior. The goal is enhanced adaptivity and flexibility [Mbang et al. 02a].

Constraints are typically the major sources of feature information that the designers employ to express their design intent. Constraints attached to features define the behavior of the features and describe the consistent state that a feature is able to assume. In some cases, design constraints are hard to formalize since they relate to the functionality of the design object rather than to the location and shape, and therefore they cannot be attached to the parameters.

Constraints help to maintain embedded relationships and thus entail a high degree of modeling effort. The concept of constraints is very useful for working with geometry based on parametric systems: dependencies between the parameters are defined in the form of equations and unequations. The resulting constraint network describes the geometric design problem. Processing the constraints for a set of parameter values is called constraint solving. In principle, two approaches are differentiated for the processing of constraints:

- ***Constraint propagation***, which describes the reproduction of a parameter change in the constraint network and whose consequence can be made visible.
- ***Constraint satisfaction***, where all parameters are to be more or less defined in such a way that all constraints are fulfilled.

This task becomes more difficult with growing complexity of the product, since the dependencies are often nonlinear, unstable, and not differentiable and since the number of dependencies can be large. Problems also arise if constraints are contradictory (i.e., there is no configuration of the object that will satisfy all the defined constraints) or if the specified set of constraints is incomplete. Altogether, constraint methods can be applied to nearly all numeric problems and also to simulation in order to examine influencing factors, for example. Substantial disadvantages are, however, that constraints are non-causal and the processing of character strings or complex data structures is extremely hard to do [Werner 01]. Constraints serve as the representation of relations between variables. They are suitable, in particular, for the representation of non-directional local boundary conditions for the characteristic development of objects which must fulfill a problem solution without giving a concrete problem solution.

In conclusion, parametric and associative modeling allows feature objects to be represented by means of parameters and relations to be stored in objects related to the desired changed behavior. Moreover, the underlying principle of constraints offers a powerful medium for feature processing: parameters and constraints play a key role in expressing object semantics, which will serve as the foundation for the definition of intelligent features discussed in the next chapter.

5.1.2 Capturing knowledge using rules and formulas

One fundamental approach in current product modeling capturing product knowledge and steering the upstream and downstream processes requires linking formulas and rules with geometry or parameters. A rule is a logical expression using appropriate instructions based on a formal or a programming language, whereby free variables refer to appropriate elements of a model (if... then...).

During the evaluation, a set of instructions is compiled. These can analyze either effects or dependencies, seek out knowledge conflicts (what else...) and generate reports, suggest appropriate corrections to the designer, or even carry out the necessary corrections automatically. Rules thus represent a possibility of seizing and putting existing organizational knowledge into a suitable form for further processing by the user. Formulas and rules enable constraints for both geometric elements of a product model and for its parameters to be formulated. Within design, the consistency of the parametric is additionally assured by rules and test mechanisms, enabling the geometry to be easily changed.

5.2 Knowledge integration, representation, and management

Knowledge has been the subject of fundamental interest and attention in artificial intelligence (AI) since its earliest days, particularly in the area of expert, or knowledge-based, systems [Smithers 02]. Mostly, the definition of knowledge is taken from the standard philosophy of knowledge or epistemology: this defines knowledge as justified true belief. Newell introduced a practical, very different definition of knowledge in his concept of knowledge level, in which knowledge is defined as a capacity for rational action [Newell 82]. According to Newell, an intelligent agent is composed of goals, actions, and a body. The medium, the composition of the body, is knowledge (what the agent knows), and the law of behavior is the principle of rationality; an agent uses its knowledge to select one or more of its actions to achieve its goals. It this sense, Newell concludes that systems that are observed to act rationally can be said to have knowledge or to behave intelligent.

5.2.1 Knowledge integration and management

Knowledge management embodies, in general, organizational processes that seek the synergistic combination of data, information processing of information technologies, and the creative innovative capacity of human beings. It concerns strategic processes around which knowledge and information are defined and managed.

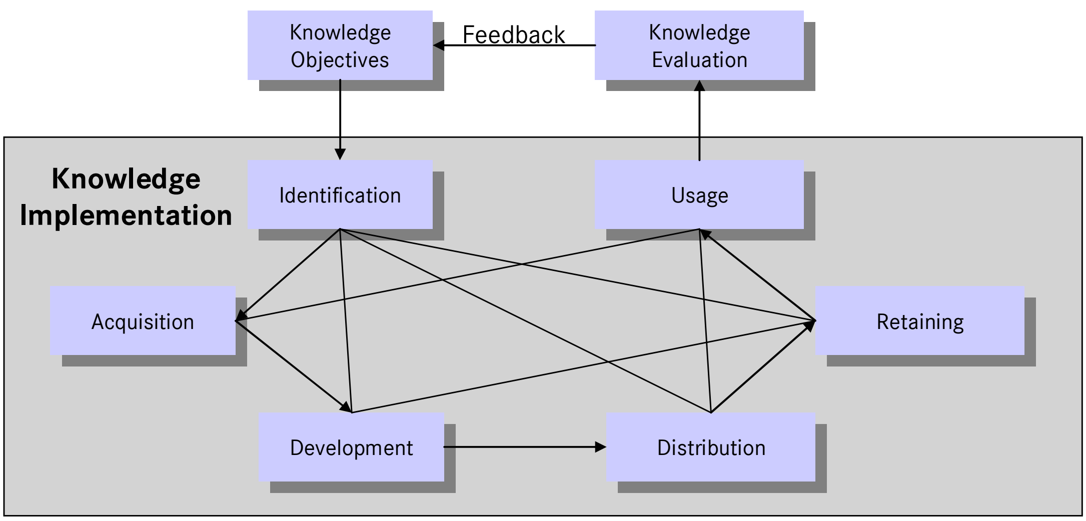


Figure 5-1: Knowledge management.

The task of knowledge management is to make available a continuous, spatially distributed individual and group knowledge as well as data and information in an unstructured or semi-formal or formal manner. The central goal of knowledge management is the linkage of individual knowledge resources to a flexible knowledge network in order to make individual knowledge available for the enterprise and enable it to be optimally used in order to increase the creation of its added value [Dfki 99].

Probst developed a knowledge handling model (figure 5-1) [Probst 98]. Here the objective, implementation, and measurement of knowledge illustrate the traditional management process. The internal cycle of implementation consists of six components: knowledge identification, knowledge acquisition, knowledge development, knowledge distribution, knowledge preservation, and knowledge use.

Knowledge acquisition is an important phase in building knowledge-based or expert systems. Knowledge-based systems are a kind of computer program that applies technical knowledge, or expertise, to problem solving. Knowledge acquisition involves identifying the relevant technical knowledge, recording it (development), and getting it into computable form so that it can be applied by the problem-solving engine of the expert system (distribution). Unfortunately, it is also the most expensive part of building and maintaining expert systems.

The components portrayed in figure 5-1 illustrate the structuring of the management process into logical phases and serve as a search matrix for problems. Problems occur when the organization neglects several of these components, thus disturbing the knowledge cycle. A detailed investigation of these terms is presented in Ostermayer [Ostermayer 01].

The key requirements for knowledge integration and management in the product creation process refer to some fundamental questions:

- What can be illustrated?
- How can this be supported conceptually?
- Which arranging and organizing mechanisms are necessary to precisely communicate a circumstance and to make it re-usable?
- What knowledge does the enterprise need in order to become successful?
- How can knowledge be made transparent in the enterprise, so that all those entitled to it can access it?
- How can knowledge be structured and documented?

Knowledge integration is essential in the product creation process with respect to functions, manufacturing, assembly, and cost. Here, being able to perform product checks with respect to parameter dependencies, associativity, and process-relevant parameters allows support of the development process, while mapping rules and algorithms based on production knowledge enable the generation of process connections.

Partial automation of the information flow along the process chain opens the potential for the fast derivation of process design and resource planning. Based on applied features during the design phase, the partly automated modeling of manufacturing, welding, assembly, and measuring processes is assumed. And, if product characteristics are to be modified, knowledge integration serves as link for execution and support of change management and the resulting documentation. Here it is essential to consider the subsequent treatment of information generated in the parallel and downstream processes during the manual product definition and the assignment of the knowledge to relevant sources.

5.2.2 Formalisms for knowledge representation

Knowledge representation (KR) refers to the general topic of how information can be appropriately encoded and utilized in computational models of cognition. Typically, work in knowledge representation focuses either on the representational formalism or on the information to be encoded in it, sometimes called *knowledge engineering.* Although many AI systems use ad-hoc representations tailored to a particular application, such as digital maps for robot navigation or graph-like story scripts for language comprehension, much KR work is motivated by the perceived need for a uniform representation and the intuition that, because human intelligence can rapidly draw appropriate conclusions, KR should seek conceptual frameworks in which these conclusions have short derivations.

The central topic in knowledge engineering is to identify an appropriate conceptual vocabulary and a related collection of formalized concepts often called ontology. For example, temporal or dynamic knowledge is often represented by describing actions as functions on states of the world, using axioms to give sufficient conditions for the success of the action and then using logical reasoning to prove constructively that a state exists that satisfies a goal.

To formalize the knowledge representation, a differentiation is made in principle between the data (symbol) level and knowledge level:

- ***The symbol or data level*** represents a computer-processable and therefore strictly formalized level with the goal to represent and process certain circumstances regarding a fixed objective. The data level represents materialized knowledge which is coded for processing on a computer by means of algorithms.
- ***The knowledge level*** represents the genetic origin of the data level. Here terms are developed as representations of cognitive circumstances to be able to communicate in an educated manner. Hence, knowledge is defined as the capacity for rational actions [Newell 82].

The further development of knowledge models leads us into the model world of artificial intelligence and in particular into the world of knowledge-based systems.

Definition 5.1: *A knowledge-based system is, simply formulated, a system for problem-solving of vague or unstructured tasks. The original idea is the transmission of the human expert's assessment to expert systems in a computer-internal model.*

An advancement of expert systems aims at the support, and not replacement, of humans within the problem-solving process. These models are particularly suitable for the support of routine activities. The core of knowledge-based systems is the knowledge basis for the illustration of expert knowledge and problem-solving methods.

The available circumstances and/or knowledge structures and knowledge elements are specified by representation formalisms. In the field of artificial intelligence (AI), two families of knowledge representation with opposite characteristics have been developed [Altenkrüger/Büttner 92]:

- *Declarative knowledge representation* concentrates on the description of circumstances and gives, in principle, no data for the application of knowledge for a concrete problem definition.
- *Procedural knowledge representation* places the application of the knowledge into foreground. The represented knowledge is a set of instructions that, after execution, agree with represented circumstances.

So far, research in the field of AI has given birth to four paradigms of knowledge representation, arranged between declarative and procedural representation [Eastmann/Fereshetain 94]:

- *Associative nets* with representative semantic nets, conceptual graph, and conceptual dependency.
- *Structured objects* with the representative frames (scripts), patterns, units, and objects.
- *Logic-based systems* with forms of predicated logic and modal logic.
- *Procedural representation* (constraints, scripts).

The suitability of represented formalisms for knowledge representation can be differently evaluated. Each representation form has specific pros and cons. Object-oriented knowledge representation is suitable as a fundamental form, since it can be used to illustrate real and abstract circumstances. Inheritance mechanisms permit a modular representation and additionally enable reusability on different levels of abstraction. If mechanisms are available as well for the grouping of objects, in the sense of patterns and object relations, then it is possible to model ranges of application as the context of different views on the same object designation. Constraints are, in this context, suitable for the axiomatic representation of boundary conditions, since they must always be fulfilled in the defined context. The formulation of global, arranged boundary conditions on the level of objects also calls for rule definition. Hypotheses can be modeled by means of rules in order to check facts or for the control of handling schemata. All in all, a powerful formalism thus results as a starting point for the modeling of circumstances.

5.3 Data, information, and knowledge models

A model is generally an image of something and according to Stachowiak has three characteristics [Stachowiak 73]:

- *Illustration characteristic*: Models are representations of natural or artificial originals.
- *Shortening characteristic*: Models generally do not capture all the attributes of its original but only some attributes which appear to be necessary to the respective model developers or model users. Thus an attribute selection is mandatory.
- *Pragmatic characteristic*: Models are not clearly assigned to their originals per se.

The meaning of a model is therefore varied.

Definition 5.2: *A model on a small scale can be a sample, a draft, or reproduction -- a simplified representation of a function of an article or circumstance which facilitates or makes possible an investigation or a research [Duden 82].*

In model theory, originals and model are interpreted by attribute classes. The illustration of the term, therefore, designates the allocation of model attributes (characteristics) to original attributes (properties). According to the illustration characteristic, the following model types can be differentiated [Zangmeister 76]:

- *Picture and graphic models* for the representation of visible characteristics. These are two-dimensional descriptive original representations (diagrams or technical designs).
- *Analog and/or technical models* for the representation of similar characteristics of an object. These are three-dimensional spatial, temporal, material models (e.g., flight simulator).
- Formal *and/or semantic models* for the formal representation of object characteristics by means of logical and/or mathematical methods.

In knowledge management, there is no real difference between data, information, and knowledge, and there is no commonly agreed set of relatable definitions of data, information, and knowledge. This depends upon the field under consideration. The very different terms *data*, *information*, and *knowledge* in the literature can be defined with respect to the computer-internal illustration as follows:

Definition 5.3: *Data are the values of parameters or variables of systems or models. They have only a syntactic dimension i.e., they are instantiated characters of the type number, letter or even character strings*

Data serve for the actual representation and processing of information due to well-known or subordinated agreements. The values are obtained by measurements (in the case of real systems), mathematical derivation (in the case of formal models), or computation (in the case of software systems, simulation, etc.).

Definition 5.4: *Information is communicated data, where communication involves encoding, transmission, reception, decoding, and interpretation.*

Information has form and content, thus a syntactic and semantic dimension. It extends the data by adding meaning for distinction. Hence, information gives the formal interpretation area of data.

Definition 5.5: *Knowledge, according to Newell, is the capacity to act rationally.*

In contrast to data and information, knowledge represents additional aspects, such as structure, meaning, action, reason, interpretation, and other temporal functional characteristics, in a given context.

Data, information, and knowledge models, as they are understood in the field of the computer application, are external semantic models that are characterized by a formal structure. The concrete objective is formalization of communicable knowledge for the purpose of illustration and processing on the computer. The determination of whether the model in question is a data, information, or knowledge model depends essentially on the field and the kind of communicable knowledge, which again depends on its later application. Each model generally contains knowledge; the knowledge is only more or less implicitly hidden in the code. The objective of creating a data and/or an information model is the integration and representation of all the information that can be illustrated in a uniform, formalized, and semantic description as completely as possible in order to represent relevant circumstances as exactly and redundancy-free as possible. Finally, the data model is to flow into a model executable by the computer.

To conclude,

- *Data models* serve to illustrate concrete information and foreseeable, algorithmizable conditions and status changes of the illustrated information, as they are applied in conventional software systems.

- *Knowledge models*, however, do not serve for the illustration of partly heuristic and vague, thus algorithmizable, knowledge, but rather are employed for the problem solution of vague and unstructured tasks. In contrast to conventional software systems, formalisms are used for the knowledge representation in place of algorithms.
- *Information models* have a kind of intermediate status in relation to data and knowledge models. On the one hand, they allow distinction of different data, thus closing the gap between data and context; on the other hand, if explicitly specified, they can be designated as knowledge models, since they bridge this gap.

It can be stated that there is no information without data. Communication of data, i.e. information, requires agent properties and, typically, knowledge – the capacity to encode, decode, and interpret the transmissions, for example. An agent will typically have knowledge to utilize the data resulting from the information it gets and to generate or derive other data. Thus, understanding is important when trying to build information systems to support designers in designing: information systems are systems that support the communication between agents involved in designing. Yet these design support systems do not necessarily have knowledge about designing. They just need to be able to connect effectively and efficiently to the sources of the data (knowledge) to be communicated – typically stored in databases or catalogues -- for problem-solving.

5.4 Design rationale (DR)

Design spans many disciplines and is often a group of activities. It is not a sequence of well-defined activities and involves a lot of cognitive activities such as ideation, learning, problem-solving, and decision-making.

Definition 5.6: *Decision-making is the process of choosing a preferred option or course of action from among a set of alternatives.*

The decision-making process often begins at the information-gathering stage (knowledge acquisition) and proceeds through likelihood estimation and deliberation (evaluation) until the final act of choosing (decision). In a collaborative environment, design involves distributed cognitive processes and shared understanding [NN3]. Figure 5-2 portrays the rough decision process related to the product and process behavior.

Designers follow a design process in which decisions are made about a design object, starting with high-level system decisions and progressing to levels of increasing detail. When following this process to synthesize new designs, the designer progresses through three steps at each level of detail -- problem formulation, synthesis, and analysis.

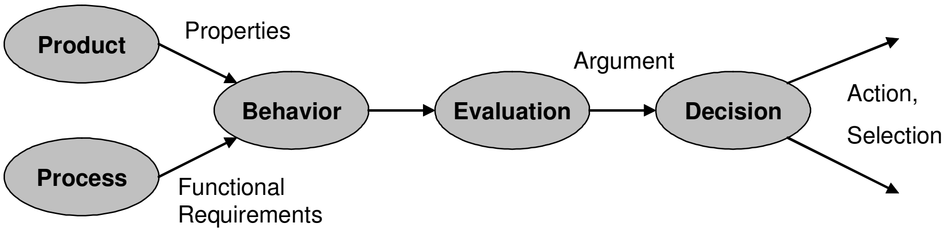


Figure 5-2: Decision process.

Definition 5.7: *Design rationale (DR) consists of the decisions made during the design process and the reasons behind them, including their justification, other alternatives considered, and argumentation leading to the decision [Lee 97].*

Various other definitions of design rationale exist: for example, design rationale as a historical record of the reasons for the choice of an artifact [Conklin et al. 95] or a description of a design space [MacLean 89].

Essentially DR can be thought of as answering these questions:

- Why this artifact is designed the way it is?
- How might it be designed differently?

On the whole, DR makes argumentation explicit and can act as a cognitive aid to design and a means of revising, maintaining, documenting, evaluating, and learning the design. It not only facilitates communication between designers but also supports design reuse and maintenance.

With the availability of design rationale, designers revising a design can use it to determine the original designer's intent or to identify the alternatives that have already been considered and why they were rejected. This knowledge can help to avoid duplicating work that was done on a previous iteration through the design. In some cases, the reasons for making a decision may no longer be valid, and choosing a different alternative may be preferable [Burge/Brown]. Rationale can also serve as a form of corporate memory, providing valuable insight into a design that would otherwise be lost if designers left the company [Peña-Mora/Vadhavkar 96], [Brice/Johns 98]. In addition, this is exactly the basis of an advanced feature technology, which offers reusable design objects with encapsulated knowledge.

Figure 5-3 depicts the application of DR in the context of an integrated product and process design. DR is also part of the backbone.

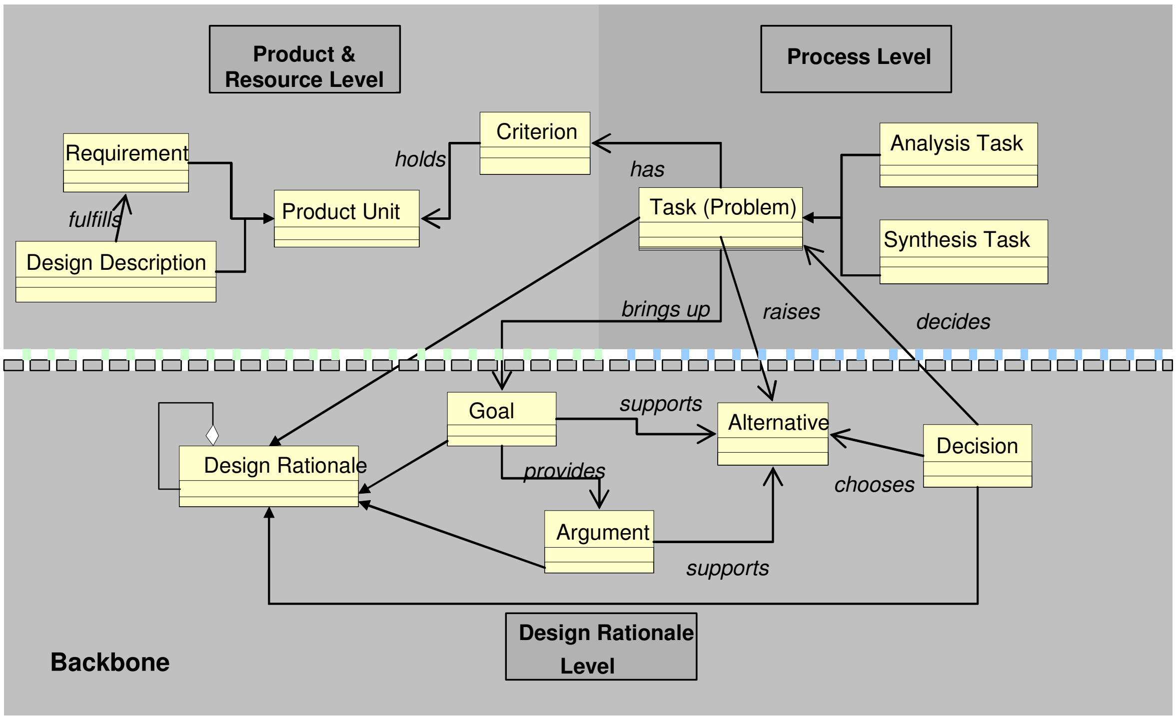


Figure 5-3: Design rationale within the product development process.

Using this concept, an improvement of communication through the product life-cycle is expected: DR coupled with feature technology allows enhanced reuse of design knowledge across products and enforces design discipline. Design methodologies can be applied, thus avoiding cost-intensive well-known procedures. Furthermore, DR organizes potentially large design space by capturing contextual information.

Much work has been done in DR and many systems have been designed, such as IBIS (issue-based information system), PHI (procedural hierarchy of issues), Design Space Analysis or QOC (questions-option-criteria).

DR systems are classified according to the following criteria [Herder 02]:

- **Criterion 1: Approach**, process-oriented and feature- or structure-oriented.
    - *Process-oriented*: Preserves the order of deliberation and decision-making. DR is the history of the design process: “Why do we take this design step?”
    - *Feature- or structure-oriented*: Emphasizes post-hoc structuring of considered design alternatives. Here, DR is the analysis of the design space: “How do we ensure that the design artifact has the desired feature?”
- **Criterion 2: Representation scheme**, argumentation-based or descriptive.
    - In argumentation-based schemes, the goal is the representation of the structure of an argumentation: “What is the relationship between questions, options,

and arguments?" A descriptive representation scheme records the history of the design steps: "Who did what, when, and why?"

- **Criterion 3: Capture,** knowledge recording and DR construction
  - This type of DR has two modes: user-interaction (user has to input rationale items) and automatic (DR system tries to capture items automatically).
- **Criteria 4: Retrieval**
  - Three alternatives are conceivable: navigating (user can browse the linked pieces of information), queries (user can search for information using queries), and automatic triggering (the system automatically accesses information and presents results if appropriate).

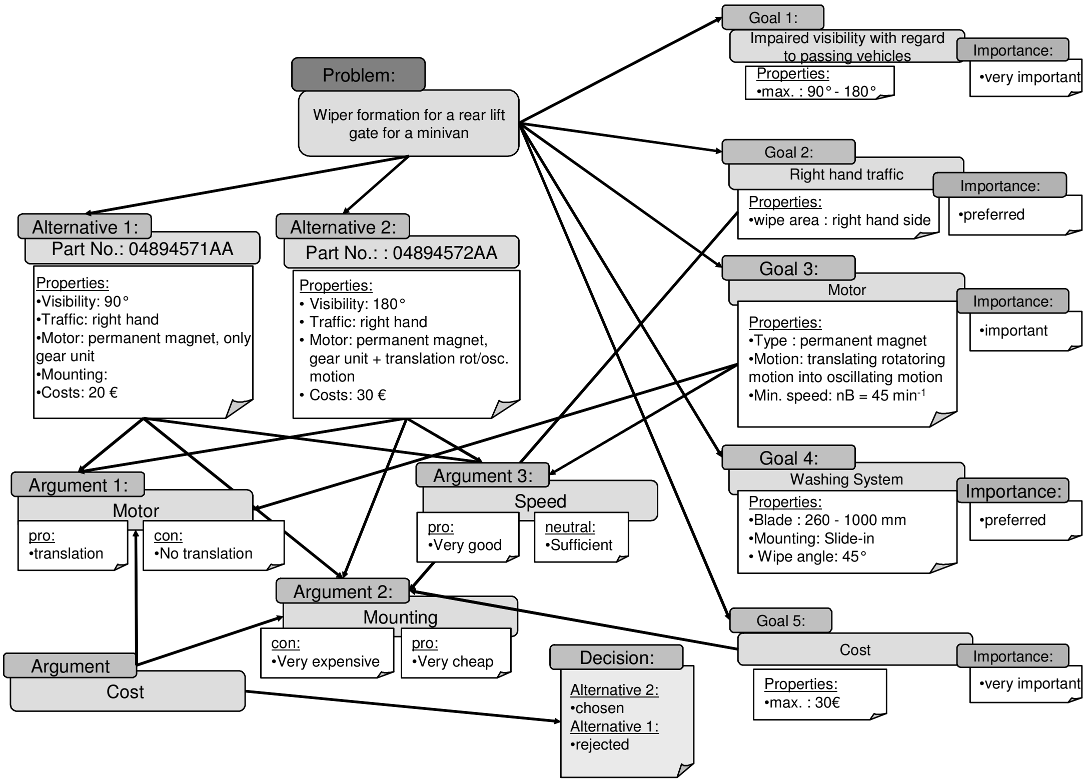


Figure 5-4: Example of a problem: selection of a wiper formation.

Figure 5-4 shows an example of a problem-solving procedure using DR.

A term that must be mentioned is psychological design rationale. The objective of this rationale is to support the task-artifact cycle in which users' tasks are affected by the systems they use. It aims at making the consequences of design explicit for users. Designers identify the tasks that the system will support and scenarios are suggested to test these tasks. At the same time, users are observed on the system, and psychological demands of the system are made explicit. In this way, negative aspects of a design can be used to improve the next iteration.

Conclusion:

In conclusion, most work on design rationale has concentrated on how DR can be captured and represented and not on *how it can be used*. This may explain the fact that none of the DR systems today are widely deployed, although designers could benefit from using them. While capture and representation are important for design rationale, the real value of a system is how well the rationale can be *put to use*. In this sense, there remain great challenges to for not only in minimizing the overhead when capturing knowledge but also in keeping close to the human way of thinking and in improving automated reasoning in integrated tools. In this thesis, the *use* of DR is investigated, but not formalized, as this is not the focus of this work. The prototype (Vehicle Conceptual Engineering Framework) presented in this work draws inferences from a design rationale in order to detect design and process inconsistencies and to assess the impact of design and process changes.

5.5 Product design and process modeling: A theoretical view in design research

Engineering design includes a variety of thought processes. It can be seen as a sequence of acts which may be described through processes. The design process may be divided into three classes: analysis, synthesis, and evaluation.

The core of design is synthesis i.e., the creation of artifacts, plans, or programs which serve the satisfaction of human needs [Andreansen 01]. In relation to industries, which depend on product innovation and development, three patterns of synthesis may be distinguished:

- ***Problem-solving***: the cognitive human activity with characteristics such as information handling, creativity, learning, experience, values, and motivation. The result is identified as means, plans, etc.
- ***Engineering design***: a synthesis procedure in which the nature of the artifact is taken into account (decomposition, composition, function, structure, part, form, etc.). The result is a specification of the artifact.
- ***Product development***: a synthesis procedure leading to a new business i.e., a product, running production system, and established sales channels as basis for a cash flow.

Design research concentrates on finding the nature of design, looking at how designers work and get to their solutions, and on research into products, methods and tools. Researchers in the light of their own disciplinary perspectives and experiences have proposed various models of design. Some examples of design models include systematic design [Pahl 96], axiomatic design [Suh 90], quality function deployment (QFD) [Haus-88], total design [Pugh 90], decision theoretic model [Haze 97], decision-support model [Mist-97], general design theory [Yoshikawa 81], universal design theory [Grabowski 01], and property-driven design [Weber/Werner 00].

Partially due to the fact that different models are based on different views of design and employ different modeling approaches, the relationships between the models are not well understood [Jin/Lu 01]. While all of them describe or prescribe certain design behaviors, Jin and Lu's review of the models has shown that little cross reference exists between the design models aimed at developing systematic and practical processes for designers to follow [Pahl 96], [Pugh 90], [Haus 88]. Some propose generally useful principles to guide design decision-making [Suh 90], [Alts 94], while others explicate types of knowledge involved in solving design problems [Yoshikawa 81], [Gero 88].

Several of the models studied within the framework of this thesis attempt to provide constructive methods to reduce ambiguity of design problems and to lead to clearer design problem definitions. To name only a few, QFD [Haus 88], total design [Pugh 90], and systematic design [Pahl 96] are typical representations.

Examples of the models that take a process view toward design include QFD, systematic design, total design, zig-zag part of axiomatic design, and property-driven design.

In the context of feature technology, feature-based engineering can be considered as the art of designing and manipulating the characteristics of a product by means of predefined design objects. To propose a suitable understanding of the term *intelligent features* (see chapter 5), especially in car body environment, we consider the underlying theory in design products and modeling systems. For our application, we examine the concept of general design theory (GDT) [Yoshikawa 81] and Ovtcharova's mapping of this concept onto the feature-based approach [Ovtcharova 96]. A further consideration is based on the concept of axiomatic design [Suh 90], which we combined with the notion of property-driven design (PDD) proposed by Weber [Weber/Werner 00]. In our context, the latter is very useful, as we understand the design process as the mapping of a set of properties or functional requirements onto a set of product characteristics. In addition, this concept proposes a more explicit description of the mapping process in the context of product, process, and resource integration.

5.5.1 General design theory (GDT)

The nature of design is one of the key aspects of general design theory. GDT is based on axiomatic set theory and aims at encouraging people to design in a scientific way, at producing practically useful knowledge about design methodology, and at formalizing design knowledge into a form to be implemented in computers. Although there is a controversy about the nature of GDT, since it presents an ideal model of design, it can however help us to understand the theoretical principle of defining design knowledge mathematically and, for our purpose, the notion of intelligent features. GDT starts with a number of definitions and axioms about the nature of objects (e.g., entity, attribute, behavior, function) and uses them to provide theorems about the nature of design [Tomiyama/Yoshikawa 87].

Definition 5.8: *The design process is defined here as the mapping of entity concepts that denote function space and attribute space.*

Based on this concept, Ovtcharova asserts that design objects and design processes can be described as a mapping from conceptual world to the real world via the logical world. Here, designing is an activity to create an entity in the real world through the logical world, with specifications and schemes developed in the conceptual world.

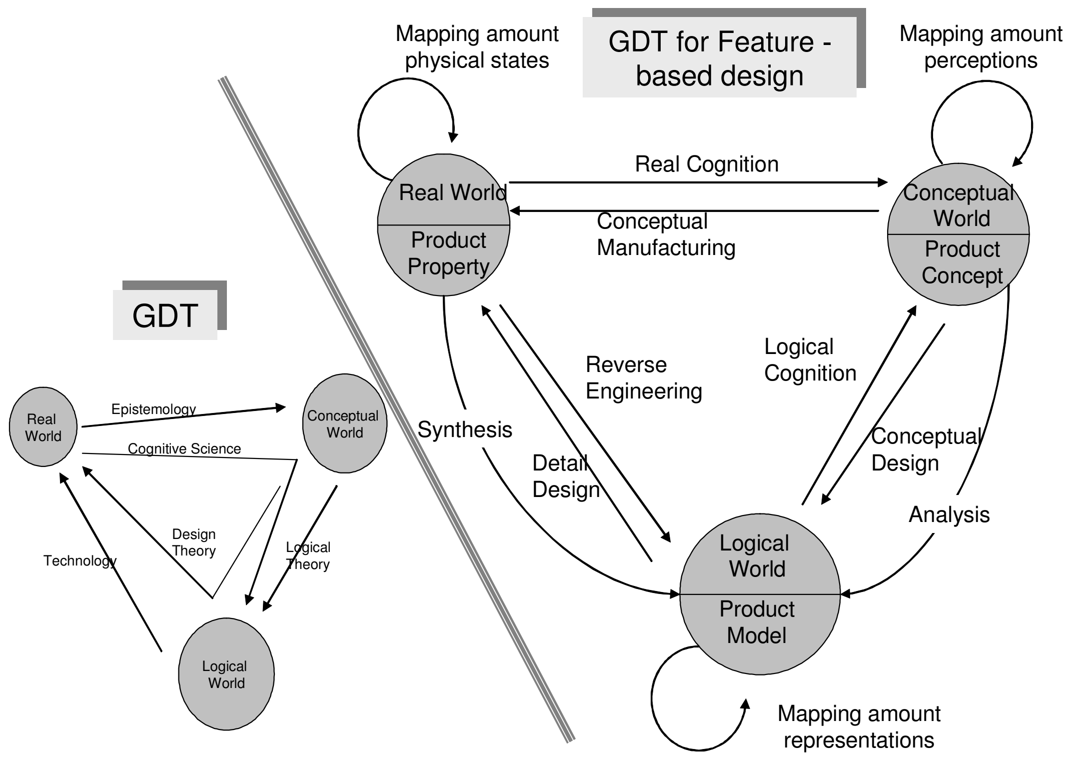


Figure 5-5: Scope of GDT for feature-based product design [Ovtcharova 96].

Ovtcharova proposed a scheme for applying the worldview of GDT in the context of feature technology as shown in figure 5-5. According to the concept of GDT, three domains are considered: the real or physical world of products, the conceptual or mental world how we think about objects, and the logical representations such as specifications, language descriptions, schemes, and computer models. This theoretical framework for feature-based engineering supports the three-world view of a product and the bi-directional relations between them and offers an essential background for the definition of intelligent features.

Tomiyama and Yoshikawa developed Extensions to General Design Theory (EGDT) and considered the real world by introducing some realistic constraints in terms of physical laws, which is a description of the relationship between physical quantities of the entity and the field. Furthermore, they defined the *function* as a physical phenomenon caused by the physical laws governing the situation where the entity exists and a *functional element* as an entity concept that materializes some physical phenomenon caused by physical laws. Therefore, the design solution is obtained by collecting all function elements, as the design specifications are described by physical laws. Furthermore, they additionally point out the notion of design specification, design process, and design solution [Tomiyama/Yoshikawa 87].

While design specification designates the functions of the design object using abstract concepts, the design solution designates an entity concept which is included in the corresponding specifications and carries all necessary information for manufacturing. Thus, in this sense, the design process can be defined as a mapping of function space into an attribute space. In this process, analytic operations are indispensable. The design solution sometimes cannot be described even when we succeed in making the specification converge into a known entity concept [Ovtcharova 96].

5.5.2 Property-driven design (PDD) and axiomatic design (AD)

Recent trends in prescriptive integrated product design research are characterized by many streams of development for enhancing the design process in order to create better design solutions [Blessings, Andreasen, etc.]. In this part, we focus on the stream related to the evaluation of the design solution by design principles (axiomatic design - AD) and on the trend related to design-driven specifications or properties (property-driven design - PDD). PDD and AD are quite similar. PDD extends AD in such a way that it provides a concrete understanding for product, process, and resource integration.

Motivated by the absence of (common, agreed) scientific design principles, Suh proposed the use of axioms as the scientific foundations for design to be pursued.

Definition 5.9: *In AD, design is defined as the development and selection of a means (design parameters or product characteristics) to satisfy objectives (functional requirements or product properties), subject to constraints* [Suh 90].

Design problems can be divided into four domains:

- ***Customer*** (what does society need?) – *Customer needs* (CNs).
- **Functional** (what does it do?) – Functional requirements (FRs).
- **Physical** (what does it look like?) – Design parameters (DPs) or product characteristics (P).
- ***Process*** (how is it made?) – *Process variables* (PVs).

FRs are defined as the minimum set of requirements which completely characterize the design objectives for a specific need [Suh 90]. These FRs must be specified in a solution-neutral environment (i.e., in terms of the functions to be achieved), not in particular solutions. Related to a product, FRs are reflected as their properties (P), as specified in PDD, which further distinguishes between determined properties and required properties, as will be discussed later.

Figure 5-6 shows the relationship between the main design steps (VDI2221) and the design equation, as specified by Suh, and its integration within the product creation process (left).

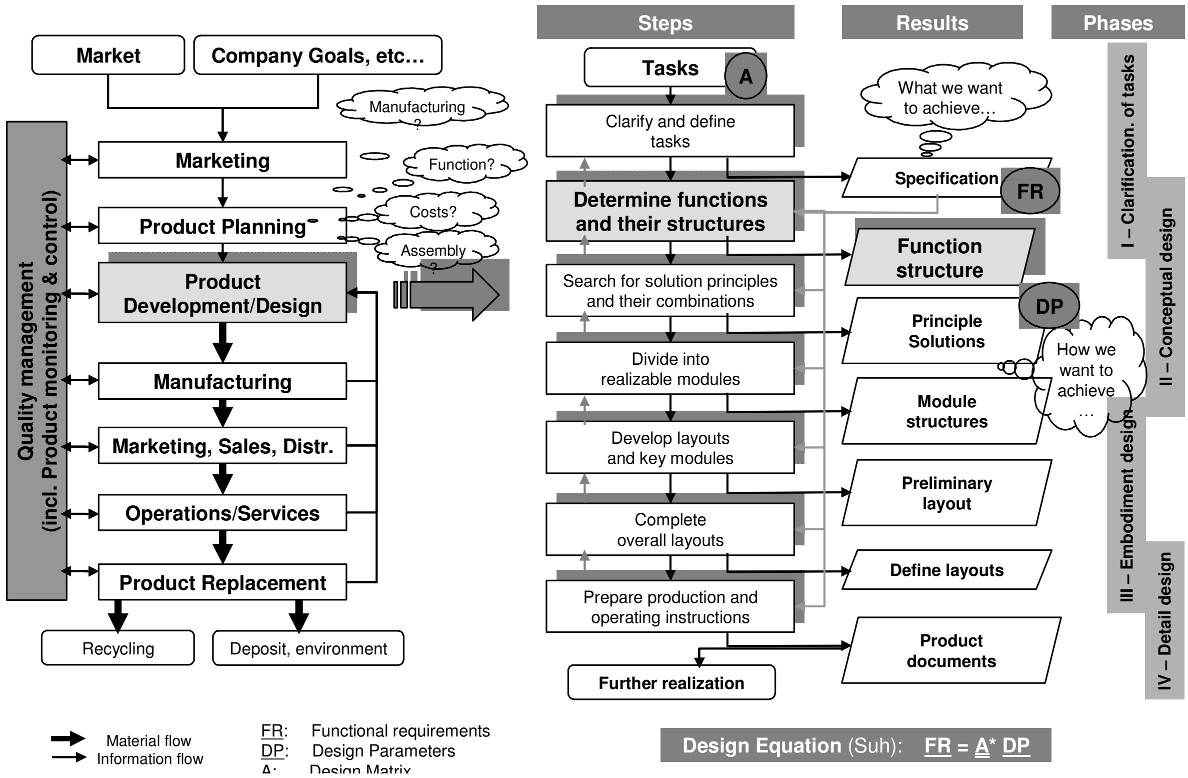


Figure 5-6: Modeling principles and ranking of the design equation of Suh.

The playing fields for the design process according to Suh are ***Design Domains***. The number of domains remains constant at four, but the nature of the design elements in each domain changes according to the field of the problem. In addition, there are constraints that set bounds on acceptable solutions.

According to axiomatic design, a design needs to satisfy two basic axioms. The design axioms provide a tool for evaluating designs, particularly during conceptual design. The two design axioms may be stated as follows:

- *The Independence Axiom*: Maintain the independence of functional requirements. This assures that designs are controllable and adjustable.
- *The Information Axiom*: Minimize the information content of the design. This assures that designs are uncomplicated and robust.

Definition 5.10: *In this context, design is defined as the creation of synthesized solutions to satisfy perceived needs through the mapping between the functional requirements (FRs) in the functional domain and the design parameters (DPs) in the physical domain.*

Through a series of iterations (decomposition process), the design process starts with the decomposition of the overall functional requirement and converts customer needs into functional requirements and constraints, which, in turn, are embodied as design parameters. DPs determine, but can also be affected by, the manufacturing or process variables (PVs).

Hence, the designer goes through a process in decomposing the design problem. This iterative process is called zigzagging (figure 5-7). Zigzagging also involves other domains since manufacturing considerations may contain design decisions, while over-specified requirements could virtually prohibit the discovery of feasible design solutions.

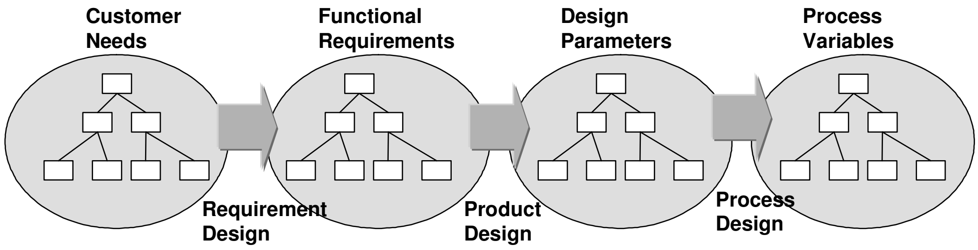


Figure 5-7: The principle of zigzagging of axiomatic design.

In the context of product, process, and resource integration, while design parameters or the product's characteristics ***C*** **(DP ~ C)**, in general, describe the product's structure and its shape and can be directly determined by the designer, functional requirements or the product's properties ***P*** (FR ~ P) describe the product's behavior and cannot be determined by the designer [Weber/Werner 00] (figure 5-8). Characteristics are more than simply design parameters, since design entities are not necessarily numerical values.

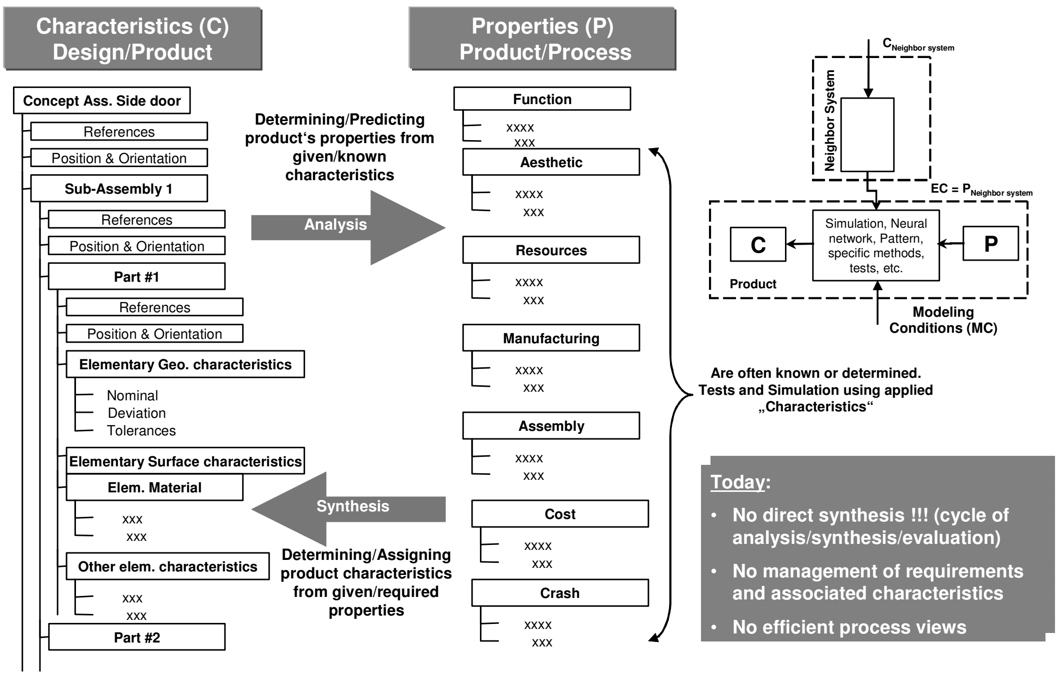


Figure 5-8: Link between product's characteristics and properties [Weber/Werner 00].

Specific behavior of an entity is manifested correspondent to a certain situation when this entity is exposed to it. Another behavior of this entity is observed in a different situation. This behavior is called function. The function field is the situation in which it is effective for a function to manifest. In this sense, a part creates and maintains proper relationships between work fields (effect fields), work surfaces and work skeletons. And properties are functional requirements which are fixed by the process either in the conceptual or in the detail phase. The product thus has behavior in the form of properties which the users appraise as qualities. Various classes of properties have to be designed into the product: manufacturability, packaging, low cost, reliability, liability, environmental friendliness, and many others.

Designing a product therefore consists of using given characteristics e.g., package information, or assigning them (e.g. materials, technological elements) in order to fulfill the required properties (functional requirements), which may vary depending on the components and the process step. The designer determines or predicts the actual product properties i.e., its behavior from given or known characteristics in an analysis process. Figure 5-9 illustrates an analytical view of this design process model.

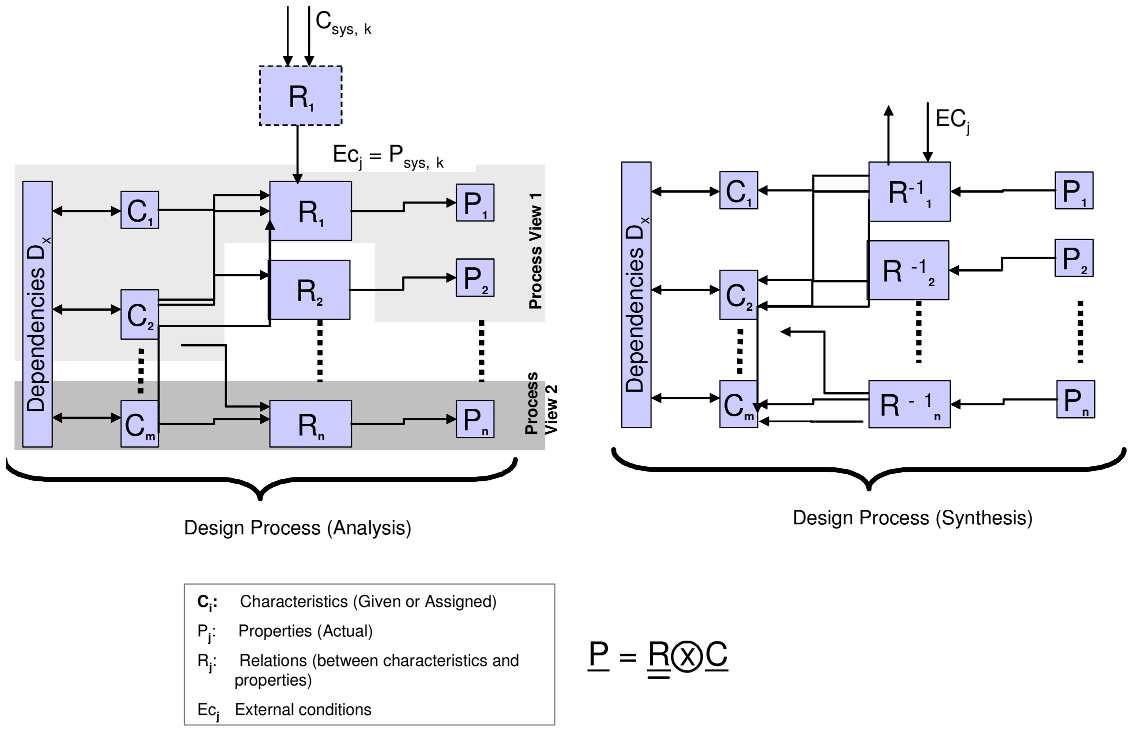


Figure 5-9: Formalizing the design process model: relationship between characteristics and properties (analysis and synthesis) [Weber/Werner 00].

The design process according to PDD considers both the analysis and synthesis processes, whereas in AD the starting point is the synthesis. Once a set of properties has been formulated and possible sets of characteristics have been synthesized, the two design axioms are applied to evaluate the proposed designs. In car body development, some characteristics or design parameters are known in the concept phase. In the design phase first, all the required properties and all the known characteristics are listed and structured and the relations between them determined. In this case, a distinction should be made between adaptive and variation design. In practice there are more variation or adaptive designs than new designs (see also the concept of solution patterns or intelligent feature-based templates later in this work). The process starts with many characteristics and properties, but the procedure remains the same. And the traditional product development process is one way of getting from (functional) properties to characteristics.

The second step in this phase is to assign or determine the characteristics related from corresponding properties (synthesis). Those, at the end, determine or predict properties from given or assigned characteristics.

According to the approach taken in Suh's design equation, this design process model can be formalized at each level of the design hierarchy in the form:

$$\{P\}_{m\times 1} = [DR]_{m\times p}\{C\}_{p\times 1} \tag{5-1}$$

Where $\{P\}_{m\times 1}$ is a vector of independent properties or functional requirements with *m* components, $\{C\}_{p\times 1}$ is the vector of characteristics or design parameters with *p* components, and $[DR]_{m\times p}$ is the design relation matrix. The element in $[DR]_{m\times p}$ is the sensitivity coefficient of the property or functional requirement $\{P\}_{m\times 1}$ to the design parameter or characteristic $\{C\}_{p\times 1}$ and is expressed in the form:

$$DR_{ij} = \partial P_i / \partial C_j . \tag{5-2}$$

The design relation matrix (at one level of the hierarchy) is a formal mapping process from one domain to another. It in fact contains functions expressing how a certain characteristic contributes toward modeling the related property (figure 5-10).

$\underline{P} = \underline{\underline{R}} \times \underline{C}$

	C_1	C_2	...	C_m
P_1	R_{11}	R_{12}	...	R1m
P_2	R_{21}	F_{22}	...	R2m
⋮	⋮	⋮		
P_n	R_{n1}	R_{n2}	...	R_{nm}

C_i: Characteristics
P_j: Properties
R_j: Relations matrix (functions of characteristics to model each property)

Figure 5-10: Design relation matrix.

In this table, each row represents the influence of all characteristics on a property, and each column shows the influence of a characteristic on all properties. The design relation matrix can be represented by different methods and tools such as estimation, experience, physical tests or experiments, calculation, or even computer tools e.g., model-based, numerical solutions (constraint-solving), rule-based, or neural networks.

Furthermore, the design process can also consist of determining the product's characteristics from given or required properties (synthesis), as illustrated in figure 5-9 on the right. Here the tasks are not as simple since some characteristics can only be determined after inverting the design relation matrix, and there may be conflicts between characteristics. Additionally, it should be assured that all the functions in the design relation matrix can be inverted:

$$\{C\}_{p\times 1} = [DR]^{-1}{}_{m\times p}\{P\}_{m\times 1} \tag{5-3}$$

Type of designs

Depending on the type of the resulting design relation matrix, three types of design exist [Suh 90]:

- ***Uncoupled:*** Each property is influenced only by its own characteristics. The characteristics or design parameters can be adjusted in any order to satisfy the functional requirements (properties) without iterating. The resulting matrix is diagonal and the design equation has exactly one solution, i.e. the independence axiom of Suh is satisfied.
- ***Decoupled*:** The design equation is triangular, which means that a sequence exists where, by adjusting characteristics or design parameters in a certain order, the functional requirements or properties can be satisfied. This is a very important finding, as the design process is determined largely by this sequence.
- ***Coupled*:** The design matrix of a coupled design contains mostly non-zero elements and thus the functional requirements cannot be satisfied independently.

A coupled design can be decoupled, for example, by adding components to carry out specific functions. It follows that avoiding coupled designs allows excessive iterations to be avoided, thus shortening the product development cycle.

Axiomatic design favors uncoupled designs, but practice has shown that coupling of functions needs to be considered in the context of a trade-off between cost, performance, and quality. In this sense, Guenov proposed a measure intended to estimate the costs and benefits of a functional coupling related to the system performance and introduced an Index of Value and Cost-effectiveness. Further details can be found in Guenov [Guenov].

When characteristics (design parameters) that fulfill the functional requirements (properties) are found, the next step in the axiomatic design method is to integrate them into the technical system. Integrating means physically embodying the product's characteristics. This can be done principally in two different ways: configuration using existing or new component(s) [Lindholm 96].

This was expressed as external conditions $\mathbf{EC_j}$ by Weber. Similar to the theory of relational properties introduced by [Andreasen/Mortensen 87], Weber considers different views of the external conditions ($\mathbf{EC_j}$): an external condition can be an output (property) of a (existing component) system or resource used to build the relation between characteristics (design parameters) and properties (functional requirements) of a product. For example, to manufacture a part, we need a stamping die. This resource has a number of properties (e.g., press speed, punch opening profile) which we use to press the part. These properties are reflected as characteristics in the product's structure, and the properties of the stamping die are determined from its own characteristics (e.g., dimensions) $\mathbf{C}_{sys,\,k}$. In the case of a synthesis, these external conditions can also be input in order to determine (configure) which system to use based on the given or required properties.

Design complexity

Quite often there are constraints or dependencies $\mathbf{D}_x$ between characteristics (design parameters) e.g., spatial, geometric (nominal). These dependencies are expressed by formulas in the CAD systems deployed today. Other dependencies are geometric tolerances, surface, or materials, for example. In this case, rules are employed for this task. State-of-the-art CAD systems provide only basic tools in this area.

These constraints or dependencies also characterize a certain degree of complexity of a design process. Most engineering design problems involve multiple functional requirements and require multi-disciplinary knowledge. These design problems are inherently complex. The complexity of a design problem can be related to the amount of knowledge that we need to solve the problem. If a design problem involves more functions, components, and relationships among components, it is likely to be more complex. The complexity of most system design problems is beyond the comprehension of individual designers. It has two effects on designing. First, a high degree of complexity makes it hard for designers to understand the design problems, although the problems are clearly defined. As a result, designers may not be competent enough to explore and generate possible solution options. Second, given that options are generated, the large number of combinations of the options makes it very difficult to evaluate the alternatives and make decisions.

When two design solutions are compared, the decision as to which one is more complex can be made on the basis of measurable physical quantities, such as number of parts or connections. At an early design stage, many of these quantities are not necessarily known and should be inferred. Guenov put forward a hypothesis that the distribution of properties-characteristics couplings gives a good idea of complexity (see also figure 5-10). This assumption stems from a corollary of Suh's first axiom, which prescribes that coupled design should be decoupled, if possible. The number of coupling operations obviously plays a role, but their distribution is equally if not more important, since it will affect the time and the probability of the iterative design process converging on a solution. Thus the estimate has to take into account both the size of the problem and the coupling distribution. The distribution aspect has a certain analogy with rank (degree of freedom) and sparsity of a coefficient matrix and their effect on finding a solution of systems of linear equations. The difference is that the design equations are not necessarily linear and also many of the entries in the design matrix do not have numerical values, especially during the conceptual stage. Thus, at this stage, the matrix is most useful in directing the design process rather than in simply producing numbers.

The complexity of the problem increases tremendously when the process factors are being considered simultaneously with design aspects (figure 5-11). The process planning evaluates actual properties (determined by the designer) against required or target properties (fixed by the process) or process variables, to draw conclusions from the evaluation, and to determine the actual driver of the process. Here also, process planning gives feedback to design in order to determine or to change the product's characteristics (design parameters) or even to assign more characteristics from given or required properties (functional requirements) based on the evaluation. The task of the process planner is, therefore, to find the deviation $\{\Delta P\}_{m\times 1}$ between required process properties (variables) $\{RP\}_{m\times 1}$ and actual properties $\{P\}_{m\times 1}$ in the form:

$$\{\Delta P\}_{m\times 1} = \{RP\}_{m\times 1} - \{P\}_{m\times 1} \tag{5-4}$$

Analogous to the design equation, the design parameters or product characteristics at certain levels of the product development hierarchy can be considered requirements for the manufacturing process. Thus the design equation for the manufacturing process (or design for manufacturability) is similarly given as:

$$\{C\}_{m\times 1} = [PR]_{m\times p}\{RP\}_{p\times 1} \tag{5-5}$$

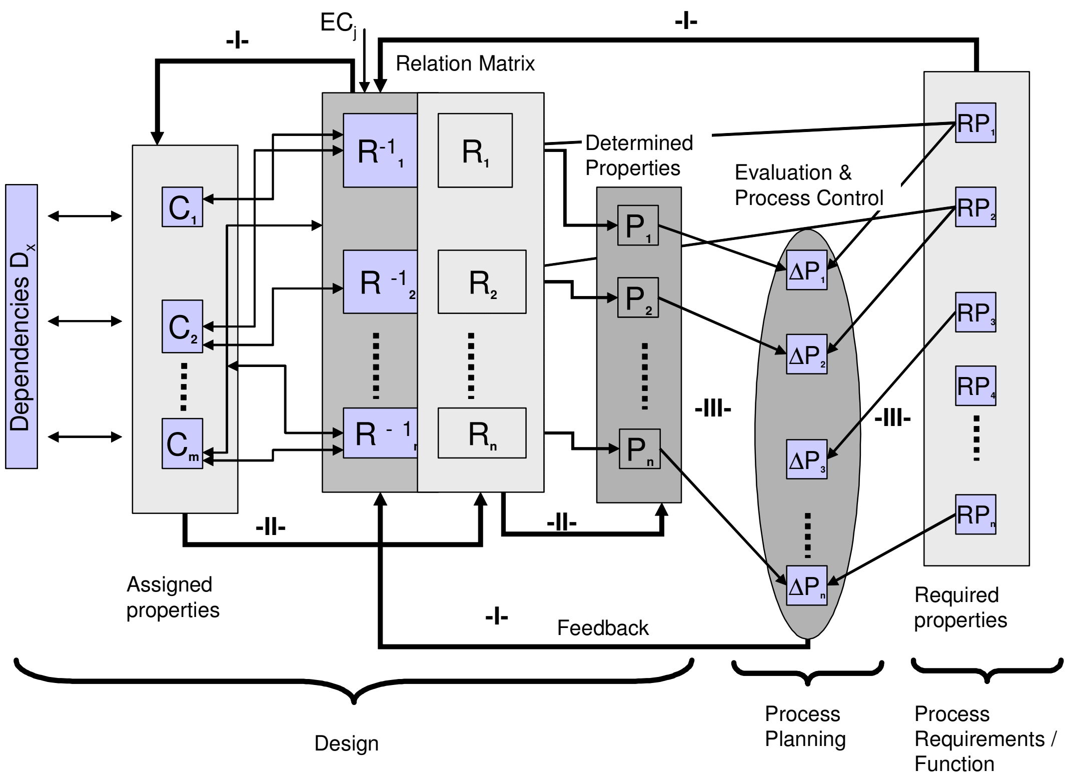


Figure 5-11: Product and process modeling model.

By substituting (Eq. 5-5) in (Eq. 5-1), the two matrix equations can be combined into a single relation, linking the product's properties with the manufacturing process:

$$\{P\}_{m\times 1} = [DR]_{mxp}\,([PR]_{m\times p}\{RP\}_{p\times 1}) = [R]_{m\times p}\{RP\}_{p\times 1} \quad (5\text{-}6)$$

where $[R]_{m\times p} = [DR]_{m\times p} \quad x \quad [PR]_{m\times p}$ (5-7)

In this equation, $[PR]_{mxp}$ denotes the process relation matrix and $[R]_{m\times p}$ the integrated product, process, and resources matrix (the resource component expressed by the external conditions EC are neglected in this representation for reasons of simplification).

The multipliable order reflects the chronological order of the design and manufacturing process. In theory, if the resulting matrix [R] is diagonal, then the design is uncoupled and all design and manufacturing parameters satisfy the functional requirements. In practice this is extremely rare and either [DR] (the design relation matrix) or [PR], (the manufacturing process relation matrix) has to be modified during the product development process. By considering the process planning evaluation matrix $\{\Delta P\}_{m\times 1}$, the integrated product and process relation matrix can be written in the form:

$$[R]_{m\times p} = \{\Delta P\}_{mx1} / \{RP\}_{px1} \quad +1 \quad (5\text{-}8)$$

Decision making

As already mentioned, design implies decision-making. Moreover, design decision-making implies that there are consequences of the decisions made. Hence, identification and documentation of consequences facilitate further decision-making. Decisions are first made as to which design solutions are to be selected to fulfill certain functional requirements and then as to which manufacturing processes should be employed to produce the design solutions. The solutions and processes that are chosen, or design parameters (characteristics) and process variables in axiomatic design terminology, typically have consequences. The term consequence is used in the sense that a solution, which cannot work or function alone, requires support systems.

Design consequence

Documenting consequences is important for downstream considerations, since some of these consequences are transformed into lower-level properties, characteristics, and attributes. If this definition is used, the design parameters and process variables on the bottom level in the design hierarchy, or abstraction hierarchy, do not generate consequences [Lindholm et al. 99]. Consequences differ from constraints in that consequences can generate constraints, functional requirements, and product characteristics, whereas constraints are used for limiting the solution space when selecting a design parameter or a process variable. Characteristics and process variables may, in turn, have consequences and therefore have a need for supporting systems. Lindholm et al. discussed different classes of consequences, where they originate, and how they can be detected and dealt with in the design process. If consequences are identified, then the decomposition process is simpler and more manageable.

Lindholm considered design consequences in relation to axiomatic design [Lindholm 96]. The sources for consequences are generally product characteristics (a product characteristic is chosen to fulfill a functional requirement or property, process variables). Consequences of process variables are treated in the same way as consequences of characteristics. Process variables can generate constraints or dependencies and lower-level properties and characteristics as well as configured technical systems.

Design automatically also implies that some tolerances have to be taken into account. In this sense, El-Haik and Yang explored the relationship between axiomatic design and tolerance design and their implications for the design and manufacturing processes. The approach they employed optimizes the setting of design parameter tolerances through non-linear programming formulations. The key issue is to set the individual tolerances of design parameters to achieve minimal quality loss subject to functional requirements. In this sense, they stated that there exists a target performance for the functional requirements (quality characteristics), and any deviation from the target value will incur an economic loss usually represented by the Quality Loss Function (QLF) [El-Haik/Yang].

The product development process is terminated when all the characteristics needed for manufacturing, inspection, analysis, and assembly are assigned ($\boldsymbol{C_j}$) and all the properties can be determined or predicted ($\boldsymbol{P_j}$) with sufficient safety and accuracy. The condition is thus that all determined and predicted properties are close to the required properties i.e., $\boldsymbol{\Delta P_j \rightarrow 0}$.

Conclusion and importance for the work

To conclude, a framework based on axiomatic design and property-driven design has been presented in this section, describing the design process. It enables designers and process planners to quickly understand the relationships between the intended functions of a product and the means by which they are achieved. The design axioms provide a rational means for evaluating the quality of proposed designs, and the design process used guides designers to consider alternatives at all levels of detail and to make choices between these alternatives more explicit. The underlying hypothesis of axiomatic design is that there exist fundamental principles that govern good design practice. It is a general theory of design which provides a time-tested, scientific basis for designers to make design decisions. It is a scientific approach to design in which decisions are made at multiple levels of abstraction, starting at the system level and progressing in more detail until the design is completed. PDD extends this approach and proposes a more clear description of product and process modeling with consideration of resources.

5.5.3 Discussion and summary

According to Jin and Lu, a synthesis of most of the approaches discussed in this chapter leads to the classification of the design process in three views: process, decision, and knowledge [Jin/Lu 01].

The process view of design attempts to reduce design ambiguity, complexity, and uncertainty by restricting designers' activities to a set of predefined ones. On the one hand, this restriction can maintain the consistency of designing and keep it "on track". The premise here is that since process and IT-methods are results of past successful practice (best practices), following these will lead to good design. The logic of this premise is based on appropriateness rather than consequence. Yet, the restriction may also limit the designer's thinking space and cause the designer to miss possible good designs that are not on the "track" of the process flow. The challenge here is how to respect both considerations, allowing an appropriate decision process.

The decision view of design emphasizes the designer's value and believes that the designer's role in design is decision-making and that designing is thus essentially a decision-making process. It attempts to manage the complexity of design by relying on designers' option generation capabilities and through rigorous option evaluation. The decision-making process in design or decision-oriented design treats designing as repetitions of a simple two-step process namely, option generation and decision-making of which decision-making is considered the most essential part. Decision-oriented models assume, or require, designers to be purely rational in the sense that designers have clear, consistent, and stable preferences and utility functions.

A knowledge view of design treats it as a knowledge-based problem-solving process. The knowledge view of design modeling calls for a clear definition of design problems. It deals with complexity and uncertainty by acquiring and organizing knowledge about products (including fundamental natural laws) and the knowledge about design and production processes that controls application of product-related knowledge. Unlike the process view, which thinks design has its unique processes and ways of doing things, knowledge-based design models focus on the uniqueness of knowledge and see little difference between designing and other goal-driven problem-solving processes. Prevalent issues here are what knowledge is needed to carry out designing and how the knowledge should be organized to make efficient design. Design decision-making is rather implicit in these models. It is treated as an integral part of the application of knowledge.

It is widely recognized that the decisions made during the first 25 percent of the design stage incur approximately 75 percent of the total product costs. In recognition of this fact, major sectors of industry such as the automotive branch are currently trying to reduce risks by front-loading their engineering programs to increase the percentage (by at least 15%) of the total resources that are spent during the early stage of the product creation process. The challenge at this point is to provide integrated tools that enable engineering analysis and synthesis tasks that could aid high-level decision-making in the comparison of alternatives on the basis of design, costs, value, performance, and technical risks.

The initial step should be to capture the characteristics (design parameters) which define the product, the properties (behavior or functional requirements), and the relations between the two by means of a digital model.

Second, these tools are needed to identify both the consequences of the product characteristics and process variables chosen for several reasons and the consequences of system configuration.

There should be a tool that guides designers in their work to find and identify the inputs and outputs of the design parameters as well as selected process variables, for example. Depending on the type of design, new or old, not all dependencies are detected automatically. Identifying consequences in advance and keeping track of them during the design work may save money and -- often more important in design projects -- time as well.

Third, an integrated product-process-resource model should make it possible to trace the functional requirements, product and process characteristics, and constraints to their origins. If their sources can be found and the rationale for the decision understood, it is easier to adjust the existing design.

Thus, to be effective, the tools should incorporate a number of desirable features:

- Be able to represent all the relevant characteristics and properties and clearly separate characteristics from properties.
- Distinguish between required and determined properties and manage part of the internal relations between characteristics.
- Enhance design reuse by referring to known solution patterns (set of characteristics-relations-properties from past processes).
- Control the process by capturing deviations between determined/predicted and required properties.
- List open problems and facilitate checks and modifications.
- Help to identify design degrees of freedom based on known relations between characteristics and properties and design methods.
- Keep track of the synthesis-analysis-evaluation-conclusion cycle within the entire product creation process.
- Enhance simultaneous/cooperative engineering and integrate the CAx tools deployed throughout the product creation process.
- Document the product creation process and show potentials for its improvement.

As the product creation process is comprised of several steps, different tools are required to assess the same properties. In very early phases only a few characteristics are considered, while in the detail phase many characteristics impact the process. CAD systems are the most commonly used CAx component. They capture geometry, product structure, geometrical relations, and constraints (parametrics and associativity). That is, they capture the characteristics of the product and are not primary applied to model properties (analysis tool in a narrow sense) today.

Presently, for the analysis task, integrated tools provide simulation modules to determine or to predict properties based on currently given characteristics. In synthesis, CAD systems can provide support in the framework of specific classes of products or elements if the design relations between relevant properties and (geometric) characteristics are known and captured as solution patterns or templates.

The invert function of the design relation matrix can be easily transferred into a software, but it requires a completely known and reversible interrelation between the characteristics and the properties of a product. Therefore, this strategy cannot create new designs or solutions (only pure variation design, morphing). Here, catalogues, solution databases or process guides, or even design rationale can only support these tasks, since they cannot create solutions themselves. These extended CAD systems can be trained (e.g., using neural networks) to build up geometry automatically. Solution patterns (here, product or process templates) can be utilized by means of feature and template libraries and intelligent feature-based modeling. However, the implementation of synthesis tasks in CAD systems is not easy to do. At present, only structural optimization tools or genetic algorithms claim to do so, but they require an initial solution as a starting point [Weber/Werner 01].

CAD remains the carrier of the geometric master-model, as already mentioned. This explains why there is currently a trend toward 3-D representation. Furthermore, existing software systems are now integrating an increasing number of CAx functionalities. However, something is still lacking: the synthesis supporting CAD modules for variation design or for product and process morphing.

Conclusion

The innovative methods and concepts presented in this chapter open up completely new possibilities for product and process modeling, thus confronting users with new operational sequences and procedures and, of course, leading to great psychological impacts due to their complexity and new ways of proceeding. A suitable technology is therefore required to provide an IT-based solution for the technical implementation of reliable process changes: in general, a method that offers an efficient methodology to encase and exchange information as a logical unit at the process pools (interfaces). Continuity of the process chain in this case means the linkage of information in design, process planning, prototyping, and volume production. The data models utilized must have a suitable structure in order to cover the different processes as storage mediums and corporate knowledge. The organization and implementation of structured objects as information components is a challenge aimed at arranging the product creation process continuously and more controllably in the sense of the PPR with PLM on a long-term basis. These new objects are called intelligent features and intelligent feature-based templates, using other concepts such as design-rationale decision-making and PDD. An attempt to do this is the prototype presented in chapter 8.

PART III

INTEGRATED PRODUCT DESCRIPTION, PROCESS MODELING, AND RESOURCES USING THE CONCEPT OF INTELLIGENT FEATURES AND TEMPLATES (SOLUTION PATTERNS)

Chapter 6

6 The concept of intelligent features and feature-based templates

As stated, feature technology acts as an innovative and benefical structuring method which can be applied consistently throughout the product creation process. IT embeds the approaches and trends described in chapters 4 and 5, and moreover it supports the user through intuitive interfaces.

A premise of this thesis is to provide a feature concept that fits the way industrial engineers work in practice, particularly in the automotive industry, and which can also be implemented in current CAx systems. Thus, the object-oriented framework is employed for features in this thesis, combining new research results in the area of feature technology and feature-based templates

In this chapter, we focus on two key points: intelligent features and feature-based templates (solution pattern) as a basis for the systematization and integration of product, process, and resources

6.1 General feature definition

The original definition of *feature* by Grayer was motivated by the development of methods for the automated creation of NC programs:

Definition 6.1: *"A feature describes a region that can be manufactured with a machine operation." [Grayer 76].*

The focus on linking more than one process was already evident in this statement. And Shah gave one of the first generalized definitions:

Definition 6.2: *“A feature is a physical constituent of a part, is mappable to a generic shape, has engineering significance, and has predictable properties” [Shah 92].*

The working group FEMEX (Feature Modeling Experts) summarized the similarities of the different approaches in the following definition [Weber 96], which was incorporated into VDI recommendation 2218 (feature technology) in 1999 [VDI2218]*:*

Definition 6.3: *“Features are information-technical elements, which represent ranges from special (technical) interest of single or several products.*

A feature can be described by the aggregation of the properties of a product. The description contains the relevant properties themselves, their values, and their relations and constraints.

A feature represents a specific view of the product description that stands in connection with certain characteristic classes and certain phases of the product life-cycle. "

In fact, many different approaches have been grouped under the term *feature*. Current research activities have substantial approaches whose common characteristic is the modeling of highly semantic objects. In these schemes, a feature is closely linked with the term *object*. According to object-oriented programming, a feature possesses properties which do not exist on their own but are assigned to it. However, objects are not bundles of properties that can be expressed by observable attributes and laws. Attributes are assigned or predicted by the observer to define or recognize properties of objects, while laws (rules and constraints) are based on possible combinations of the values of attributes.

The ontological view of product leads to the view that a product emerges as an object and is known through its characteristics. These product characteristics can be expressed by generic entities and constraints, depending on the application context (external conditions), to fulfill a certain functional property. For example, one of the functions of a car side door is to allow rotational movement (defined by the door opening angle, among other things). It is also constrained by hinges to avoid translational movements. A set of characteristics is then employed to define the properties of a side door, defining the door behavior.

Following object-oriented programming, where matching data and code are summarized in objects which communicate with the external world only over defined procedures and functions, this concept is suitable for the modeling of standardized design elements and process cycles. Thus the code of the object can be used without needing to know the associated data structures.

These objects thereby present themselves for the user as components which can be integrated as units in the design or planning activity. The problem here is that such program codes are often hard-wired with the system, since the systems works mostly via hard-coded objects, making re-compiling necessary with step-wise aspects of design. The resulting expenditure is typically not justifiable in the running process. Similarly high expenditure is incurred through the coding of the prepared knowledge into a kind of solution catalog to be used during the design process.

Yet attributes and methods of design components may shift in the product model. They are then provided and changed at run-time and after the instantiation of the object. Also useful is the concept of inheritance, which permits rapid adaptation of pre-defined, generalized objects to a special purpose.

In general, the following elements make a model object-oriented: abstraction (main characteristics of an object that distinguish it from others), modularity (decomposition into a set of cohesive and loosely linked modules), encapsulation (process of hiding all the details of an object that do not contribute to its main characteristics), and hierarchy (ranking or ordering of abstractions). Figure 6-1 shows an example of a hole feature object.

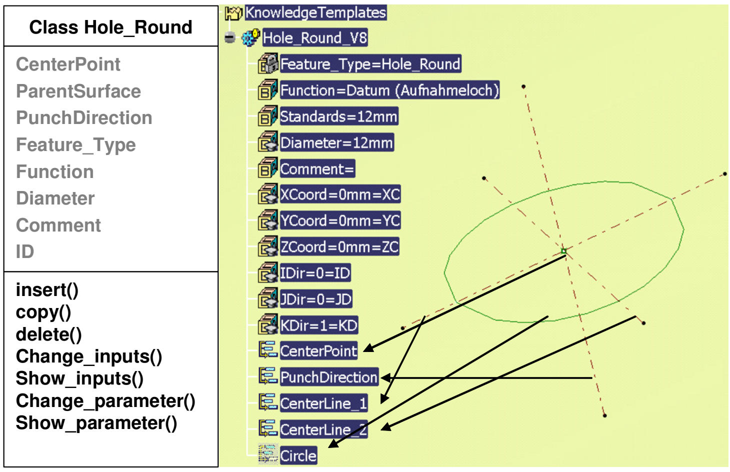


Figure 6-1: Description of the class *hole feature* (left) and its representation in a CAD system

Therefore, the term *feature* itself can be based on the object-oriented paradigm. The underlying concept is to manage the complexity of systems in such a way that objects represent components of a modularly decomposed system or modular units of knowledge representation [Booch 91].

Combining all these aspects, the author extends the feature definition to the following:

Definition 6.4: *"A feature is a* ***functional characteristic of a product or a process*** *which can be defined as an* ***object*** *that is referenced to or encapsulates geometrical entities (e.g., shapes) and technological elements. It is then defined by* ***syntax*** *(parameters, attributes) and has a* ***semantic*** *or interpretable functional meaning within a specific phase of its* ***life-cycle****."*

Technological elements can be tolerances and their function or quality definition. Furthermore, a distinction should be made regarding the CAD implementation. Although the common approach lies in the object-orientated nature, the term *feature* has a different meaning in the intrinsic computer representation, namely:

Definition 6.5: *"In the intrinsic computer representation, a feature is a reusable, captured or recorded design sequence with a common functional meaning or an image of a piece of technological information".*

Hence, on the CAD side, a feature is a geometric group which contains the required geometry, parameters, formulas, and rules to describe the constraints between parameters. This is the reason why some CAD/CAM systems define all geometric entities (e.g., lines, points) as a feature.

In general, we can affirm that a feature is a knowledge module which clusters design knowledge in such a way that design knowledge can be reused directly from one design project to another without considering all the knowledge contained in the feature.

Libraries and catalogs are created specifically to order features. They are instantiated in the destination model using reference elements to position them properly and ensure orientation. The features can then be adjusted by changing the parameter values or the reference elements.

Figure 6-2 sets out a short scenario illustrating the use of features. The element on the far left (1) shows the required input elements: a surface and a curve. The second depicts the same surface after feature instantiation. The last two elements illustrate the consequences of an input modification (curve modification) (4) or a parameter value change (bead width change) (3). The input surface or the other bead parameters (e.g. depth, flange angle, fillet radii) could be similarly modified.

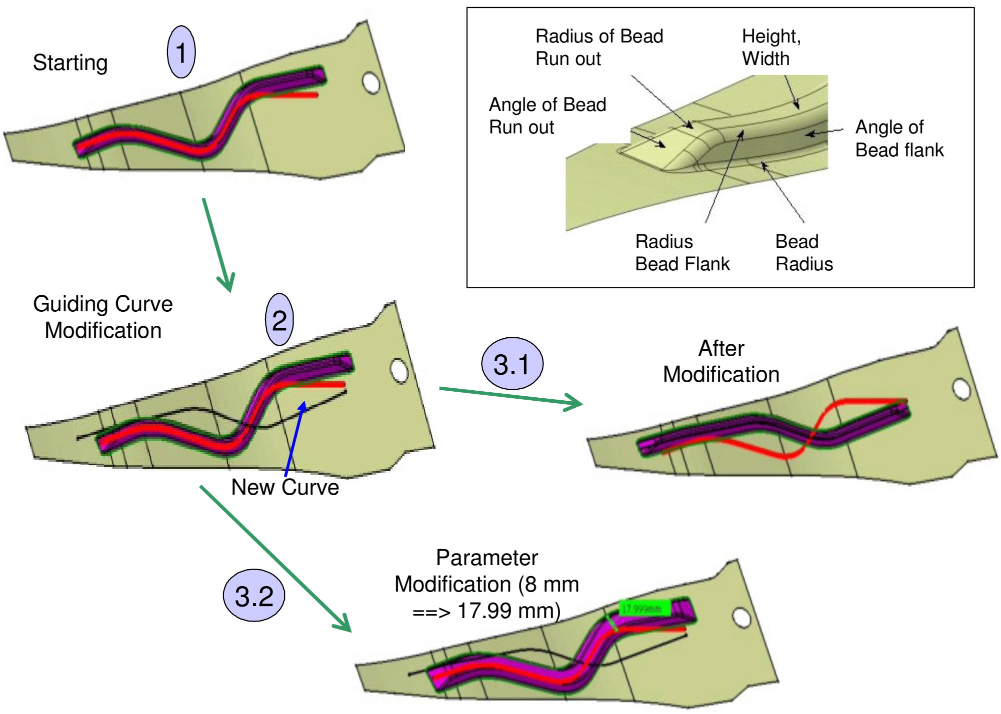


Figure 6-2: Scenario for bead creation.

6.2 Intelligent features and intelligent templates as a structuring and integrating technology

The concept of intelligent feature technology is based on such an object-oriented approach as described in the previous section, with the difference that the intelligence is first completely shifted into the feature model, which communicates with defined interfaces both to CAx systems and along the product creation process. External programs can be called by these interfaces (e.g., constraint-based programs) in order to accomplish specific operations. The wiring with the system takes place only around the basic functionality to allow for example the manipulation of the geometry or invocation of methods, for example.

Before explaining the concept of intelligent features, the following section tries to illuminate the term *intelligence*, as this is used to extend the behavior of current (simple) features.

6.2.1 The notion of intelligence in engineering

Terms such as intelligence have vague general meanings that are employed in a variety of contexts. Various approaches have been proposed in attempts to understand it. Ideally, the definition of intelligence should answer the following questions:

- What, in precise mathematical and scientific terms, is intelligence?
- How do we objectively identify, measure, or quantify intelligence?
- How do we install or embed intelligence into our man-made system?

Definition 6.6: *Intelligence could be understood in terms of the information-processing components underlying complex reasoning and problem-solving tasks such as analogies [Sternberg 77].*

Building on his earlier work, Stemberg proposed a triarchic theory of intelligence, where information-processing components are applied to experience, to adapt, to shape, and to select environments [Sternberg 90]. Intelligence is best understood in terms of performance on either relatively novel cognitive tasks or in terms of automation of performance on familiar tasks. Sternberg argued that intelligence comprises three major aspects: analytical, creative, and practical thinking.

Binet and Simon, in contrast, had already conceptualized intelligence at the beginning of the 20^{th} century in terms of complex judgmental abilities [Binet/Simon 16]. Binet believed that three cognitive abilities are the key to intelligence:

- *Direction* (knowing what has to be done and how it should be done).
- *Adaptation* (selection and monitoring of one's strategies for task performance).
- *Control* (the ability to criticize one's own thoughts and judgments).

The metacognitive emphasis (i.e., memory monitoring, self regulation) in this approach is apparent and will serve as the basis for the definition of intelligent features. Binet's views are more relevant, both because his theory seems to better capture intuitive notions of intelligence and because it can be applied to engineering design.

Definition 6.7: *Somewhat more formally, intelligence is seen in computer design, or in the engineering context as the ability or capacity (or the appearance of an ability or capacity) of a system to solve problems.*

Intelligence is thus some type of force that increases the ability of a system or entity to solve certain types of problems.

Definition 6.8: *In this sense, intelligence is the capacity to find solutions to problems based in part or in total on expected or anticipated fitness values rather than actual or manifest fitness values.*

Therefore, this allows large numbers of possible solutions to be evaluated without an actual manifestation or cycle. The usage of expected fitness values to eliminate or greatly reduce cycles and manifestations accelerates the speed and efficiency of problem solving. But intelligence is more than just problem-solving. For example, knowledge, skills, and culture are commonly associated with intelligence.

Furthermore, intelligence or intelligent behavior is an outgrowth of multiple factors for example, the information processed by the system (data). Efforts to define intelligence often exclude "simple and obvious" techniques and tricks which create the appearance of intelligent problem solving from the definition of intelligence. For example, the stored solution technique, where a system produces a solution to a problem by accessing a stored solution, is often not considered intelligent behavior. Nevertheless, the current approach suggests or predicts that all intelligent behavior can be modeled and simulated, and thus scientifically explained, using an identifiable set of techniques and processes.

It is readily apparent that intelligent behavior involves a great deal of activity preceding the finding of a solution to a problem. To be able to solve a problem intelligently or to exhibit intelligent problem-solving behavior, a system must have, must develop, and/or must evolve a wide range of the prerequisites to intelligent problem solving. Intelligent behavior is to be viewed as involving three levels: learning/evolution (flexibility), intelligence itself, and adaptive behavior.

Using the computer or logic machine analogy, adaptive behavior is the set of "input causes output" or "stimulus causes response" (S-R) algorithms that are responsible for the observed developmental and operating behavior of a living system. Intelligence, in this analogy, is a fixed or static program capable of quickly changing S-R algorithms to keep them adaptive. This ability can be extended with neural networks, for example, to describe general S-R relationships. Quickly changing S-R relationships is what we would commonly call problem-solving. Intelligence, using this approach, can be viewed as a combination of efficient search engine and efficient storage device. To survive in a complex and uncertain universe, an organism needs the capability of quickly changing how it reacts to the external environment. Finding adaptive solutions can be described in terms of finding solutions using search engines or finding a solution based on stored information. The mathematical concept of intelligence comprises the mathematical/logical operations that combine efficient search engines and efficient storage to produce efficient problem-solving. So, this efficient problem-solving *forces* intelligence.

Finally, there is more to intelligent behavior than adaptive behavior and efficiently finding adaptive behaviors: there is the whole issue of setting up and developing the processes and procedures which will be used to solve the problem. Using the computer analogy, if adaptive behavior is a set of S-R relationships, and if intelligence is a static program for efficiently finding and maintaining adaptive S-R relationships, then learning and/or evolution are the processes responsible for developing or writing the static programs which efficiently find adaptive S-R relationships. This is the foundation of the term *intelligent features* as introduced in the next section.

6.2.2 Intelligent features

In the design phase, the creation of highly semantic features not only increases the quality of the design but also influences the performance of downstream processes. In this context, product design features are paramount because information units with process-specific data are defined in them. They encapsulate information about both semantic (or functional) meaning and the shape of a part, thus facilitating communication of the design intent to downstream applications by providing a means for the direct generation of process parameters.

Basics of intelligent features

- ***Feature semantics*** are generally expressed by constraints, which are used by designers to express their design intent. The designer's intent represents information that should be verified and maintained throughout the product life-cycle and should be utilized to drive the decision-making for downstream applications. Therefore, the designer's intent acts as a suitable medium for the validation of a feature-based representation and helps to determine a specific feature attribute or configuration [Case/Hounsell 99]. In general, normal features do not have the ability to check the context before instantiation (e.g., checking the direction of the surface) and do not consider feature interaction or their hierarchical state. To do so, these constraints need to be formalized through functions or formulas that have to be called via interfaces to execute some specific checks according to the semantics required by the feature.
- ***Feature interaction*** is a consequence of feature operations in the same model. Feature interaction affects both the representation of the part and the functional intentions embedded within the features. However, in the design context, operations such as modeling and editing may corrupt the validity of the feature representation.
- ***Feature consistency:*** As the various aspects of feature semantics could all be expressed differently, the feature data must be exposed to a consistency check to preserve the engineering significance of the features. This consistency must be ensured during insertion of new features into the model, during deletion of features, and while the parametric modification of existing features of the model is being carried out. Also

this check should be embedded inside the feature or linked with external sources. This is the means of tracking changes along the product creation process (change management)

Considering these three aspects, the author introduces the concept of adaptive or intelligent features and suggests the following definition:

Definition 6.9: *"Intelligent features are those features which have the ability to react adaptively and flexibly to product and process changes."*

Example of feature interaction and consistency

Figure 6-3 illustrates these three aspects. Here, the definition of a function for each feature is paramount, as we will see in later sections. For the creation of flanges, the designer has to investigate the geometry of the other parts involved in the joining of parts and examine whether the flange would impact the functions of the features which are in the area upon which the flange has an influence. To do so, the designer has to know the function of all the features that might be affected by the flange or, if such data is not available, obtain additional information about them. This also leads to feature interactions -_ a consequence of feature operations in the same model. Feature interaction affects both the representation of the part and the functional intentions (i.e., also its semantics and consistency) embedded within the features.

In figure 6-3, a flange affects a hole. If the hole in part1 is used to fix part1 during the stamping of part1, the relief in the flange of part2 is unnecessary. However, if it is used to lead a cable through the part, then the relief in the flange of part2 is necessary. The reason for the difference is that the stamping of part1 is done before the two parts are welded. Therefore, the hole has already fulfilled its function when the flange closes it. If the hole is used as a lead-through for cables, it has to fulfill its function after the joining of the parts takes place.

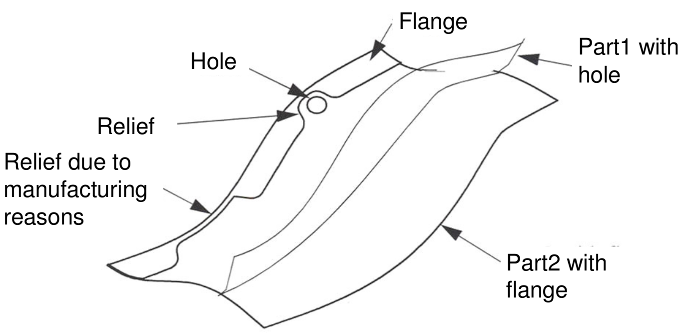


Figure 6-3: A hemmed part with a hole in the affected area.

If the hole has both functions, the relief is still necessary. If the hole is used as a drain hole during painting, then to a certain extent the flange might close it without impairing its functionality.

This example clearly shows that the function of an affected feature and its time-related appearance during the life-cycle of the product are decisive for the quality of that product.

Intelligent or adaptive features are able to analyze the current context (shape properties and direction, for example) and perform their insertion into the shape itself in the correct position under consideration of the prevailing process conditions. They then possess both passive knowledge (e.g., experience) and active knowledge. That is, the intelligent feature is also able to examine knowledge conflicts (design- and process-related) and suggest an appropriate correction to the designer or even carry out the necessary corrections automatically. All these capabilities are possible due to the features integrated rules, process and engineering knowledge, constraints, and references to sources of knowledge. Benefits of this innovative method are manifold: intuitive product modeling and planning, automatic adjustment of product changes, and the transfer of expertise regarding design methods and process interpretation.

Considering all these aspects, an intelligent feature may be defined as set out below:

Definition 6.10: *"Intelligent features are consistent and highly semantic objects which reflect both passive knowledge (e.g., experience and usage) and active knowledge with respect to the geometrical operations (dynamic behavior during interaction with other features) and engineering reasoning (executive procedures for design and process consistency and for the features automatic processing related to the different phases of their life-cycle)."*

Thus, intelligent features also contain modules for their automatic processing. Intelligent features may therefore have a high-level functional aspect, which represents the behavior of an object or information unit. This functional aspect defines a proactive or reactive operation that states not only what the designer does and does not incorporate solely for design purposes but also manufacturing and life-cycle considerations.

The adaptivity can also be performed interactively. An example of an interactive intelligent feature would be a weld point feature which contains technological attributes such as welding current or electrode diameter and is linked with input such as the surface to be welded. If the surface thickness changes, or even the distance between two spot-welds, the applied weld changes automatically. Such intelligent features could be smoothly integrated into a CAD system, as described in section 7.5.

Defining intelligent features

The process of definition of an intelligent feature is very similar to the zigzagging process of Suh:

- Decomposition of the overall functional requirement of a component.
- Listing of the functional requirements and known characteristics describing the relation between them.
- Determination of the guiding parameters.
- Consideration of the situation-oriented adjustment of changing requirements.
- Characteristic-specific allocation of product, process, and resources.

Figure 6-4 portrays the main steps for creating intelligent features and allowing for their use:

- Using the principle of structuring, a design is to be understandable, alterable, and maintainable.
- A well-structured design is developed if the principles of hierarchy and modularity are applied.
- A module forms thereby a context-dependent, functional unit which exhibits defined interfaces for external contexts.
- All relevant information should be locally compressed.
- The expenditure for the product development is reduced by the reuse of well known results. Prerequisite for this is the standardization and documentation of results.

Furthermore, to use the feature intelligently, knowledge mechanisms are assigned to the model.

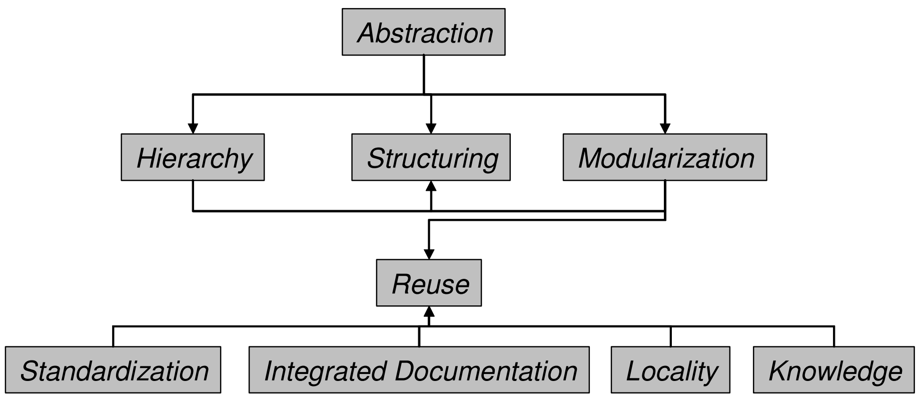


Figure 6-4: Principle for creating features.

In fact, the description of an intelligent feature is based on both the design relation and the process relation matrix explained in chapter 5. This is the fundamental difference from a simple feature. An intelligent feature already contains design-for-X requirements. An additional mapping from design to inspection or to manufacturing is no longer required. The feature supports design-for-X, with the extended ability of adaptivity and flexibility for change management. Figure 6-5 below depicts a rough description of such a mechanism. The adaptor control contains different solution alternatives, and its capability of solving complex tasks can be extended through neural networks or other artificial intelligence mechanisms.

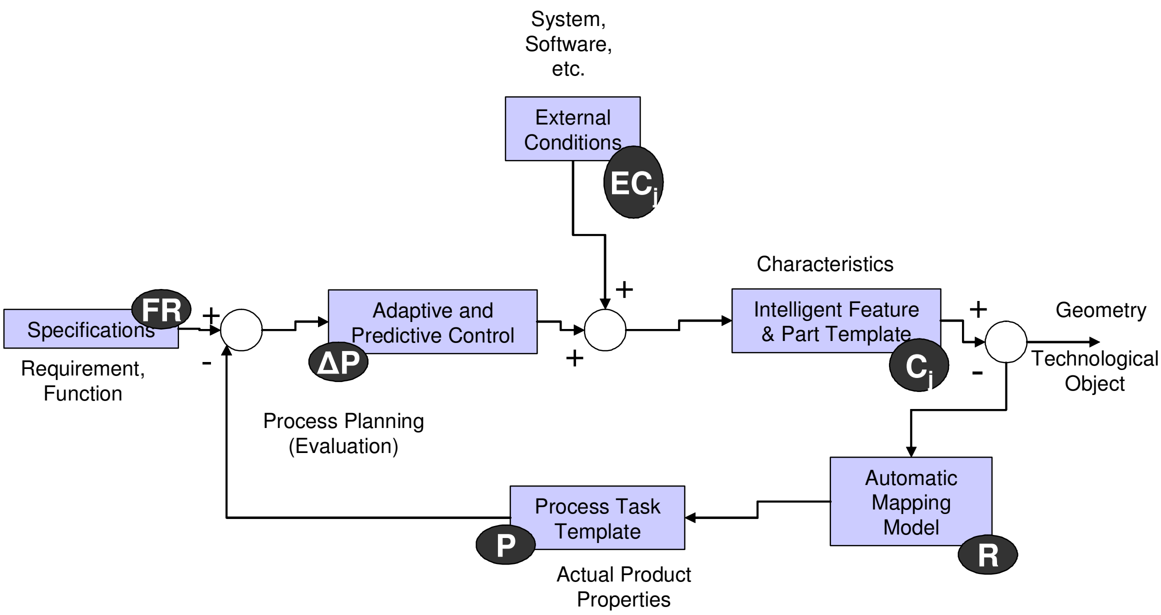


Figure 6-5: Example for intelligent feature behavior.

Benefits

Due to the uniform representation of the variety of product information, intelligent features become a suitable platform for the implementation of an integrated system concept. The application of intelligent features as the backbone for the product creation process not only allows influencing factors to be considered proactively or reactively as well as adaptively and flexibly, it also permits process-relevant areas to be linked with respect to the complete integration of all process steps.

Figure 6-6 illustrates the content of an intelligent feature model. Not all of the information given is a necessarily part of each intelligent feature. Each feature satisfies these requirements according to the specific functions it has to fulfill. For example, a flange feature is used both during concept development and in the detail phase as well as the stamping flanged die structure design phase. This intelligent flange feature then has a parameter that defines the necessary view for analysis, detail, and stamping die.

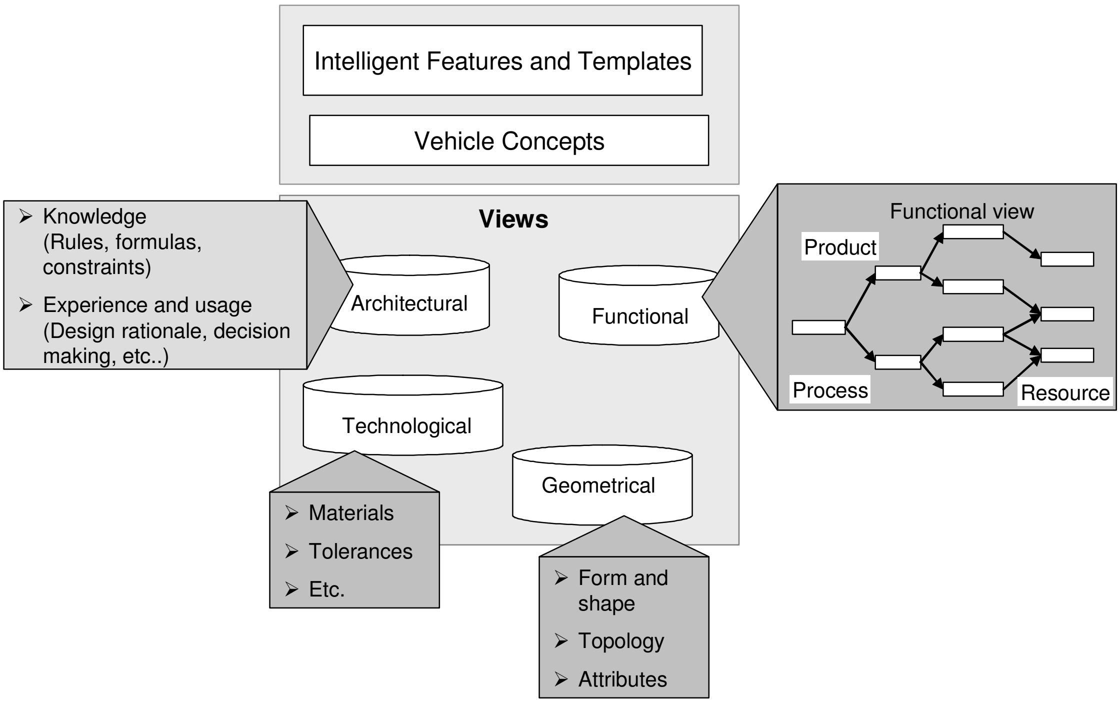


Figure 6-6: Content of the intelligent feature model.

In conclusion, the concept of the intelligent feature is critical because it is the logical link to automated knowledge-driven engineering. Intelligent design features such as holes or flanges are defined by the manufacturing and inspection steps commonly employed to manufacture or to inspect them. The manufacturing knowledge e.g., how to manufacture and inspect a hole is already embedded inside the intelligent feature.

6.2.3 From intelligent features to feature-based templates

Another major paradigm is to be added to intelligent features: part templates -- or better, feature-based part templates as an occurrence of solution patterns. This concept is best explained by a short summary on the history of modeling in the automotive industry. At the beginning of the 19th century, there were great benefits when automobiles were introduced, but there were also major challenges. The first vehicles were assembled by hand. The same components were typically manufactured slightly differently. Implementation of design changes was very slow due to the necessary labor. The common approach was an explicit technology that allowed quick surface generation; yet this in no way eliminated the need for manual work. Each surface was constructed individually. Every surface changed in the 2-D model forced the surrounding surfaces to be manually reconstructed. So every 2-D model was different.

The next concept to arise was reusability. Some styling, structures, and closure panels were reused from one car line to another. Today, the same issue remains and the same concept of reusability is commonly applied, despite the advancement of new technologies.

The following table examines different levels of details that could be used for a template and the issues associated with each level.

Detail level	Description	Key issues
100%	An original, complete design is stored for reuse.	▪ Due to the complex relationship, the part template becomes large and unmanageable. ▪ The part template presents maintenance problems: o How to maintain a specific architecture for a part? o How to improve the methodology and apply new manufacturing processes? o Security is problematic due to the fact that all the proprietary knowledge is provided to the supplier, who might be working for other OEMs.
60%	This is achieved by eliminating various features that have local relationships rather than global relationships.	▪ Although the semi-flexible template solves the problem of model size, it does not solve other maintenance problems and requires additional details to complete the part.
20%	This is the same procedure as the 60% part template; it has however a smaller model with a more manageable graph.	▪ To complete the part, the user has to add a large number of missing details. ▪ While template creation is faster, there is not a considerable increase in productivity, and some maintenance issues still remain.

Table 6-1: Detail level of product solution patterns (templates).

However, engineers need a solution that offers 100% detail and the speed and flexibility of the 20% part template. What engineers need to understand are the characteristics common to all templates: intelligent features. Intelligent features can be the building blocks of every single part (figure 6-7). It is easier to update the individual features than a detailed component.

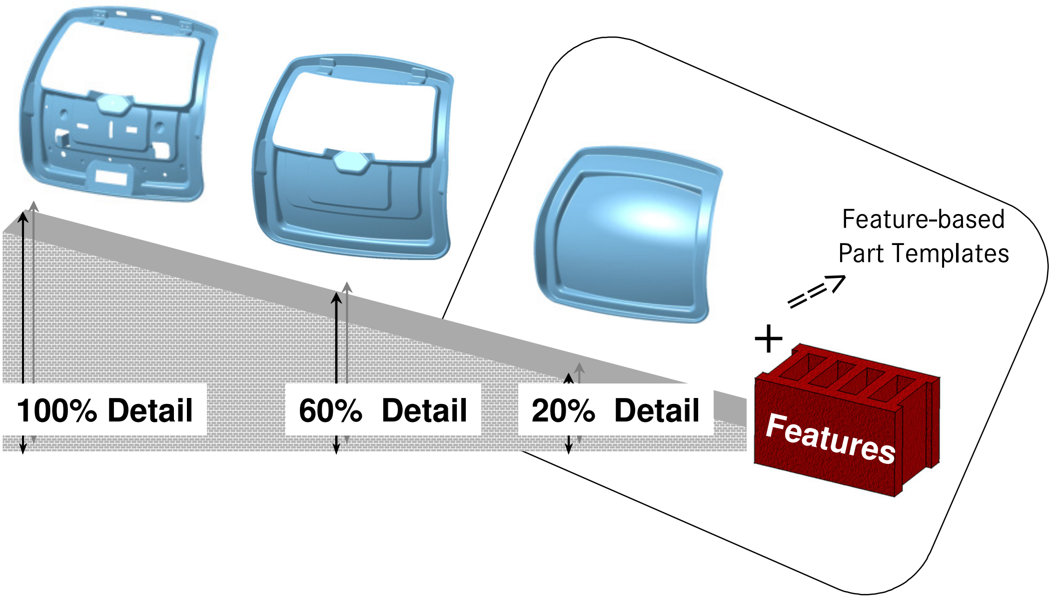


Figure 6-7: Intelligent Features as building blocks for part template.

Definition 6.11: *A template is a description of a principle solution in a CAX-model or a CAX-assembly which is transferred to a special application by exchange and adjustment of the initial parameters (e.g., length of the vehicle) and geometrical elements (e.g. styling curves, basic surfaces). This behavior is also called morphing. In product development, templates can be used both for the study of geometric dependence (study templates) in areas such as packaging, or as the basis for detailed design.*

As a component is analyzed, it can be completely defined by features and stored in the feature library. There when an engineer is required to create, for example, a new door inner, the design process is simple. Just select the relevant features as needed from the library. This process allows designers to use the same features repeatedly.

Just as a hinge information may be derived from a pad feature in the library, the same pad feature may be used to create other features such as a wiper mount and trim. A flange feature in the library has many functions as well. This same library will be utilized for all other components: a body side inner, a hood inner, etc. This feature library makes it possible to capture most of the no less than 200 body-in-white components in a vehicle (figure 6-8).

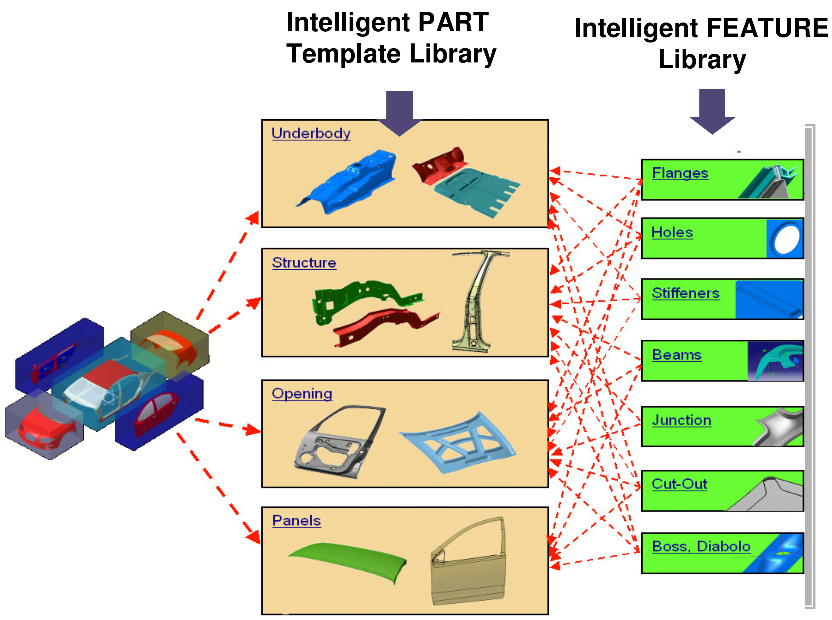


Figure 6-8: A concrete example of structuring part templates and intelligent features.

A template can then be completely described by features. In general, the author distinguishes two kinds of intelligent features (figure 6-9):

- ***Functional intelligent features***: Features that are common for all parts and have a direct link to a process task. A hole feature may be linked to a pierce assembly in die design, or a flange feature may be flanged. On the other hand, the same flange feature may be welded with another part.
- ***Formation intelligent features***: Features that occur in an individual part or group of parts. Their primary task is to form the part. Their usage is mainly in forming dies.

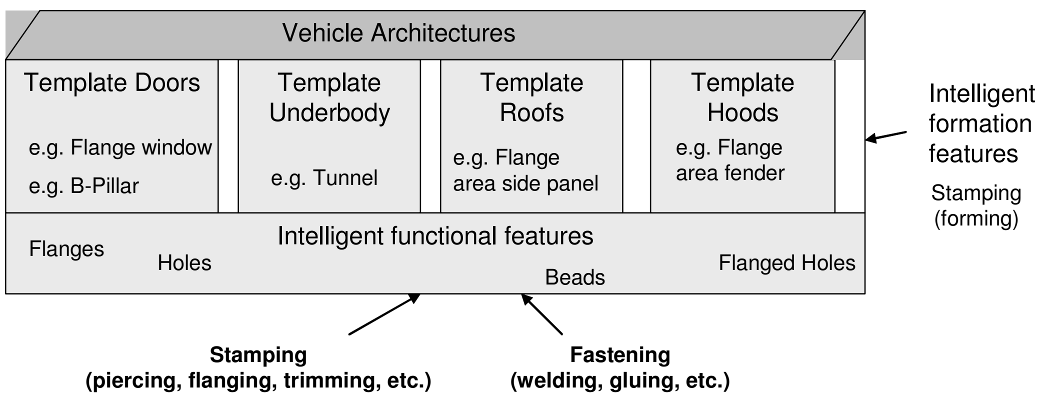


Figure 6-9: Relationship between functional features and formation features.

Figure 6-10 shows an extract from the feature library for car body design and production developed within this thesis.

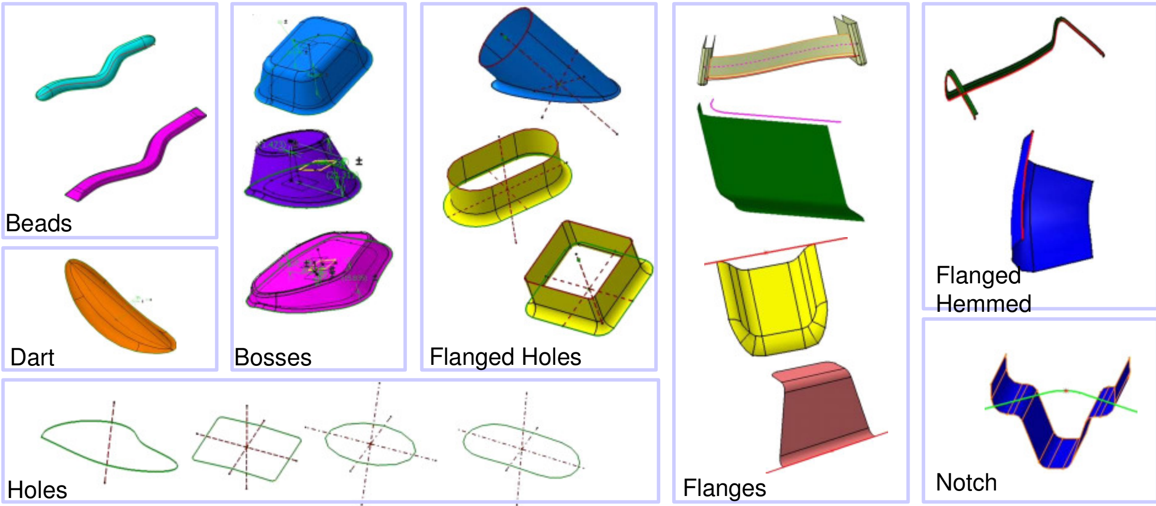


Figure 6-10: Extract from the intelligent functional feature library for car body development and production.

Figure 6-11 shows how such features may be applied to a part

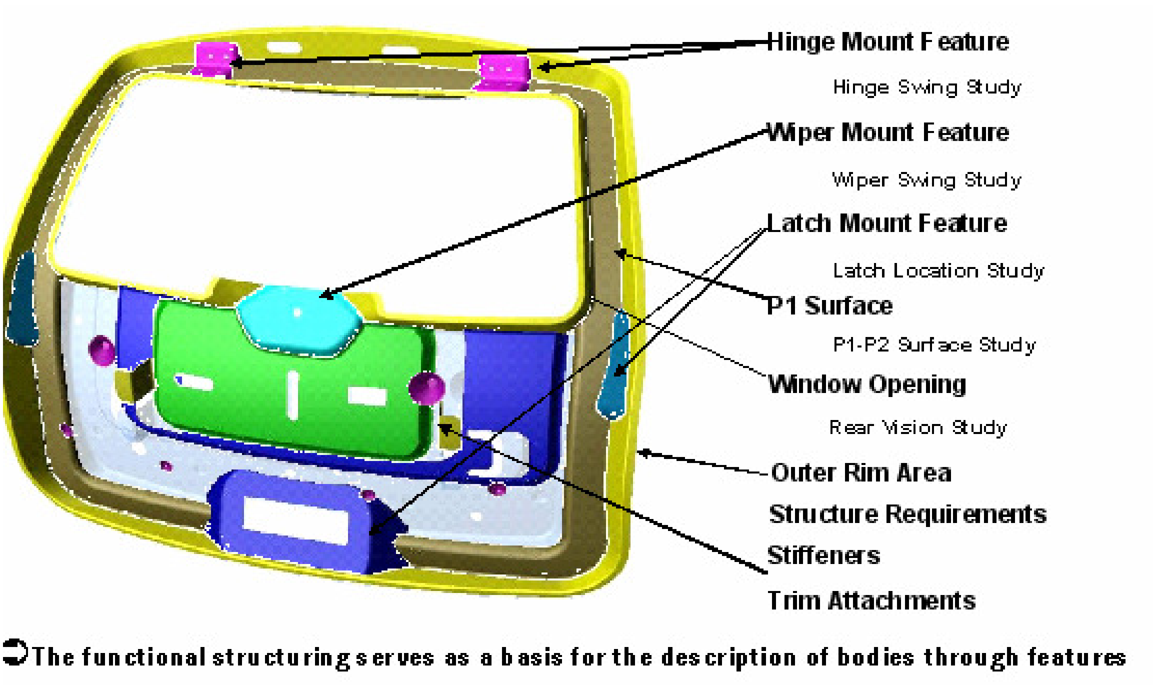


Figure 6-11: Definition of a part by means of formation features.

Process view of intelligent features and templates

Traditionally, most of developers transpose design aspects in creating a feature-based template (figure 6-12). The properties related to process are not taken into account. In this thesis, feature-based templates have the same PPR consideration as intelligent features. Depending on the process step to be satisfied, related properties are added to the design template (front loading), as shown in figure 6-13 and figure 6-14. Thus an earlier evaluation can be performed. Both intelligent features and templates are seen as solution patterns, linking known properties with known characteristics using encapsulation and associativity.

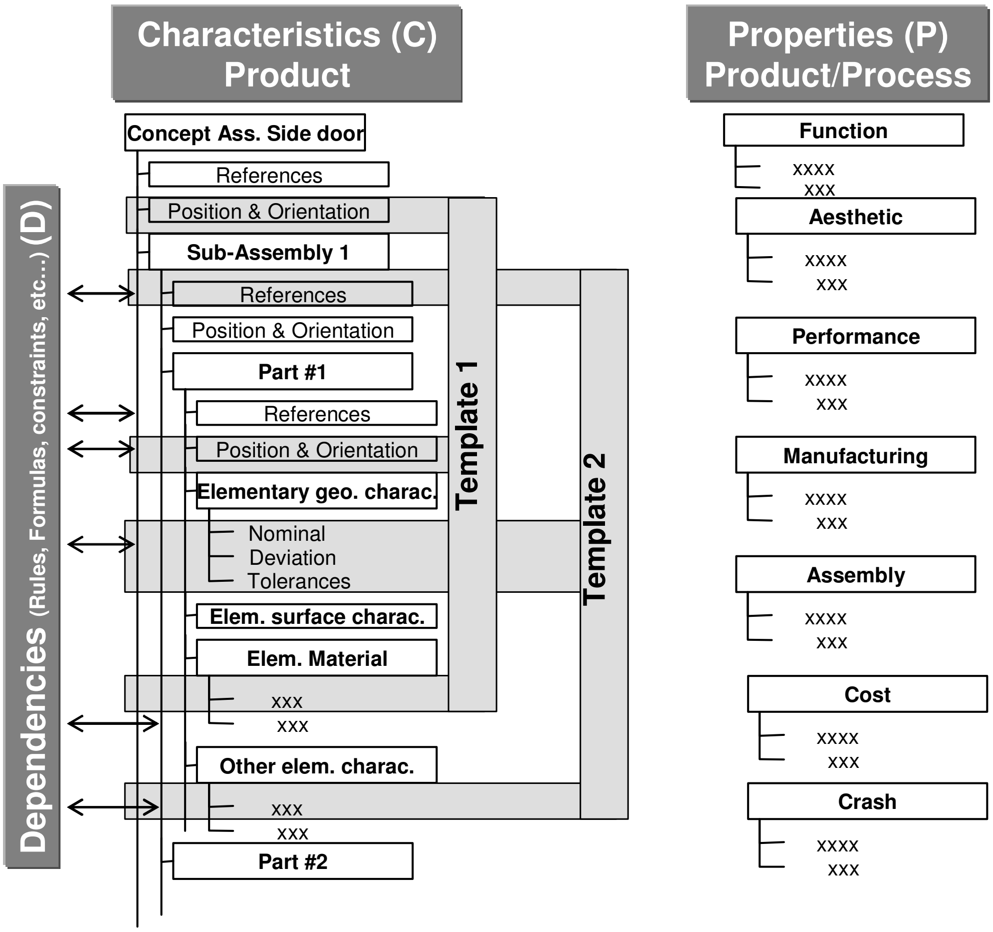


Figure 6-12: Product templates as commonly modeled today: Only design characteristics are considered.

Therefore, a feature-based template is a design start-up document based on formation intelligent features mainly to structure the areas. The functional intelligent features are used to detail the template according to downstream process requirements. As intelligent features, feature-based templates are expected to be the result of a design best practice. The templates are not merely the result of a reduced amount of data intended to provide a large number of identical components, but rather the result of well structured intelligent formation features.

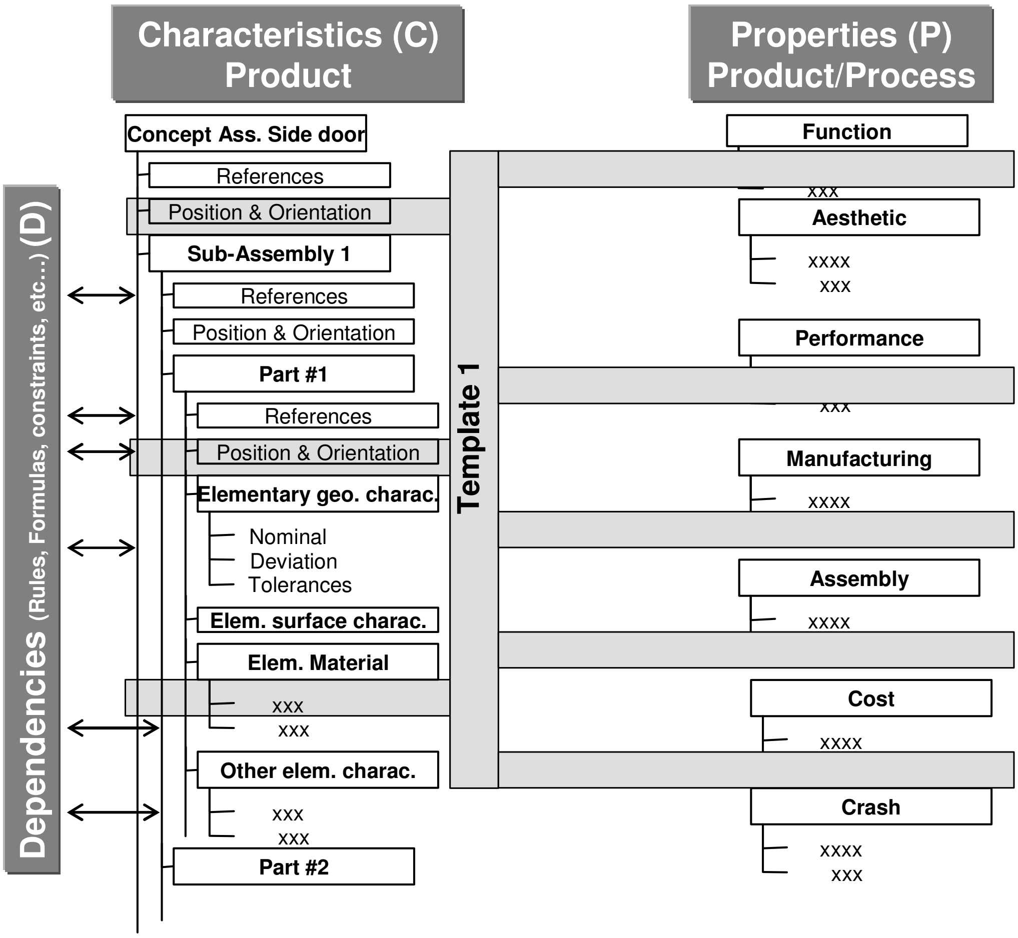


Figure 6-13: Product templates considering process properties.

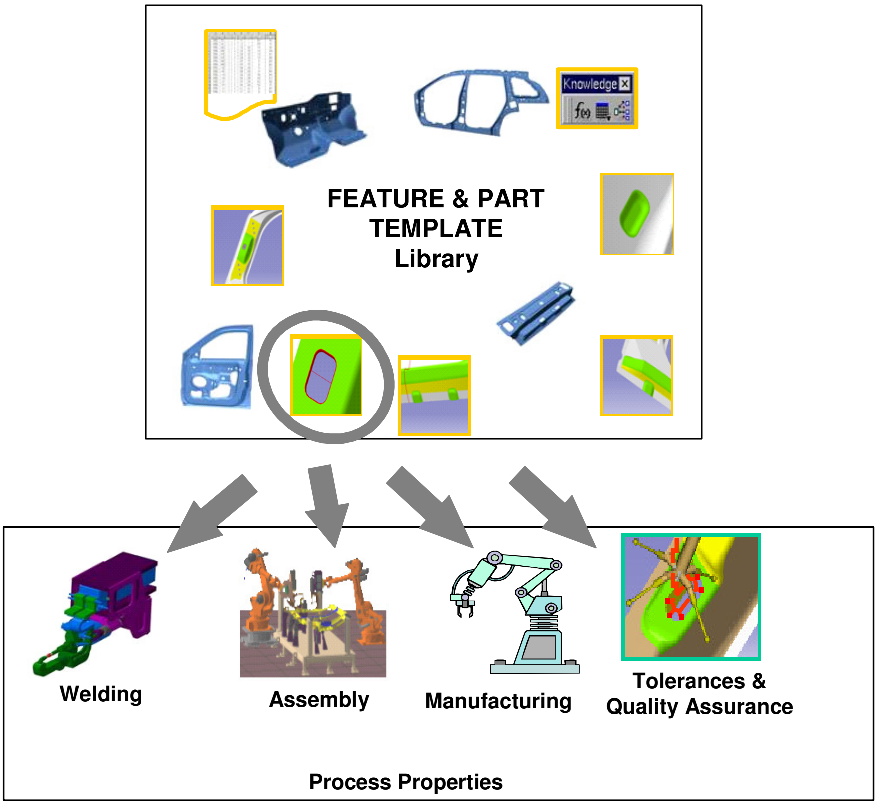


Figure 6-14: Product templates considering process properties.

Example 1: Hole creation

In the traditional process, a further step of using hole features in die face design, for example (see section 7.4.3), would be the closing of break-troughs and holes. Yet there is no hole in the die geometry. If the component designer were to merely hand over the result of the model to the die designer, the latter would have to close the holes or to delete them and recreate them in a further step for piercing in die design. This operation is sometimes quite time-consuming, as subsequent elements have to be adapted after each modification of the part.

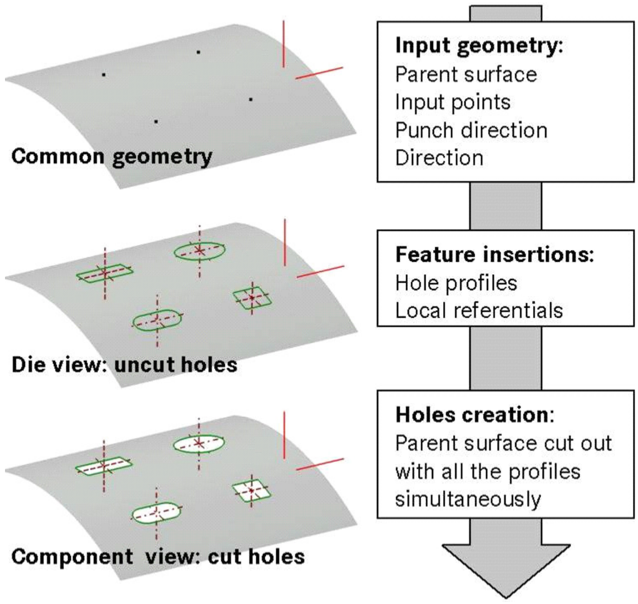


Figure 6-15: Hole creation process.

Thus, with intelligent features, hole creation (figure 6-15) assumes its correctly defined place in the modeling method of die face design, making hole creation independent of shape creation. The hole is represented merely by a curve and some additional geometry for the downstream process such as punch direction and center lines. The chosen solution has two benefits: the existence of holes does not affect the die, and any desired hole change is facilitated.

Example 2: Flanged holes

of the flanged hole offers a better understanding of integrating both the product modeling and die modeling views into an intelligent feature. As for the flanges, which have to be developed (unfold) in the die model, this type of element is accorded a different form that is contingent on the modeling which it is located. Flanged features have two views: a design view and a tool view. In our example of the flanged hole (see figure 6-16), these views are composed of the flanged hole and a font which closes the hole.

These intelligent features with a hybrid behavior (i.e., two different explicit design representations) have to be inserted at the normal feature insertion stage (i.e., with other features such as flanges or depressions). They are located in the common geometry, but, for the component model, the closing surfaces are ignored. They are then added to the remainder of the geometry in the die face model. An enclosed parameter may specify its type, and rules can automatically adjust the feature view.

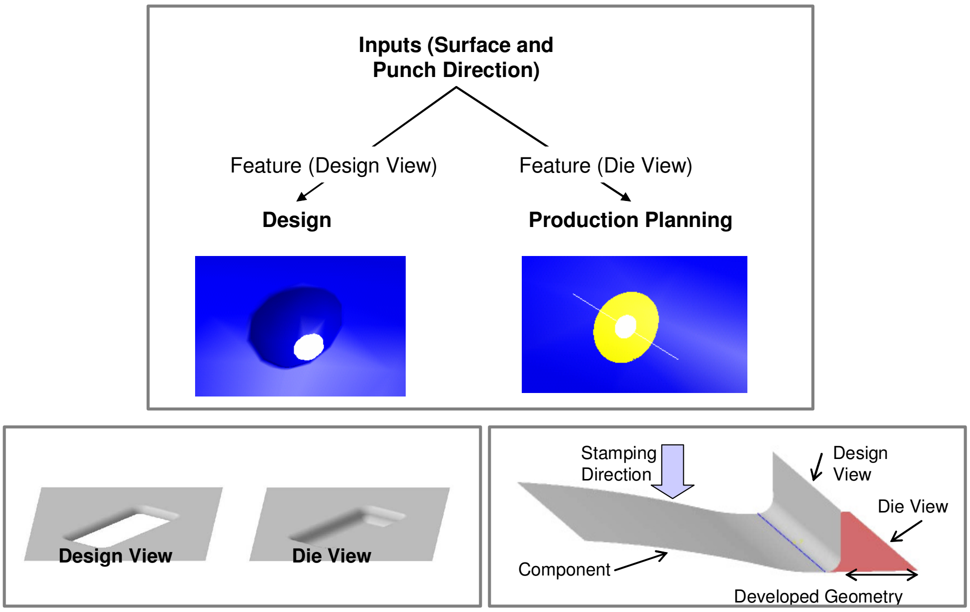


Figure 6-16: Flanged hole in the component model (above) and its corresponding view in the die model.

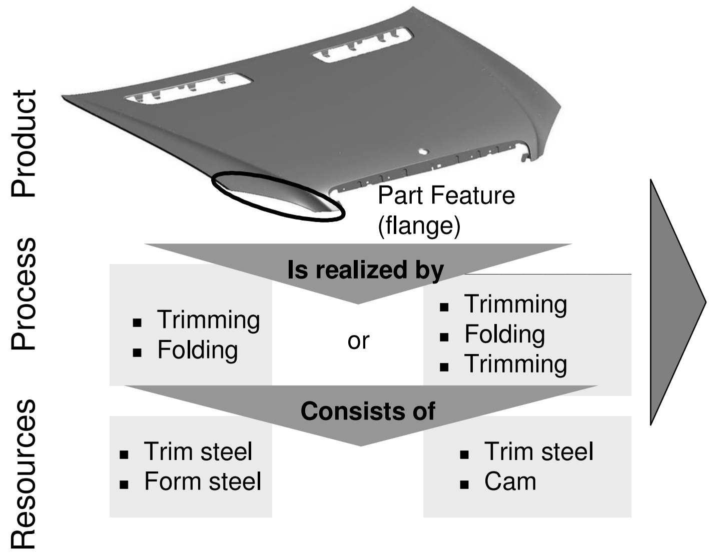
Example 3: Flange

Flanges are important and critical intelligent features, because they directly affect many processes (design, fastening, and stamping). A first step for the definition of an addendum is the development of the flanges. For this purpose, bent sections, hemmed flanges, and radii are brought into a feasible position by the deep-drawing procedure. This position is found through tangential extension of the component geometry.

The geometry of the radii, creases, and flanges is automatically completed as illustrated in figure 6-16, bottom right. Both design and die view can be switched automatically using a single parameter, for example.

Table 6-2 explains generally how to link product, process, and resources using intelligent features. In this context, the definition of a function for each feature is paramount, followed by the assignment of a quality criterion (a tolerance, for example). This information is then analyzed and evaluated in order to assign the appropriate process and tool to realize the function.

Intelligent Feature	Function	Tolerance	Process	Resource
Hole Feature	{gage, clearance, datum, access, etc.}	{+/- 0.5mm, +/- 0.1mm, …}	Measuring strategy in quality assurance	Measuring tool
			Piercing strategy in stamping	Piercing tool
Flange Feature	{hemming, bending, etc.}	{+/- 0.2mm, +/- 1mm, …}	Stamping operations strategy {flanging, folding, restricting}	Flanging tool, etc.



Main steps:

- Automatic recognition of **part features** (e.g. a flange)
- Set a **die process standard** according to the tolerance of the flange
- Each die process standard includes different **modules** (e.g. folding) themselves consisting of several **die components** (resources e.g. form steel, cam).
- **Partial automatic distribution** of the die components into the die operations

Table 6-2: Example of linking product feature, process strategies, and resources.

Tolerances represent an important quality criterion in the overall product life-cycle. They substantially affect the strategic success factors for an enterprise: time, cost, and quality. The wise specification of dimensional tolerances for manufactured parts leads to enhanced stability of product and process definition, and is a key element to increase productivity. Tolerances thus act as mediators between functional requirements and technical restrictions. The feature-based approach set out here allows not only downstream requirements to be included in the tolerance definition at an early stage in development but also a process-oriented definition of reference elements to be obtained.

6.3 From design to process: intelligent feature processing along the process chain

Each process step application has its own view of the product because it has to fulfill special tasks using specialized technical knowledge and modi operandi for problem solving. More generally, downstream processes need feature information to apply their specific information (figure 6-17). IT solutions must adapt to this multitude of characteristics in order to be able to represent effective and intuitive tools and aids for the users.

The derivative and additional modeling of missing process information resulting from features used during the product development phase have so far been generated by using feature mapping (one-to-one relation) as explained in chapter 2. Design features were transferred from the CAD model to the feature-based planning system of the respective process section and subsequently transformed to process features (e.g., inspection feature, manufacturing feature, analysis feature, assembly feature, as they have been understood so far) in a downstream process. In this context, a key requirement to achieve the necessary functionality is to be able to incorporate the design features into downstream applications. Furthermore, some methods were needed to create user-defined links between product and process parameters, thus defining individual mapping rules.

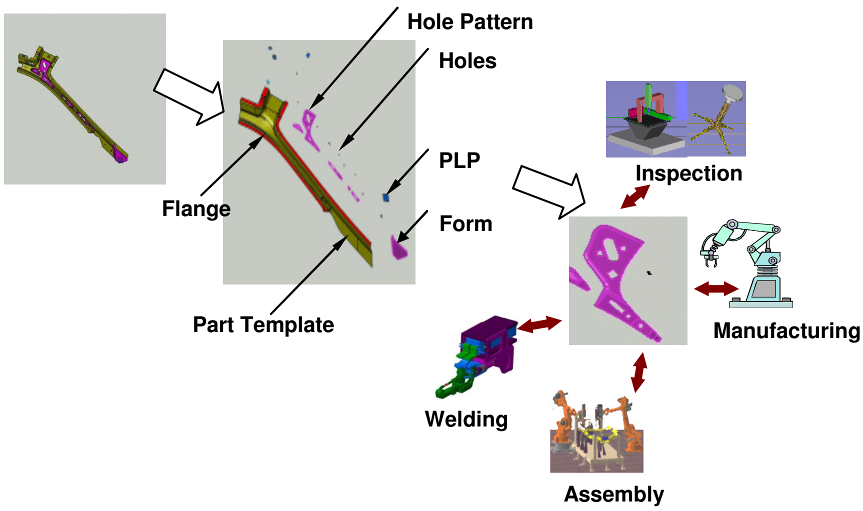


Figure 6-17: From product to process: first define a product by features, then assign process information to each feature.

Intelligent feature technology is an efficient tool for this purpose. Intelligent features skip this step and directly provide the geometric, technological, and functional aspects to the process planner, facilitating process planning. Mapping between feature classes is replaced by feature decomposition to related process tasks and process strategies. The user may choose one or more machining strategies (as solution pattern) from a catalogue and apply them to the feature. All the necessary information the machining strategy needs is already modeled inside the intelligent feature. In the case of a design or a process change, these features serve as a link for the execution and support of process modifications.

Thus, intelligent features are essential for automating process planning applications: cost estimates, for instance, can be prepared with a few mouse clicks and much less guesswork, and requests for quotes can be fulfilled more expeditiously. Chapter 7 elaborates the processing of intelligent features in related process phases.

Intelligent features play a key role in efforts to create an integrated digital product model. More important, intelligent features complement knowledge-based engineering as a genuine step toward automated CAPP (computer-aided process planning). If the features are processable (inspectable, machinable, or assemblable), intelligent features are identified and linked automatically using feature decomposition rules or applications to corresponding planning routines (process templates) stored in a database or catalogues.

More generally, the author introduces the layer concept to link product description, process planning, and resource allocation (figure 6-18). Each process step such as tolerance simulation, die process, or fastening creates its own process layer template or process study template, containing process-specific geometrical elements representing its reference view of the feature-based templates as well additional process information, which have relevance only in this process step.

The process layer template is also called "study template" since process planners can use it to quickly evaluate different variants and test some principles, before releasing a final template for serial use.

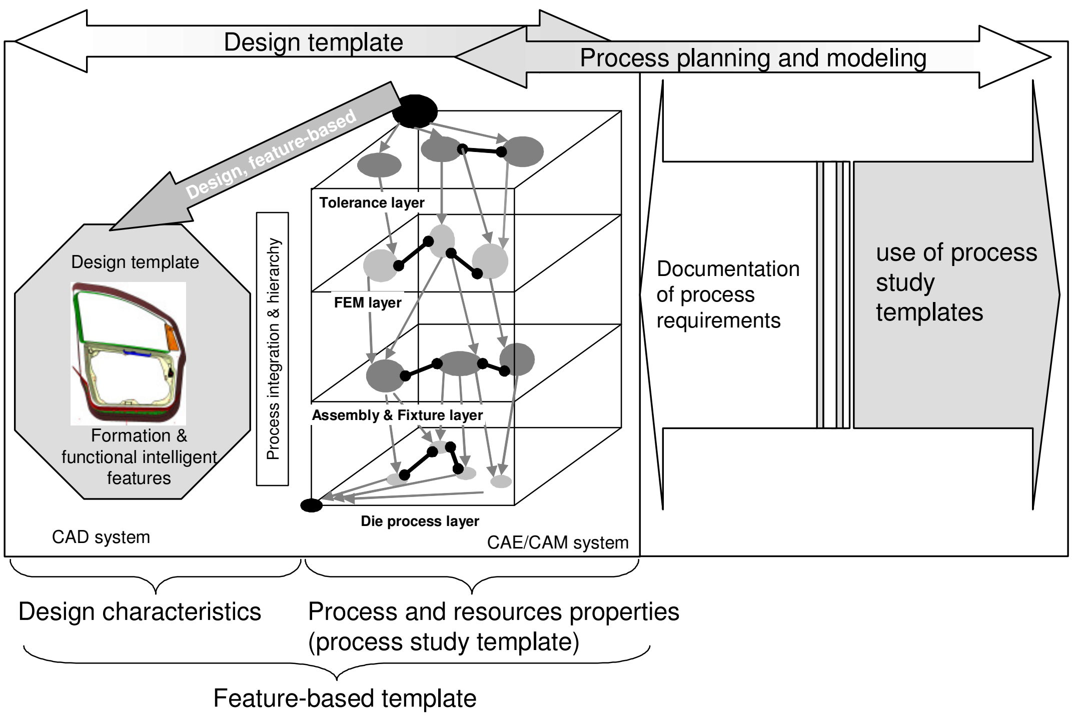
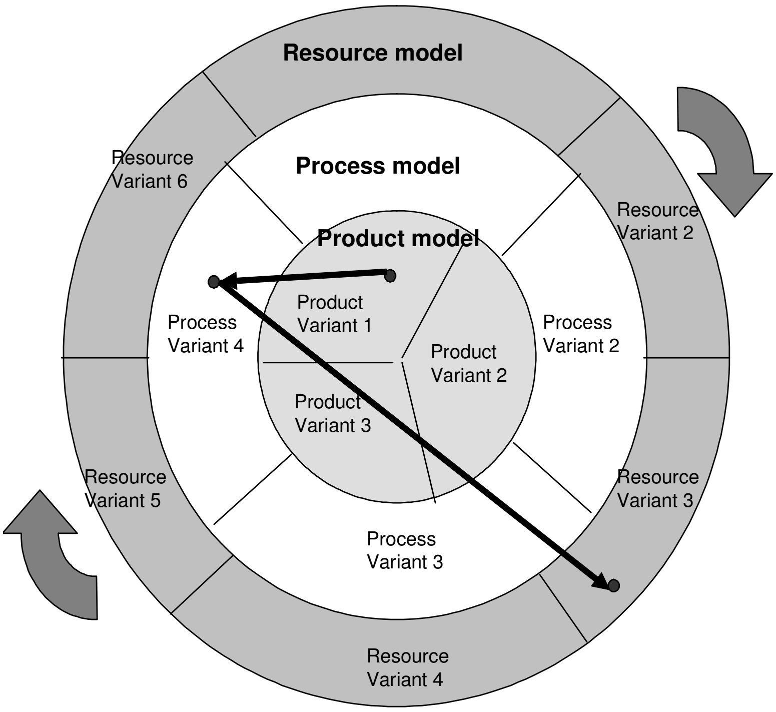


Figure 6-18: The principle of layer concept for template modeling.

With this concept, process planners can be more productive: process planning can be prepared in much less time, easing the burden on overworked planning departments and eliminating a major bottleneck in workflow. Designers and planners can spend less time on repetitive tasks and more time on programming challenges that build skills and test creativity. If all this happens, then fewer mistakes and omissions will occur.

Another simplified view (two-dimensional) of this process layer concept is sketched in figure 6-19. With this concept, more process alternatives can be evaluated, taking into account all aspects related to product modeling, process planning, and resource allocation.

Furthermore, process planners can start their work earlier (frontloading), as the necessary inputs (product and process requirements, information about resources or external conditions as well as modeling conditions) are available in feature definitions at any time during the product creation process.



PPR x = Design Template 1 + Process Template 4 + Resource Template 3

Figure 6-19: The PPR layer.

Processing along the process chain

Figure 6-20 illustrates the concept of intelligent feature processing along the process chain. It compares the previous concept, mainly based on feature mapping between design and other process features, and the new concept, where decomposition instead of mapping takes place between intelligent design features and process templates (e.g., inspection or manufacturing strategies).

In the new approach, design features are modeled in such a way that they already contain geometric elements that were remodeled by extensive feature mapping to correspond to other process features. The clear relationship between intelligent features with its linked feature mapping and knowledge-based engineering is very evident. The process template allows the user to generate the specific view or behavior of the intelligent feature: The same intelligent feature has various behaviors, depending on the context (concept, detail design, tooling, machining, inspection, etc.). This relationship shows how automated CAD/CAM is evolving in line with feature technology and knowledge-based engineering.

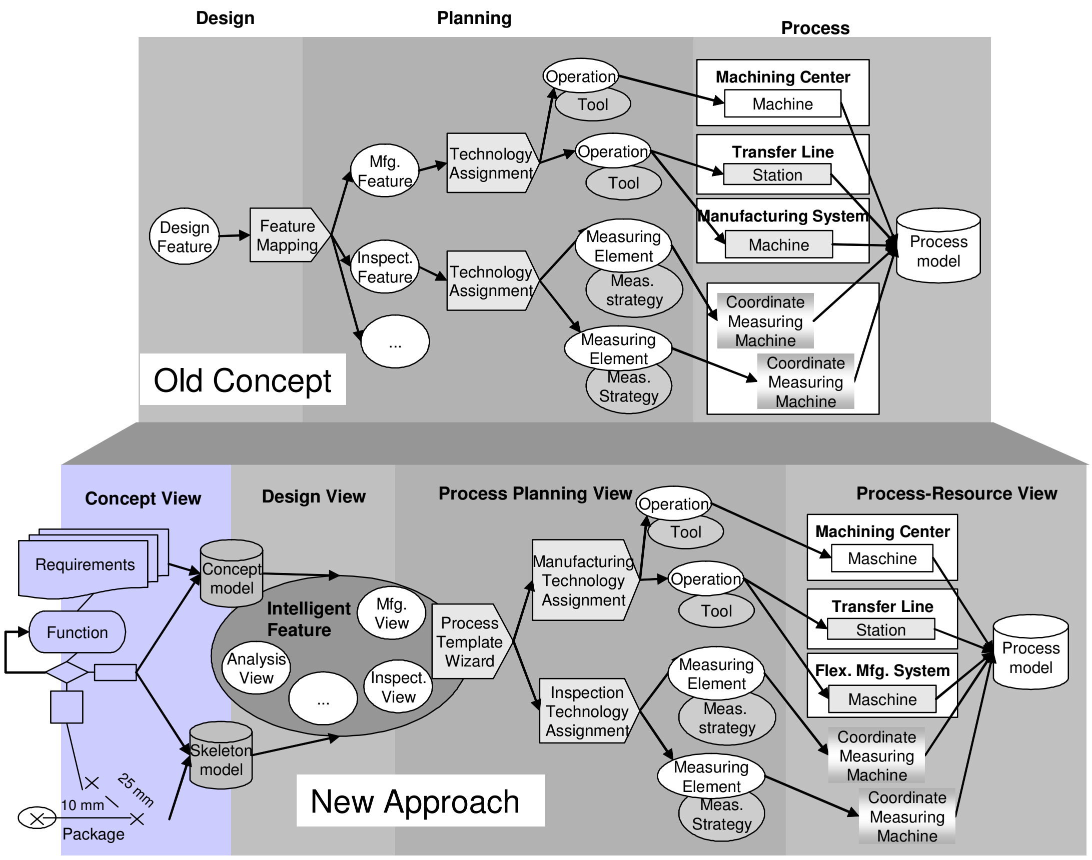


Figure 6-20: Feature processing along the process chain (product, process, and resource integration).

Lean process template

To better integrate the process chain, the last step is the so-called lean process template, a single template covering different views of the product creation process. Figure 6-21 shows the product view of the lean process template, whereas figure 6-22 shows the process view.

In this lean process template, the term *product* is related to all the results of design activities (component, die, tooling, etc.). Thus, an intelligent design feature, for example a hole feature, has a clear relationship in other product categories, such as die process (the hole is to be closed for forming purposes) and die design (the hole is to be pierced).

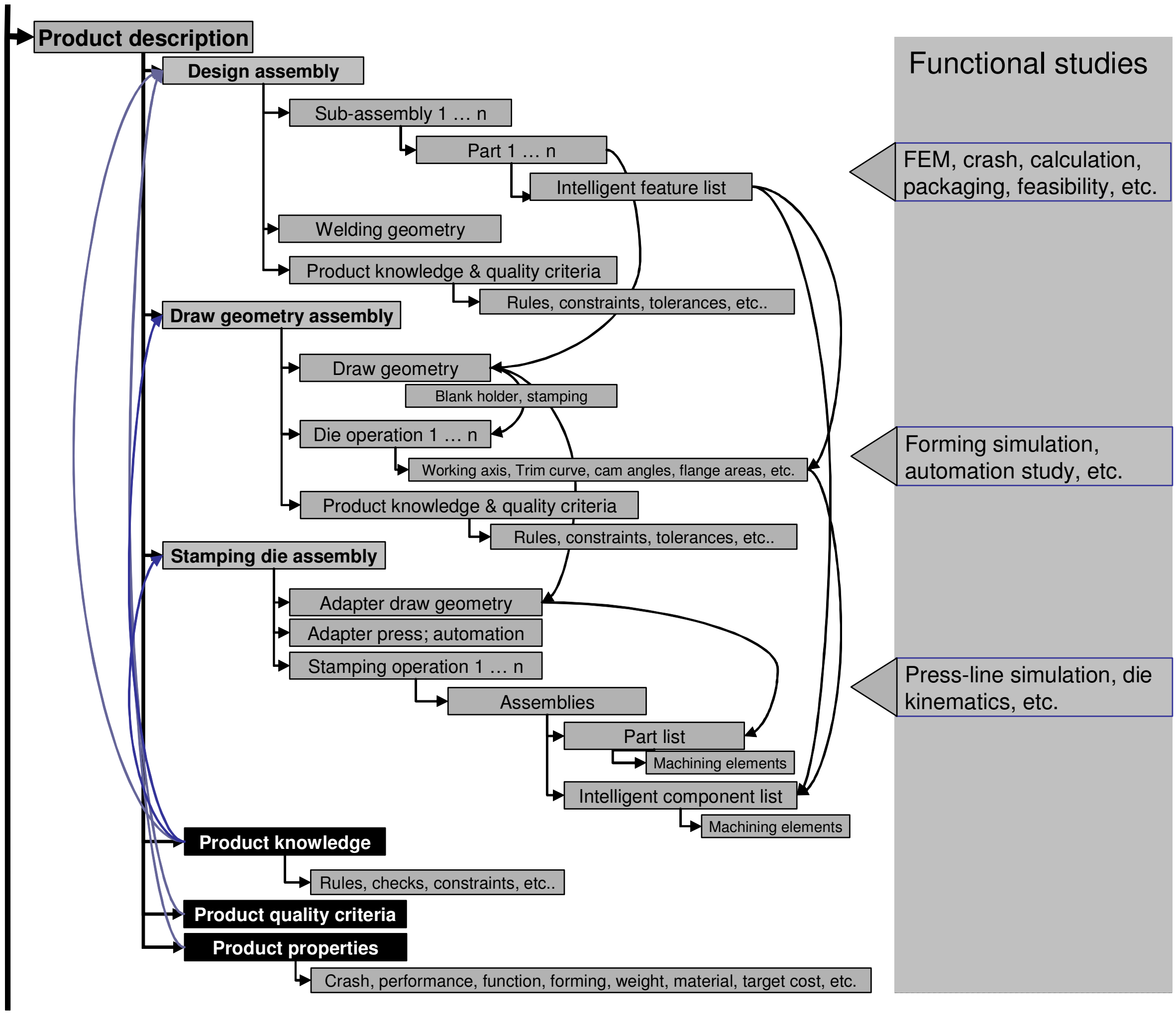


Figure 6-21: Product description as part of the lean process.

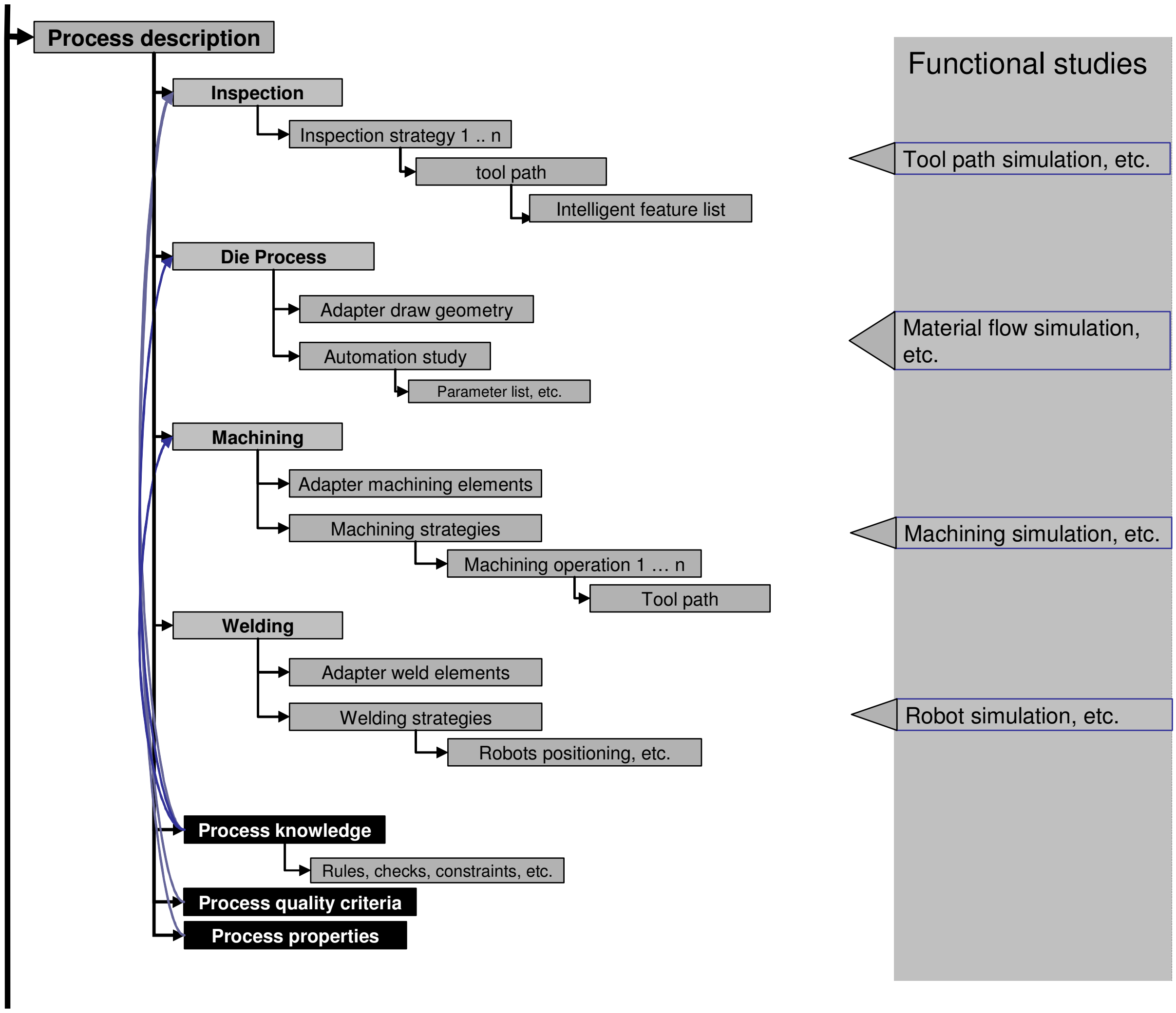


Figure 6-22: Process description as part of the lean process.

6.4 Intelligent PPR-oriented feature model

The long term goal of product creation is the definition of a constant, formal model that will illustrate the entire product life-cycle, i.e. from product planning to design, process planning, and production up to recycling of the product. The requirements set for product models are multi-layered, since product models not only have to reflect comprehensive information capacities, but also must be able to optimally support the design process. This calls for a multi-domain representation, taking in extended concept also mechatronics aspects into account.

Product models can be divided into the followings three classes based on the underlying model philosophy [Grabowski et al. 90]:

- *Geometry-oriented* product models, which contain essentially shape-oriented information capacities and which can be used in different applications. The passing of the shape model for NC programming is an example.

- *Phase-oriented* product models, which contain specific partial models for each design or product phase and which apply the resulting information in the respective phase.
- *Integrated* product models, which are based on a uniform data model for all product phases. The entirety of the product characteristics are integrated in the model with regard to the subsequent treatment.

Most of the commercially available systems for mechanical engineering, PLM systems for example, use geometry and phase-oriented models [Dankwort/Hoschek 00]. A product model approach, which serves as the integration core of all product life phases, is based on the following principles [Seiler 85]:

- *Integration principle* -- semantic, plausible, activity-oriented consideration of phase-spreading dependencies.
- *Model coherency principle* -- updating of product contents without model transformation.
- *Data accumulation principle* -- explicit illustration of all relevant product information which cannot be illustrated using other information.
- *Association principle* -- derivable from implicitly contained information elements by inference rules.

Based on these principles, a logical, complete, and redundancy-free product model can be developed: this model serves as the obligatory integration foundation for all the applications within the product creation process. With an implementation of the model in a product database, PLM for example, all the relevant data for specific applications can be made available or data can be exchanged between applications. Information contents of integrated product models focus primarily on the illustration of all relevant product and process information that is gathered along the maturing steps of a product and process planning and development. They are the knowledge containers of an enterprise.

All these requirements necessitate the building of an intelligent feature structure. The intrinsic implementation of such a methodology in the computer can take place using object orientation, since the methods of object-oriented programming support the feature-modeling concept, allowing both complex type formation and the grouping of features and methods as a unit. The object-oriented representation has been established as a suitable representation formalism of integrated product models. These considerations lead to the following requirements for the intelligent feature model:

- Deposition of object-oriented problem-solving knowledge, so that solutions with a given problem can be suggested by the system for.
- Capability of extracting the required and current information from a feature and of supplying it in any format for any purpose.
- Implementation of algorithms for the automatic recognition of items from features or for detecting the features of a specific view.

Thus, when targeting the building of an integrated PPR information model (PPR model) for intelligent features and templates, the following issues are considered:

- What contents must be stored in the PPR model?
- Can all the contents be stored in only a single model? Or are their contexts so different that different models are necessary?
- Is the context readable independent of any particular system (formalism is required)?
- Which systems have to be integrated?
- How is the PPR model to be maintained?
- What about encapsulation of the complexity -- is this possible or necessary?
- How can the logical representation of the objects and their relations be accomplished?
- What is expected of PPR model? How are the data to be stored and extracted?
- Who uses which view of the information and when?

A fundamental prerequisite is to clearly specify the function and behavior of intelligent features and templates. Based on the representation of the function as a target behavior of parts as given by Mortensen [Mortensen 99], an intelligent feature model is developed to link product and process with respect to the function. The starting points are generic models with templates and the behavioral model essential components of an integrated information model. These must be integrated into IT systems to create services that enable holistic control of the product creation process. The PPR model illustrated in figure 6-23 offers a foundation for the integration of all CAx applications in body modeling

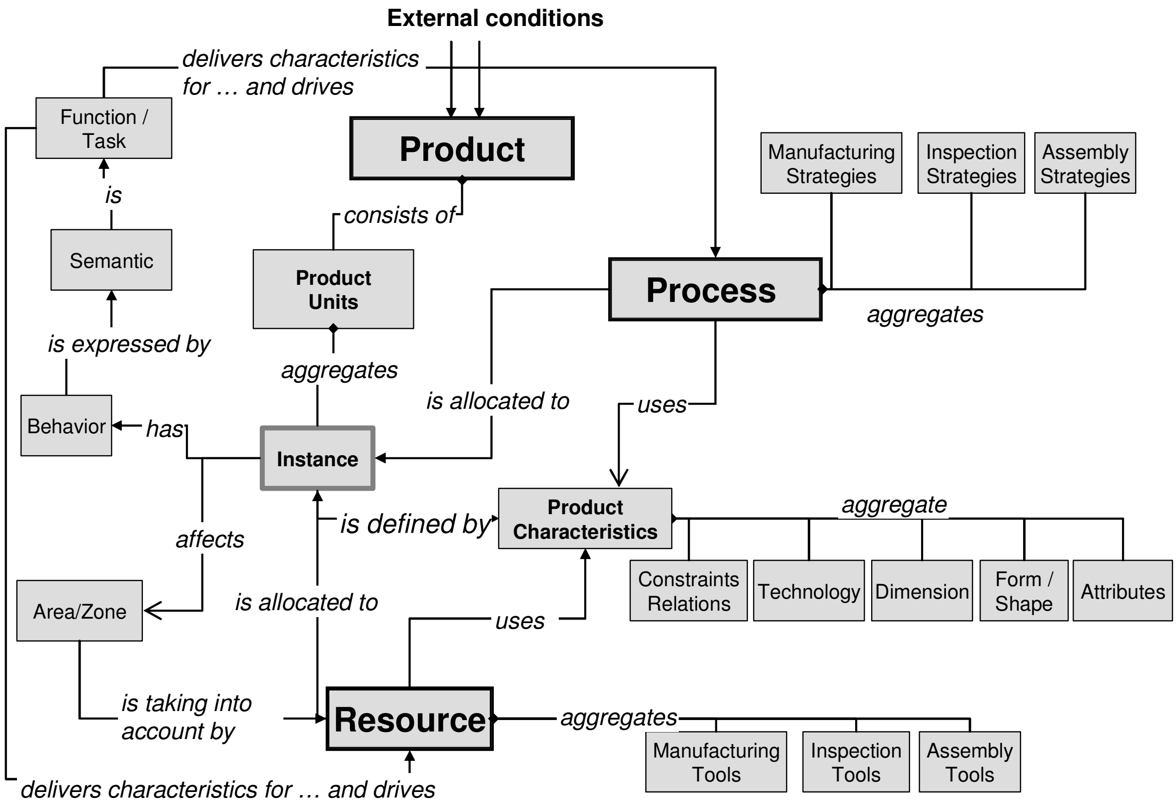


Figure 6-23: Semantic description of the PPR model
for linking of product, process, and resources in car body engineering.

The underlying foundation is the PPR-Matrix explained in section 5.5.2 and portrayed in figure 6-24. The basis for the definition of this PPR-Matrix is so-called product logic. The component or product is broken down into functional areas. Generally, the author proposes the following:

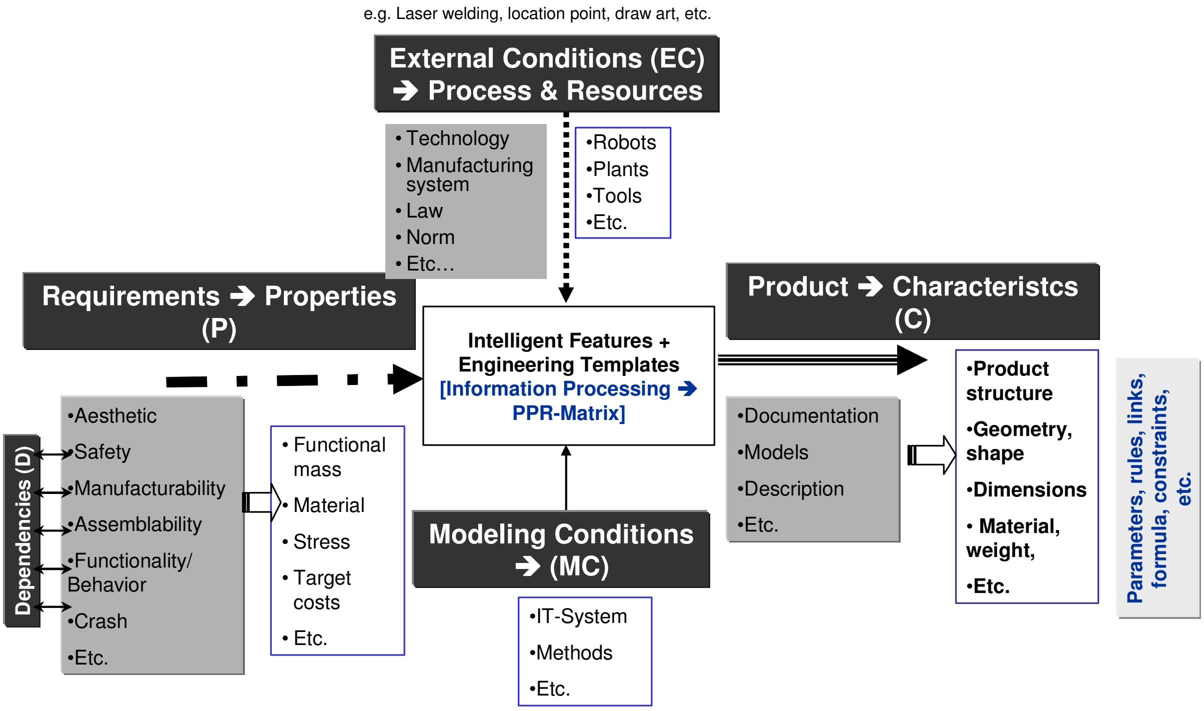


Figure 6-24: Product creation process in the context of intelligent features based on the PPR-Matrix.

Figure 6-25 gives a concrete example of this model according to following steps:

- couple geometry elements with component functions (here related to the design function as well as its behavior in process) (1)
    - Example: the function “*assemble*“ has a relationship with the geometry element “*weld point*“
- Couple the geometry with a reference axis system (2)
- Link geometry with quality criteria (3)
    - Quality criteria are expressed, for example by tolerances. Measurement elements are points, planes, curves, etc.
- Insert into part (4)

For the representation of the function “assemble” for example, the relation can be reconstructed to show which components are in relation one another.

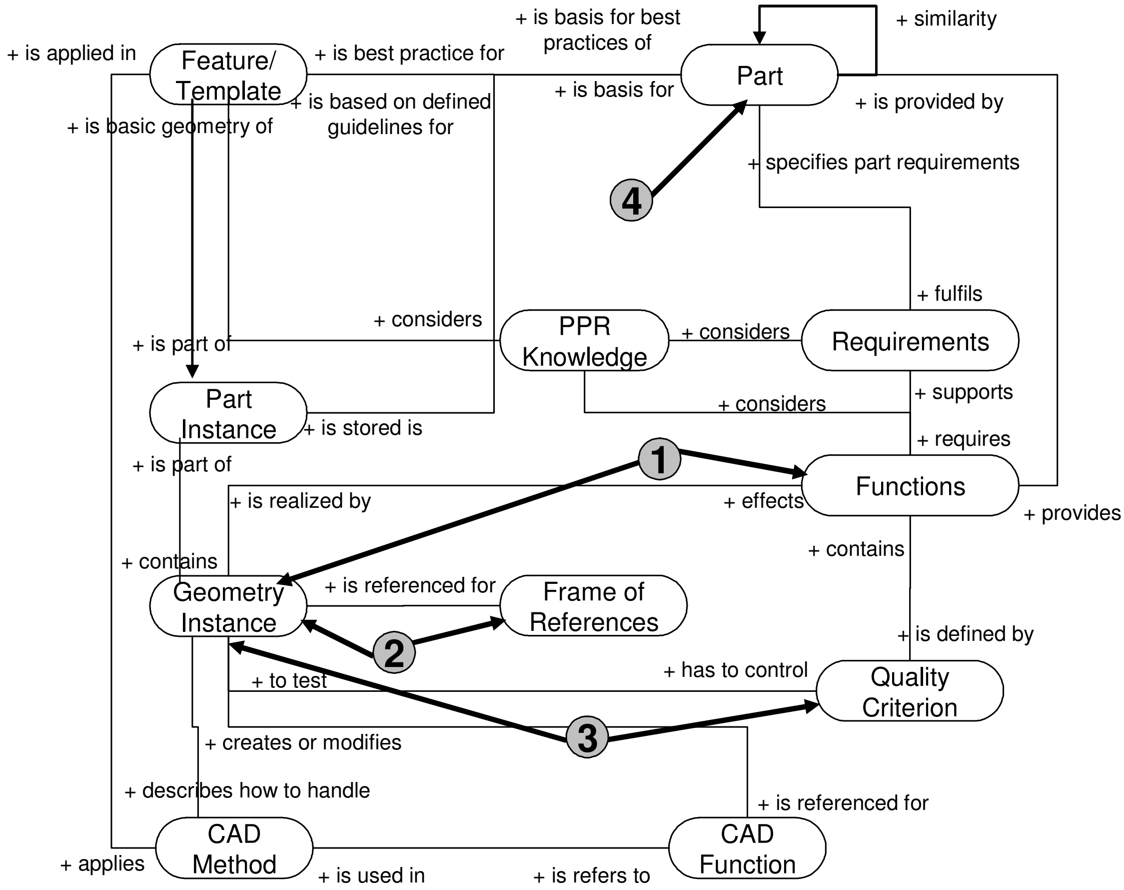


Figure 6-25: Product creation process in the context of intelligent features based on the PPR-Matrix.

6.5 Conclusion and benefits

The concept of intelligent features and feature-based templates as occurrences of solution pattern, as described in this chapter, is an IT-based method intended to fulfill engineering requirements especially in vehicle creation process and as applied to the design, planning, and manufacturing of car body components.. This concept, completed with the PPR model, offers new opportunities for the cooperation and parallel handling of dependent car body assemblies, in the sense of concurrent engineering performed by more than one technical designer. Moreover, it leads to the coupling of processes through consistent transfer of data, decision alternatives, and modifications, resulting in a seamless process chain within the body creation phase.

The contents of the PPR model and applications operating thereupon primarily focus on the interests of design and manufacturing in product planning and development. The PPR model offers a foundation for the development of progressive engineering applications e.g., the access to existing design solutions on the basis of solution samples or distributed product development. A substantial concept is the uniform, life-phase-oriented description of all product or tool properties and the strict separation of the definition and representation of characteristics.

Car body engineering based on the PPR model achieves efficient reduction in the effort required for design and shortens modification loops. The comprehensibility and reuse of the design knowledge and a more effective adjustment of design and package modifications in other model versions, for example, are benefits of this methodology. By accelerating evaluation of the production of variants, the approach allows predictions about feasibility to be made. Not only is the consistency of process data improved, the approach also shows enormous potential for the early simulation of process cycles, permitting early recognition of bottlenecks or undersupply of critical resources. In addition, since both the design and production process are supported by knowledge processing based on the PPR model, the following potentials can be developed:

- Modeling with functions.
- Generation of completely new product structures and effect principles.
- Intelligent system guidance and knowledge management.

Productivity is enhanced through the integration of knowledge and experience and by implementing process-specific rules and appropriate standards and ensuring that they are observed. Moreover, storage of the methodology of structural design and the intention of the technical designer in the model (feature) yields two benefits: not only do the information content and the resulting quality of the models increase but also process reliability. Due to the partly automated digital planning of product, process, and resources, the user's level of acceptance rises and excellent process transparency is achieved. Furthermore this solution represents an important foundation for the support of active information exchange (computer-aided conferencing) and the use of multimedia in the design process (video conferencing) [Dankwort 98].

In summary, the intelligent feature model offers new alternatives for integrating various technological process chains within the so-called digital product creation process. The basis of this digital process with intelligent features is the product process and resource matrix developed in chapter 5.

PART IV

REALIZATION CONCEPTS AND PROTOTYPES

Chapter 7

7 Realization concepts for modeling integrated processes in car body engineering using intelligent features and templates

This chapter discusses methods for designing process steps by means of intelligent feature technology. Figure 7-1 sets out the emphasis of the concepts presented in this work (represented by shaded blocks). Most of the concepts can be applied to design the entire car body process chain.

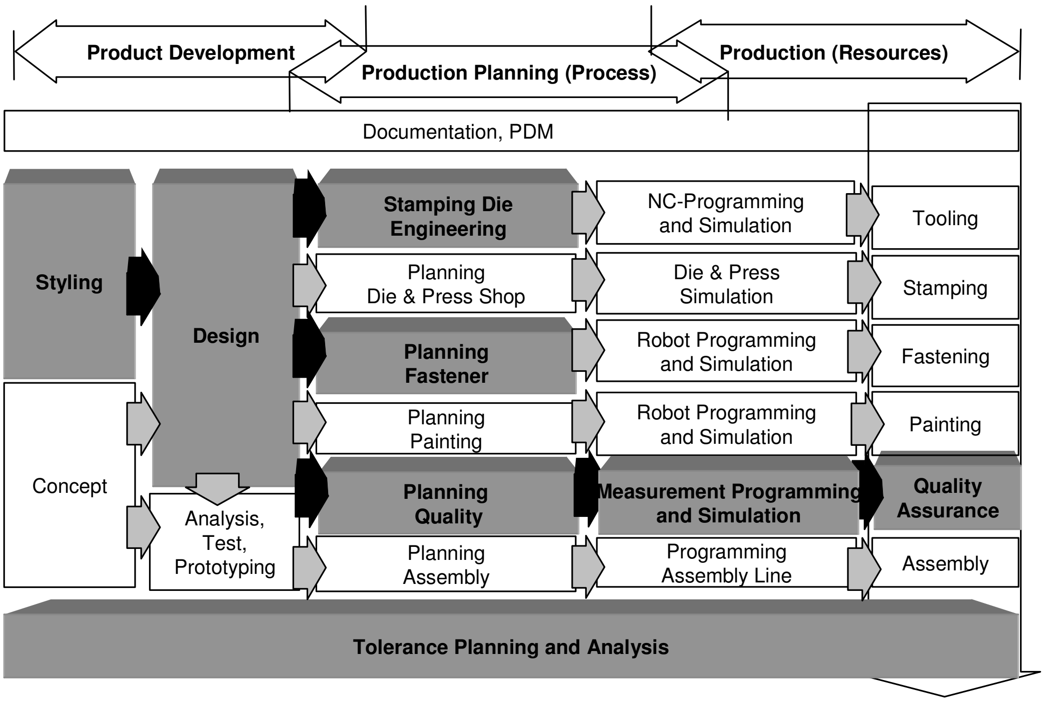


Figure 7-1: The car body process chain and the scope of the work.

A process chain can be defined as the concatenation of the technical information flow of several overlapping process steps (concurrent engineering) which are necessary for the achievement of a concrete goal [Storr 99].

One aspect of body development is the design of body components. In the context of this design, these components unite their geometrical target shapes and the permissible variations expressed by tolerances. These CAD models are the information-technical basis for the downstream processes -- body production and geometrical quality assurance as well as analysis and tolerance planning.

The body-in-white (BiW) process is made up of several process steps from BiW design to the BiW manufacturing process and ending with quality assurance. In the planning and the start-up phases, in particular, a number of correction cycles are necessary to achieve the required product quality. Therefore, the BiW process in this context should be considered more than just a process chain: instead, it is a closed loop based on process relations or process network.

To manage and structure the information flow in such a complex context, it is not enough to merely target the product level. Adding the part level still does not suffice. Decomposing the existing complexity thus becomes necessary. Using intelligent feature technology, as a common and associative information structure, meets this need by providing a method to decompose a complex task into intelligent features, with their ability to react flexibly and adaptively to product and process modifications.

7.1 Modeling of car body parts

This section provides a concrete example of how to design with intelligent features and feature-based templates.

Design work today is characterized largely by the obligation to minimize development time. Yet other concerns are also of interest: meeting individual requirements of customers and of the market, as well as considering the process and resource conditions in order to attain an economical, competitive product of high quality. These requirements call for holistic concepts based on simultaneous or concurrent engineering.

7.1.1 Relational design using the mating model concept

Relational design, which concerns fast, variant, and adjustment design, is a possible solution to control the changing development field. The possibility to link different models with each another associatively leads inevitably to the question of how such linkage structures are to be meaningfully and efficiently constructed and managed. In practice, the terms structured model, adapter model, or skeleton model are often heard. All these models are summarized here under the term *mating models* (to mate, i.e., to connect in pairs, adapt to each other, assemble, and connect).

The fundamental goal of relational or even of parametric-associative design is the rapid, simple design of variants and adaptation to parameter variations as well as reference geometry. These options, particularly in upstream development phases, serve for the examination and accelerated evaluation of different styling or design concepts. In addition, the options apply as well in the later phases, for example in stamping die and tooling engineering, since changes arise very frequently. In this context, the guiding idea of modular-based vehicle development moves into the foreground: in this connection, a component is a reusable design template.

The requirement of speed, variability and reusability leads automatically to the well-known principle: design simply, surely, and clearly. Alternatively, get it right the first time. This has a fundamental influence on relational design. The notion of the mating model lends itself, in the initial approach, to the principle of the deductive system representation of design engineering, the decomposition principle, and hierarchical, functional, and structural design concepts. Targeting increased variability and transparency with given complexity, both substantial driving and determining geometry (reference elements) and the associated relations are clearly grouped and centralized in a mating model, which consists of an adapter model and a skeleton model.

Adapter model

The goal of the adapter model is the fast and controlled adjustment (adaptation) of the design to changed environmental conditions. This leads via the relational structure to a hierarchical structure with a unidirectional relation flow, considering only the respective input relations and neglecting the possible influence of a model on its environment (output).

Not only the task of grouping relations but also the component hierarchy is crucial. An adapter model consists solely of primary elements and always contains the sum of the input relations (elements) of all sub-components in an assembly context. Another important characteristic is the notion of design orientation: although the aim is to define the component hierarchy and the relations between part and assemblies, the affecting characteristics of the component change frequently. With the uncoupling of the result design from its environment in an adapter model, the so-called dummy elements can be integrated in the adapter model, in order to describe the whole model. An additional reason for using adapter models is the frequent occurrence of design fluctuations of inputs in later phases. These fluctuations can be easily handled by replacing dummy elements with new inputs. An adapter can therefore have a design part for the improvement of the adaptation. Furthermore, an adapter model can in principle cover all the available geometric elements. Design changes are usually made by exchanging reference elements in the adapter.

Skeleton model

This topic is concerned with modeling, using geometric references and their parameters for the description of the component in an assembly context. This method enables both a consistent and component-spreading administration of wire geometry references and parameters, which clearly improves change management, and an early evaluation of body components based on changed dimension or package concepts [Mbang et al. 02b].

A skeleton is the basic underbody or basic structure of a part. A skeleton model drives essential structures and basic wire frame geometry (macro parameters) of a design object with respect to its spatial arrangement and basic dimensions. In practice, these kinds of models are generally used for kinematics specification.

The skeleton model is based upon the hierarchical organization of the design, similarly to the adapter model. The difference is, however, that a skeleton model does not establish relations with the system environment. Instead, it defines the fundamental internal structure. These internal elements are usually not replaced by other elements. The internal structure of a skeleton model is not affected by system structures of the same arrangement. A skeleton model contains largely proportional geometric elements such as points, lines, curves, and planes. Surface elements are rarely part of the skeleton models. Design changes made when a skeleton model is used are parameter changes of the reference elements. Skeleton modeling is thus also an important foundation for functional modeling.

Mating model

A mating model is not a physical component of a product structure. The underlying concept is based on physically separate storage media (multi-model structure), but it is also suitable within the design structuring of a component. Figure 7-2 shows the general concept of a mating model using the example of a door.

The adapter part of the mating model is illustrated by the relation of the door to the outer skin design, among other things. Moreover, a simplified door outer skin can be designed and stored in the adapter model. The system of the door inner panel design is referenced with its environmental relation on this substitute design. Thus, a certain uncoupling of the design from styling can be achieved. Also, extensive shape fluctuations of the outer skin are compensated, which achieves flexibility and adaptability of the design at the same time.

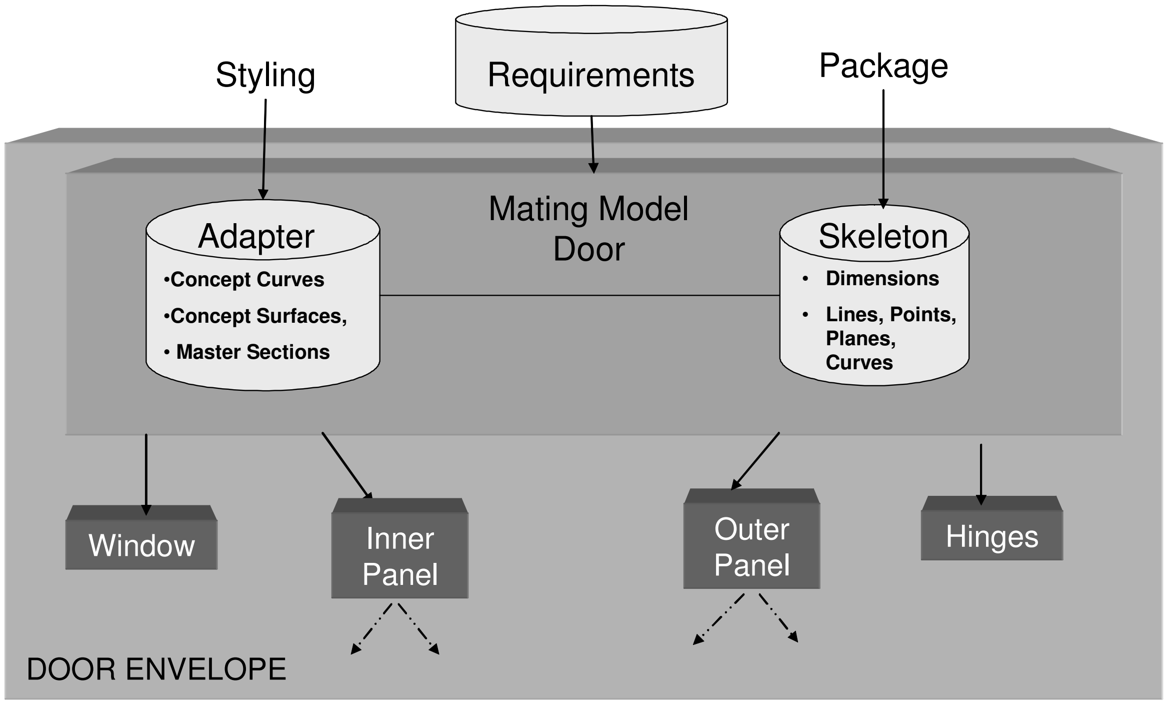


Figure 7-2: Principle of the mating model.

If design adaptations are to be carried out on changed or new styling, only the original outer skin surface needs to be replaced in the adapter. Furthermore, a design possesses an environmental relation to the vehicle package (e.g., concerning the size of the door opening), and this forms the skeleton part of the mating model. Adaptations here can only be made through parameter changes.

This design component affects other design systems such as hinges or door lining. That is, it stands in relation to other mating models.

Another descriptive example is the correlation of the wheel housing to a basic model of suspension geometry (figure 7-3). Here, the skeleton model serves both as kinematics model and as the underlying structure for component design, containing all the basic elements for the wheel suspension geometry such as position points, lines, and concept curves. All subsequent geometries contained in the adapter model are associatively specified with constraints to these concept elements. Any changes of the component take place via the recalculation of the referenced components, since the skeleton and adapter models are physically represented as separate models.

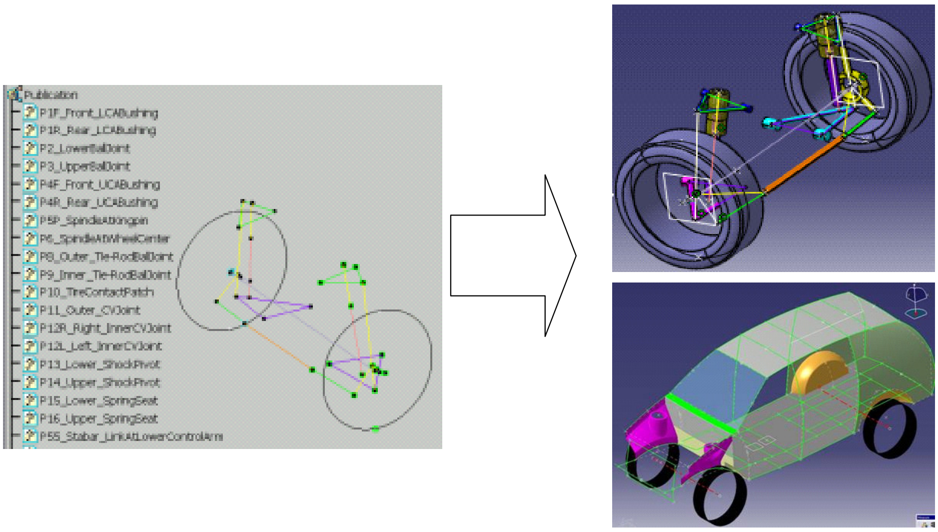


Figure 7-3: Example of a skeleton model left and, two adapter models (for kinematics and packaging study).

The description of geometric dependence and the integration of technological information, in the geometric shape of the product play a decisive role in body development based on advanced feature technology. o ensure this extension of the product description, parameters and relations are assigned to the features, and these are linked with knowledge processing. In the following, a brief example is given, using feature-based modeling of the car body side door.

Defaults for the design of the inner panel of a side door come from the styling department: the outer skin (class-A surface) and the surface of the window plane. The packaging concept, in which the external and internal dimensions of the car are fixed (e.g., the width of the door entry) come from the model type. With these, the design specifies the defaults for the position of the grasp lock. At the same time, this position specifies the width of the B-pillar. After this step, a change loop is developed with the styling department. Parallel to this procedure, the hinge positions are fixed. In accordance with applicable standards, a door opening angle of 60-70° is mandatory. This angle and the disassemblability of the door are tested, including the side panel and roof. The resulting reference surfaces are used as input for the design of the side wall and the roof frame. After renewed tuning with the styling department, the detailing of the interior and the design of the trim parts can begin. In this phase, several change loops are executed between the design department and the die process planning department.

The first step of design by features is the analysis of the component. Here, the model is divided into several levels or working planes. For example, one of the working planes or levels is the door module (containing all the electric parts and speakers). Another level may be the mirror module. Clearly the model is manipulated in an object-oriented way.

Each of these levels is the basis for a concrete description of body features such as the door lining, window cutout, and pocket for interior manipulation. This structure of the component is a key step when using feature technology to design models. Typically there are two options for the structure: object-oriented structure and function-oriented structure. In the object-oriented structure, all the reference geometries are grouped together, and input and output elements are defined. This is exactly the same procedure when defining features. Then these sub-models can be further defined as formation features and can be instantiated in other models as objects without loss of references. A door module, for example, has specific functional requirements: first, greater tightness of the door and, second, noise reduction in the interior of the vehicle. Hence, when modeling a door module as a formation feature, different seal systems can be utilized.

In the function-oriented structure, for example, all concept curves are grouped under one superordinate container (e.g., skeleton or adapter). This grouping can then be applied when trying to derive the geometry automatically from given requirements in the form of a skeleton structure. The modeling sequence is structured as follows: concept curves (skeleton model), concept surfaces (adapter), formation features or free-form sub-components (e.g., door module, window opening), and specification features (e.g. holes, bosses, beads, flanges). Figure 7-4 illustrates this procedure. As we employ intelligent features, feature interaction and consistencies are performed at any stage of the design. Due to the intelligence of the individual features, the whole door can be evaluated according to the desired view: design, trimming, flanging, analysis, concept, etc.

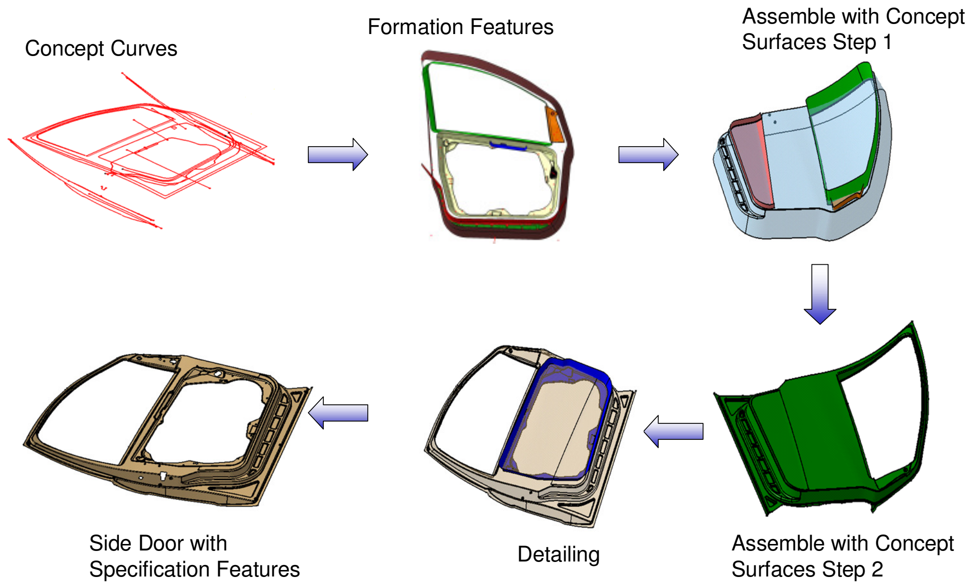


Figure 7-4: Intelligent feature-based design process of the side door.

To conclude, the availability of intelligent features and feature-based templates in product development constitutes the basis for an extensive and comprehensive improvement of the overall product creation process, and major advantages are realized. Initial surveys show that new development (not only design, but the entire development process) can be cut by 30% and that the subsequent product and process modifications can cut development time up to 70%, since the details do not have to be redesigned, but only re-referenced.

7.2 Feature-based styling: Integrating styling and design

The automotive industry is characterized by a strong emotional connection between the consumer and the product. In the market, we find that products are adjusting to one another as far as functionality is concerned and that quality has increased in the last ten years. As a key differentiation factor among products, however, aesthetic aspects still remain the fundamental criterion that influences the consumer's choice. Thus, the success of the automotive industry is closely coupled with the carmakers' ability to improve the efficiency of their styling processes.

The quality standards defined today and the high demands placed on the appearance of a vehicle have increased the degree of difficulty and the complexity of the automotive development process. In addition, frequent data exchanges within this process between styling, body-in-white design, and manufacturing are necessary because styling changes, for example, affect the exterior surfaces, which may necessitate reinforcement modifications. After each modification, the inner parts and styling must be brought in line. Today, topological structural changes in most cases involve still another completely new generation of the parametric model and the actualization of the parametrically developed body-in-white construction because changes of class-A surfaces are supported by only a few CAx systems. In this chapter, a methodology for parametric- and associative-driven design for class-A surfaces (exterior) is presented to support all the engineering functions for the translation of the styling model into the inner parts (body-in-white) and into manufacturing. In addition, it analyzes the working methods of the stylist in order to define the set of features that are meaningful for aesthetic design.

7.2.1 Problem description and objectives

With the support of state-of-the-art computer-aided systems, stylists today have gained more and more freedom to improve their creativity. However, the styling phase in the computer-aided process chain still remains a crucial issue. In the pure styling phase, these systems do not effectively support the rapid generation of shape variants based on a given template. A chief reason for this drawback is the fact that the concept of reusability has not been sufficiently implemented. Thus, before any final style decision can be made, expensive manual work is still required. The modeling activity is based on low-level geometric elements that do not preserve the stylist's intent [Fontana et al. 99]. In addition, these systems do not mesh with the way the stylist works [Bosinco et al. 98], since the modification of shapes is a pivotal aspect in the styling process. Slight changes such as accommodating local aesthetic styling requirements are often more time-consuming than recreating the entire model.

Furthermore, the translation of the styling model into the CAD model for further processing incurs a loss of crucial information and precious time. The underlying reason is a lack of formalized criteria for evaluating aesthetic shape properties. Moreover, we note that digital communication between aesthetics and design is poor. The result is an extremely time-consuming remodeling of existing information, which complicates any feedback for downstream processes. When attempting to bridge the gap between styling and design, we find that a key issue is modification due to the engineering constraints required to adjust the mechanical behavior of shapes in the styling phase. Figure 7-5 depicts an example of the closed relationship between styling, design, and manufacturing, which leads to many change processes.

Reducing the time and cost of developing new products is naturally a paramount concern in the industry. Support for all the engineering functions beginning with styling for the entirety of the product life-cycle calls for innovative solutions. Early stages objectives are accelerating aesthetic shape creation and enabling reuse of existing shapes through feature technology, which is now well-established in the body-in-white environment [Mbang 02]. Later stages involve shortening the loop consisting of surface modification and aesthetic requirements. A major challenge would be to design a surface area as a feature in order to determine all the aspect criteria such as the target evaluation line and additional constraints.

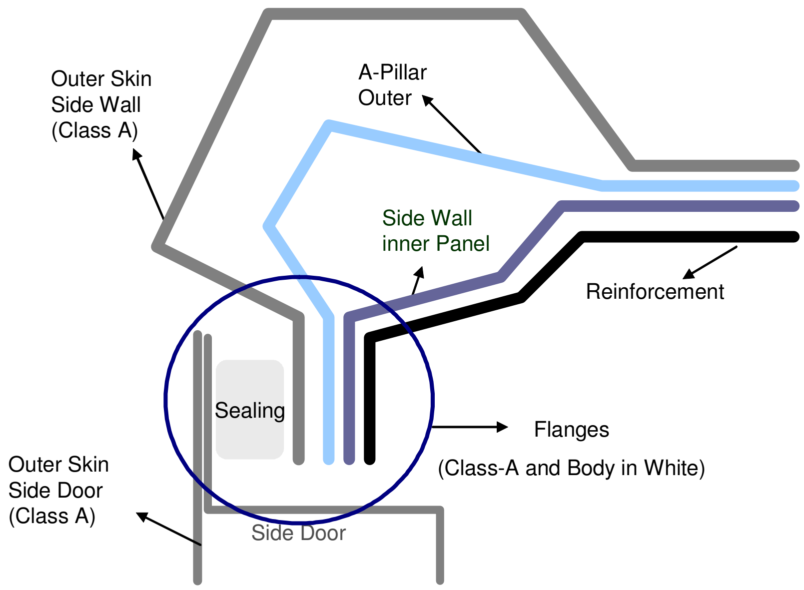


Figure 7-5: Profile section of an A-pillar: dependencies between styling, design, and manufacturing.

7.2.2 Improvement potentials

Stylists and designers work closely together within the process chain. While preserving the character intended by the stylist (stylist's intent), this model must achieve the high surface quality and function (design intent) intended for by the departments and process steps following this step. Reliable communication between all those involved is required in order to reduce the loss of information between CAS and CAD. This is a burning issue since the stylist's intent must be conveyed to other parties involved in the process. To achieve the goal of designing with stylist's intent, characteristic patterns -- parameterized objects that can be reused -- are employed. To accommodate the numerous conflicting requirements, it is necessary to represent several solution variants in sufficient detail. This presupposes the ability to parameterize possible variants. Furthermore, the structure of the solution must also be considered and will frequently be changed.

7.2.3 New approach: styling features

Today, some basic feature approaches have been implemented in most of the conventionally deployed CAS-CAD systems. Nevertheless, they do not promote the manipulation through parameters and attributes in the sense of feature modeling by inserting high-level and semantic styling objects

The encapsulation of model specifications at any level of complexity within a feature enables the design -- or in this case the stylist's intent -- to be captured and the methodology defined interactively. The benefit of encapsulation is the reusability across the parts and along the process chain. Such features contain not only the geometry but also any associated parameters and attributes or relations, including the embedded intelligence of the styling or design rules and check mechanisms, thereby providing the ability to store the specifications of intelligent features. Once created, a styling feature can be stored in a library to allow easy access and management for reuse. Hence, it is simpler to manage captured knowledge, adapt it to the changing requirements, and accommodate improved methodologies or specific requirements.

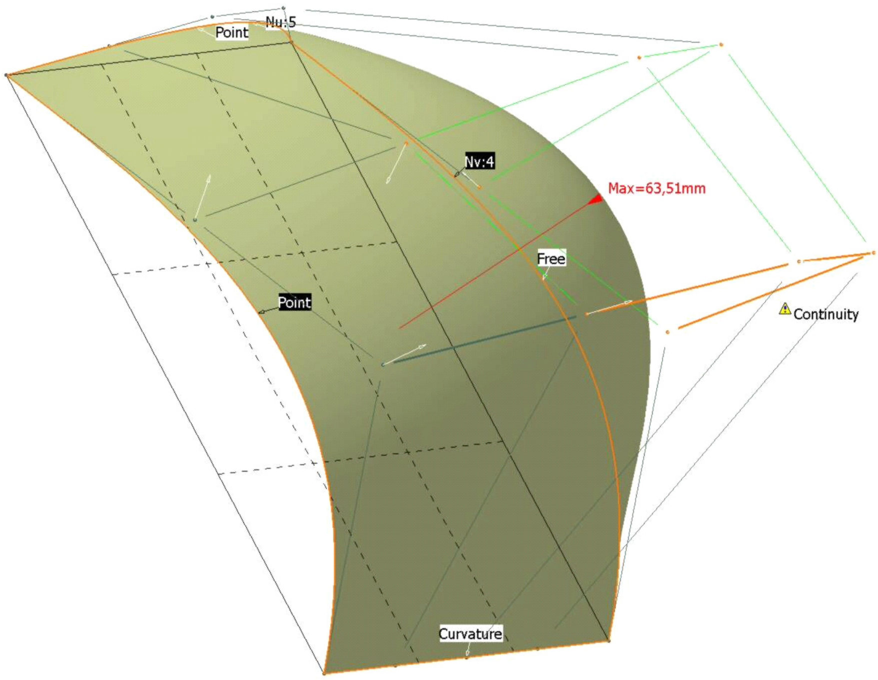


Figure 7-6: Manipulation of class-A surface using control points.

To define the set of features that are meaningful for aesthetic design, the working method of the stylist and the representation of the surface have to be taken into account. Curves and surfaces are typically employed for the representation of free-form visible surfaces on the basis of polynomial description. Thus, as illustrated in figure 7-6, surfaces can be manipulated and optimized interactively over the control polygon network with real-time analyses. Because of the large number of ratios, often badly formulated styling intentions, and rarely recurring styling surfaces, it is nearly impossible to parameterize this range of modeling meaningfully, though obviously the underlying mathematics provides essential parameters.

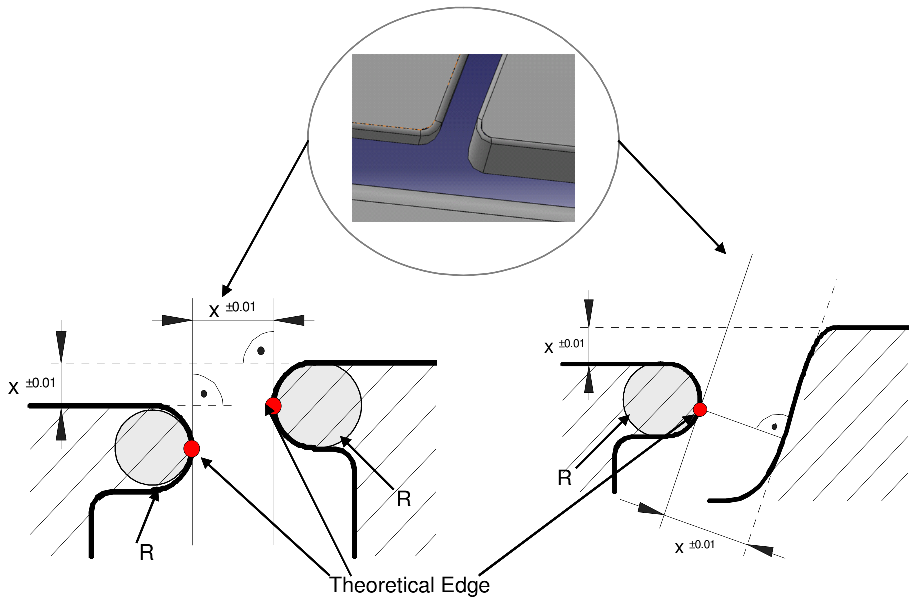


Figure 7-7: Example of gap specification to create a feature.

During style modeling, tape curves and the subsequent flanging give stylistic boundary conditions, such as character lines and component borders, and crimping processes are predominantly based on curves. Clearly formulated defaults such as gap mass or tool pulling directions make parameterization possible here, in particular, through joint optimization (figure 7-7). The application of parametric-associative models is not limited solely to detailing and change of descriptions of surfaces of the constructional outer skin. In styling, we can identify two major classes of features: those with purely aesthetic meaning (e.g., character lines) and those with both aesthetic and engineering meaning (e.g., flanges, gaps, and flushes).

The latter are pivotal since the designer utilizes these elements to design the inner panel. Thus, to achieve the continuous processing of information between styling and downstream processes, it is essential to manage the links between the two views. Figure 7-8 depicts the method of the adapter for linking and managing both the exterior and inner panels to support an automatic update when changes occur.

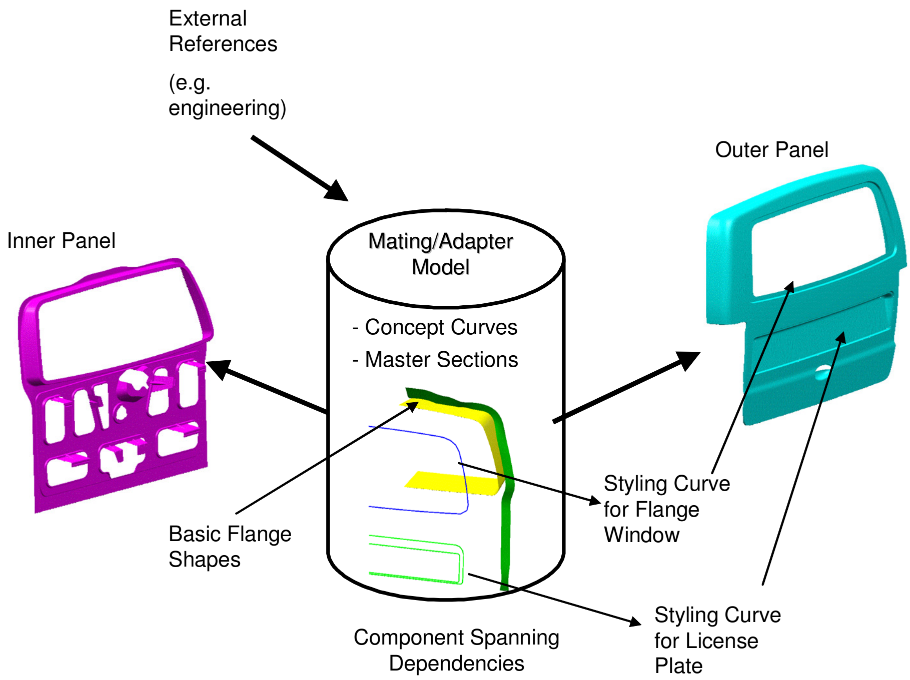


Figure 7-8: Adapter model containing formation features for associative linking of exterior and inner panel surfaces.

Formation features such as concept curves and basic flange surfaces are stored in the adapter model. In this way, we can perform changes either of the outer or the inner panel just by modifying one of the elements of the adapter model.

Figure 7-9 gives an example of two stylistic representations using the concept of adapter model. Typical depressions on the class-A elements such as the license plate or window flange can be provided as intelligent formation features. Typical parameters such as the gap width for the window can be changed simply and quickly. Similarly, inputs from the concept work are reconsidered by re-placing the old edge curves.

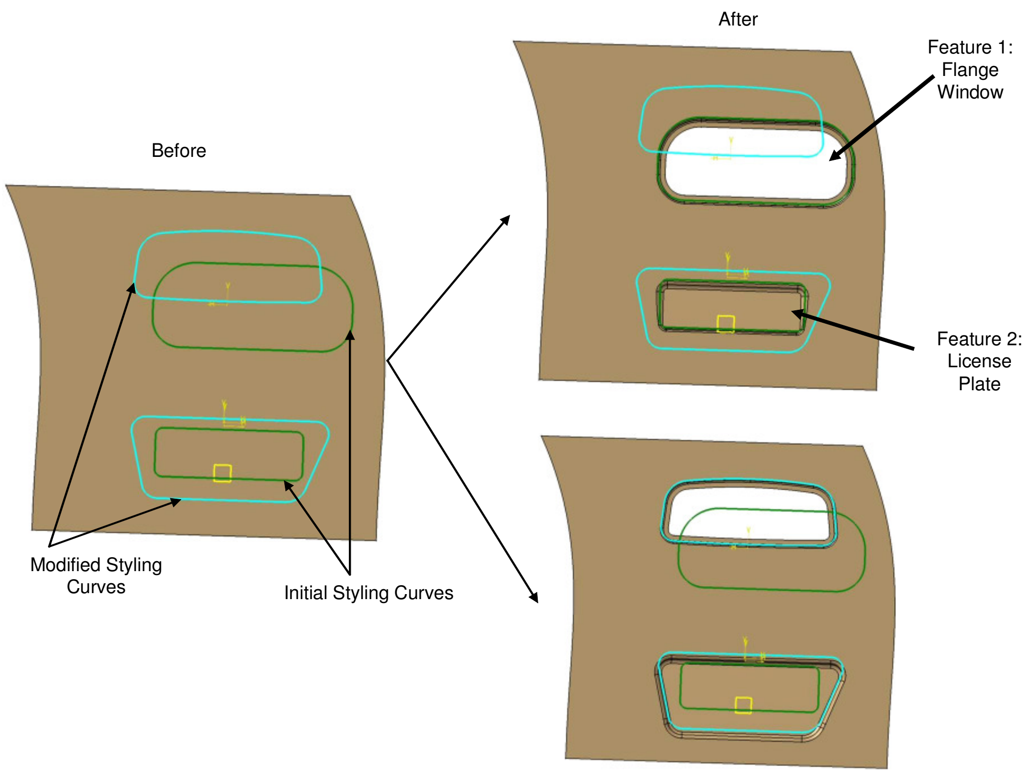


Figure 7-9: Two stylistic representations using styling features.

In general, the concepts of design and styling features are identical because of the set of geometrical and topological elements that define the shape and the appearance of the feature. In this area, we have to define a concept of objects whose functions correspond to both an aesthetic and engineering meaning.

The working method of the styling process examined above provides the basic understanding of the concept defining styling features. The initial step is to describe the visible surface by means of functions with respect to aesthetic aspects considering the relations between different parts. As a rule, inputs for component design are the surface profiles and the joint plan. The exterior and the joint or assembly plan define a component-spreading topology on the visible body-in-white.

After defining the overall structure, we now need to analyze the various classes of local shapes (free-form features) that can be recognized in complex shape products as an object. Such analyses allow us to single out the sets of geometric and topological elements that characterize a local shape over the overall surface and can be reused through a set of high-level parameters.

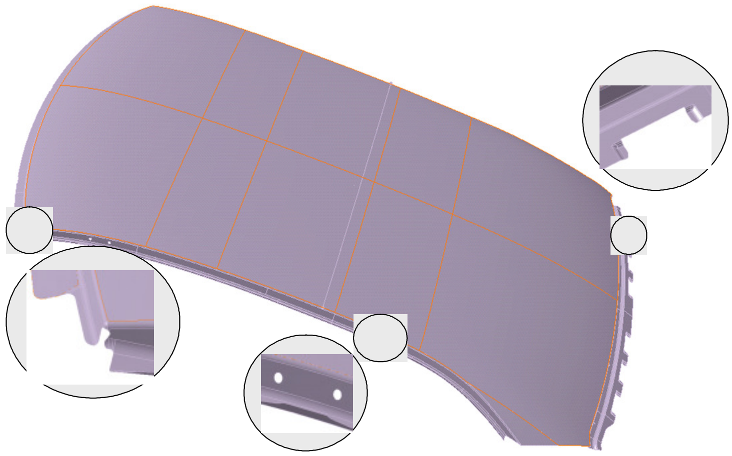


Figure 7-10: Description of a roof panel using functional objects with both aesthetic and manufacturing meaning.

Figure 7-10 shows some shape areas of the outer skin that can be defined as features with both aesthetic and functional behavior.

Certain CAD systems contain a first approach of parametric modules for this step. The evaluation of shapes depends either on the simultaneous solution of the dependence net or on the design based on history. Nevertheless, this new co-action between class-A surfaces and framework parts results in a simplification and acceleration of all design iterations. Thanks to a common feature backbone and additional benefits of enabling and supporting class-A modeling and design changes on the same geometry, much of the intensive diligence work can be transferred to the change process via the feature processor. It is now possible to realize several design alternatives and to select the best solution.

7.2.4 Benefits and outlook

Substantial savings of time during the styling process can be achieved through the use of parametric-associative surface models. Fully parametrically functioning systems are suitable for these applications; however, the parameterization depth remains limited. Yet, there is a definite need in the automotive industry to improve flexibility, reliability, and usability of parametric systems related to class-A surfaces, which also drives the need to improve the efficiency of computer-aided technology.

Using intelligent features, a new workflow in the production process of complex-shaped objects will avoid expensive optimization loops and enhance aesthetics in the final functional product. New functionality for aesthetic design will promote the efficiency of styling departments, thereby cutting development time while maintaining quality.

7.3 The CAD/CAQ process chain: Integrating design, inspection, and quality assurance

This section discusses the automation of the CAD/CAQ process based on intelligent features, starting with the instantiation of a design feature and moving through the automatic mapping of a suitable measuring strategy as a function of geometrical parameters.

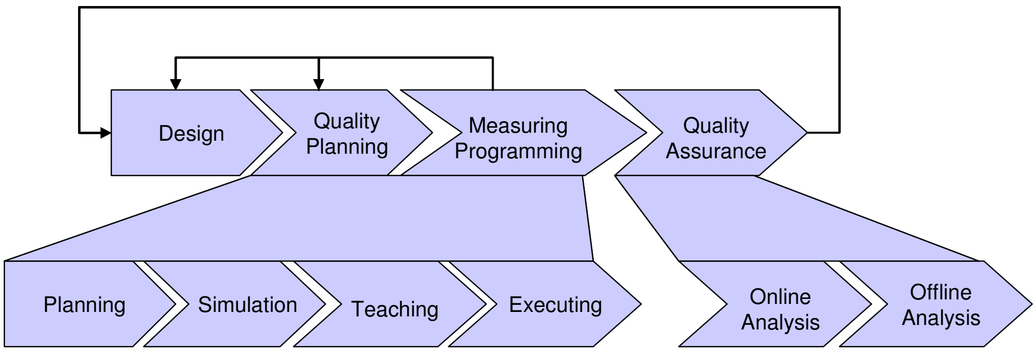


Figure 7-11: The CAD/CAQ process chain within car body development.

7.3.1 Definition of terms

According to the definition of a process chain by Storr [Storr 99], the CAD-CAQ process chain (figure 7-11) designates the linkage of technical information flow in computer-aided design (CAD) and computer-aided quality assurance (CAQ). In this sense, the term *CAD/CAQ process chain* is defined as the technical information flow between design, inspection planning, measurement planning, and measuring programming [Haasis et al. 00a].

Definition 7.1: *According to [DIN 55350], quality assurance defines all the activities belonging to quality management -- i.e., quality specification, quality inspection, and quality control.*

The objective of conventional quality inspection is to ensure perfect product quality through planned quality inspections during or immediately after product emergence [Pfeifer 98]. This includes quality inspection aspects such as inspection planning, inspection data collection, and inspection data analysis.

***Definition 7.2**: Inspection planning is defined [DIN 55350] as the planning of quality inspection. Relevant subtasks associated with inspection planning such as the inspection scheme and the programming of measuring instruments are described.*

In general, the inspection task is divided into three activities that can be accomplished sequentially: inspection planning, measuring planning, and measuring programming -- with measuring planning more closely explained as the technological detailed planning of the inspection execution. The subtasks of inspection planning, measuring planning, and measuring programming as done today are illustrated in figure 7-12 [Ciesla 97].

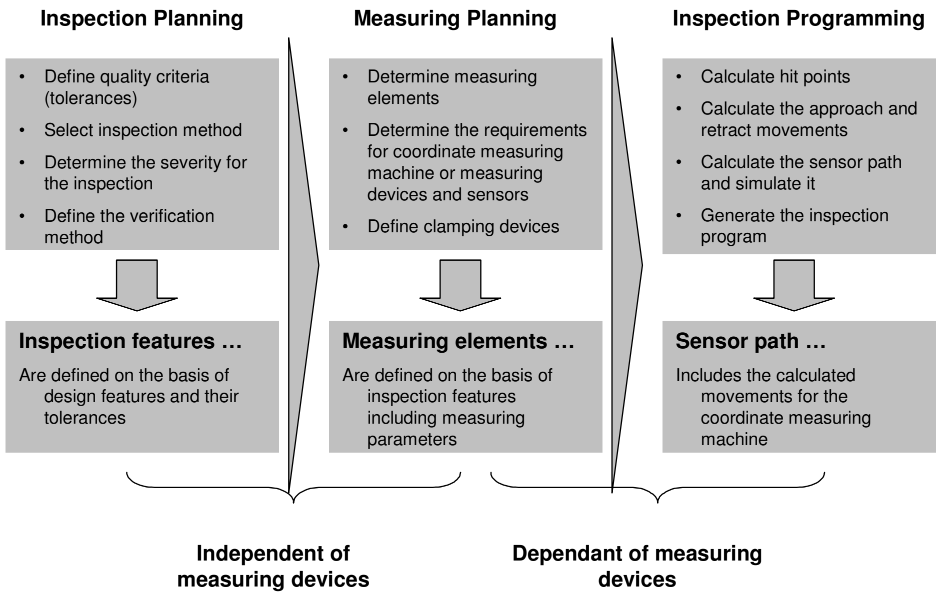


Figure 7-12: User's inspection activities divided into subtasks.

The subtasks of measuring programming and measuring planning are accomplished in measuring programming systems and inspection planning systems. Alternatively, CAD systems may even be used for inspection planning.

7.3.2 The state of the art of the information flow in current CAD/CAQ process chains

Currently, the CAD/CAQ process chain is realized through many systems. These individual systems provide extensive functionality in order to digitally link product modeling, process design, and resource planning. However, the exchange of information in these systems is unsatisfactory. Important topological information at the direct interfaces is lost and needs to be reconstructed. Also, when importing a CAD model into a measuring programming system, no information about the geometric feature parameters and the tolerances are transported.

The bottleneck of the CAD/CAQ process chain is the interface between the CAD description and the measuring program. This applies, in particular, to the representation and transmission of features and tolerances. In principle, the following interfaces are available today: DMIS version 4.0 [DMIS4.0 00], STEP AP219 (Standard for the Exchange of Product Model Data), and proprietary enterprise-specific formats.

After a thorough analysis of the state of the art, the writer concluded that the application of features is not consistent throughout the CAD/CAQ process chain: tolerances, for example, are not imported into a measuring programming system. Only very simple feature types such as holes can be visualized in a measuring programming system, and the complex measurement strategies in standard measuring programming systems cannot be automated using standard routines.

Features in DMIS have been compared with the measuring elements developed at Daimler-Chrysler. Key characteristics for the description of car body -- e.g., material thickness and material direction as well as assembly stages -- are missing in DMIS. In addition, complex feature types, such as joining points, flanges, and gaps, are not recordable in DMIS 4.0.

The feature concept in STEP AP219 corresponds to the feature concept of DMIS 4.0. Both interfaces only partly fulfill the requirements needed for an integrated CAD/CAQ process chain in car body production. Much effort is aimed at designing an integrated process to achieve automation effectively. However, today:

- The measuring program must still be prepared manually on the basis of the feature information imported.
- The quality criteria (i.e. tolerance information) cannot be transferred over the available interface to a measuring programming system. Manual registration in the measuring program is still required. Thus, the danger of incorrect data due to manual input exists.

Hence, there is a demand for an extended intelligent feature interface. The following section suggests solutions to extend legacy DMIS 4.0 and STEP AP219 interfaces.

7.3.3 Concept for feature-based automation of the inspection process

The objective in this section is the realization of a continuous information flow for the CAD/CAQ process chain and the development of methods for the automatic generation of measuring programs. Figure 7-13 illustrates the dependencies of the three domains -- design, planning and programming.

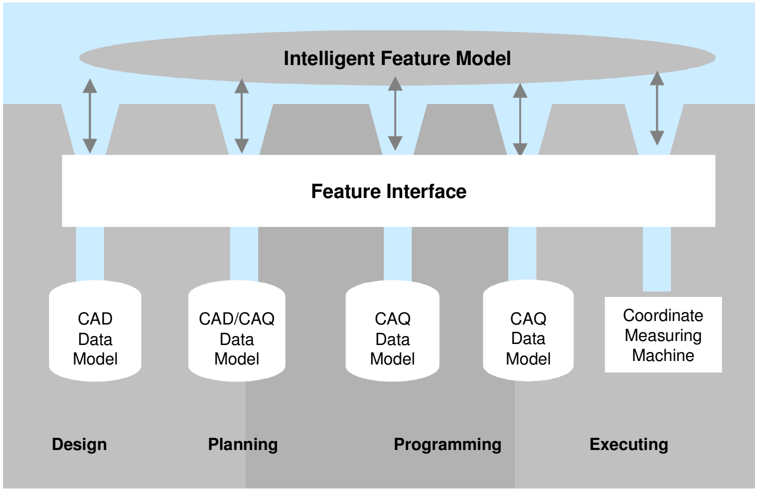


Figure 7-13: Features as an information backbone in the CAD/CAQ process chain.

The following subtasks are identified:

- Development of a method for the direct illustration of the features and tolerances in a DMIS program.
- Development of methods for applying measurement strategies by decomposing feature content.
- Specification for the external administration of inspection rules for different measuring programming systems.

The analysis of information and data models shows that, due to relevant inspection characteristics of intelligent features within the range of the body measuring techniques, none of the past models sufficiently meets the requirements of a continuous CAD/CAQ process chain.

To fulfill the demands for an integrated measuring planning and measuring programming system in the specific process chain based on advanced feature technology, the author developed an abstract object-oriented information model (figure 7-14) as a specific view of the overall PPR model in chapter 6 (see figure 6-23). This is an abstract object-oriented inspection model with a class structure founded on the internal class structure of measurement systems that support most of feature types for inspection defined in the CAD system. This not only allows a uniform notation for the illustration of model contents, it also ensures the further usage of the model for later implementation. Due to the widespread deployment of XML and the large offering of software tools, the data storage can be realized through files that meet the XML specification. This format enables the exchange of feature information among many systems. In an integrated system, this information is directly derived from the intelligent feature via decomposition.

The features can be directly selected to integrate these domains or an interface (XML or ASCII list) in the case of a heterogeneous system landscape. An ASCII list [Karthe 01] is a simple and pragmatic way to describe a continuous CAD/CAQ process chain in a heterogeneous landscape. It links feature information from CAD to the measuring programming system bi-directionally. The parameter values for the features are stored as associated ASCII text with commas as line separators (actually, this is a comma-separated values format that is importable as columns in Excel) or as XML. The format can be suitably and simply read by different measuring programming systems (e.g., Delmia, Silma, Holos, Faro). The geometric parameters are defined based on the DMIS standard. In relation to DMIS version 4.0 and STEP AP219, the car body-specific feature characteristics and the quality criteria can both be illustrated in this way. Moreover, a special nomenclature is used, allowing a feature to be unambiguously tracked throughout the CAD/CAQ process chain. The relevant measuring feature information (e.g., coordinates of the center, normal direction, and thickness) and the tolerances, which represent the inspection view of the feature, are mapped from CAD to the measuring system over this ASCII interface.

Figure 7-14 provides an overview of the class diagram of the inspect feature list, as it is employed today. Because of the similar structure of the inspection features defined, an abstract upper class *Inspection Feature* was introduced and the objects of these inspection features are then derived by reference. The automation of the CAD/CAQ process chain is achieved in this case through feature mapping. As explained earlier, the term feature mapping denotes the transition and/or the transformation between the different feature classes. For this purpose, the user defines the so-called mapping rules, tables, or databases.

With this concept, there is a duplication of geometry, as these elements can easily be designed in a CAD system. The problem is that many measuring systems cannot read high semantic feature information directly from a CAD system. Therefore, a reconstruction of specific elements (inspection view) is needed.

Now, with the concept of intelligent features, all inspection-related geometric elements are integrated directly into the corresponding intelligent design features, thus avoiding additional feature mapping as it was used in the past to link design and inspection features.

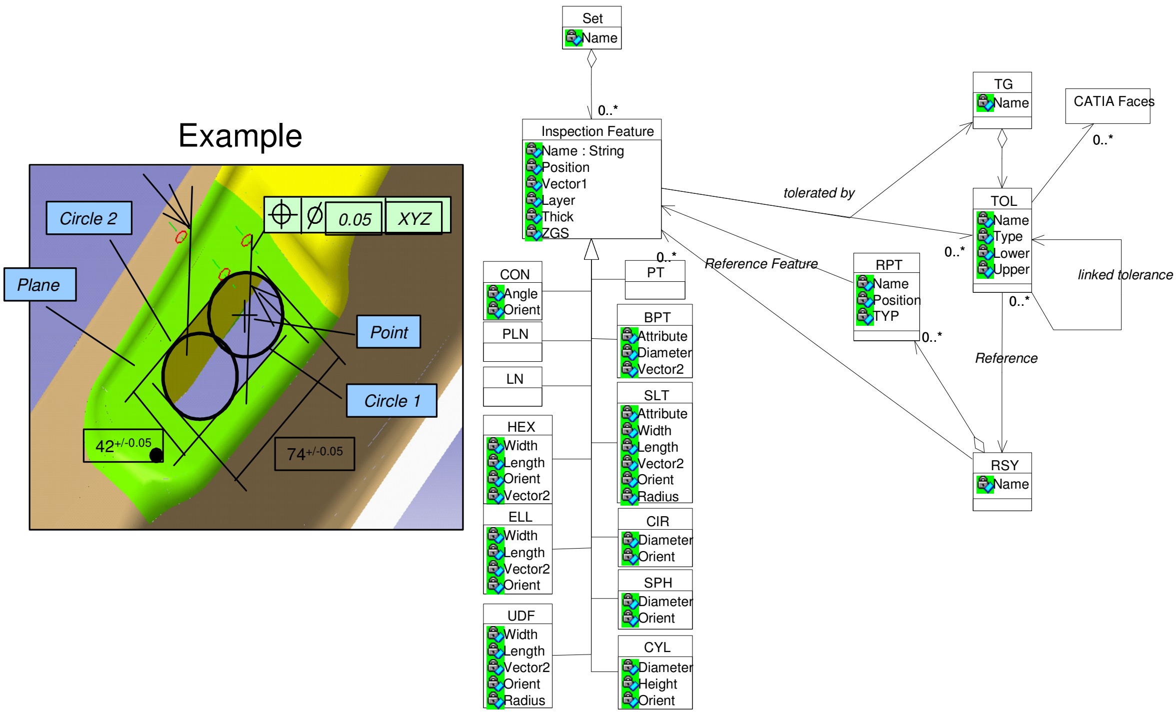


Figure 7-14: Class diagram of the inspection feature list.

This new concept that embeds both the design and inspection views represents the main aspects of the overall integrated inspection model. To enable a complete description of an inspection task, data concerning the settings in which the intelligent design feature is to be inspected are added as well as a definition of the order in which individual aspects of the geometry are to be inspected.

The rules for feature decomposition, an activity which also includes the know-how and/or experience of the user with respect to the measuring task, are summarized in a measuring strategy. The description and realization (automatic generation) of such measuring strategies is an important aspect of this concept.

Figure 7-15 portrays the different steps by automating the inspection task of an intelligent feature. The term *inspection feature* is now related directly to the inspection process template, which describes a complete inspection task. It embeds different measuring strategy for an intelligent feature. To automate the process, an inspection model is introduced (Figure 7-16): it contains feature-spreading information for the inspection process.

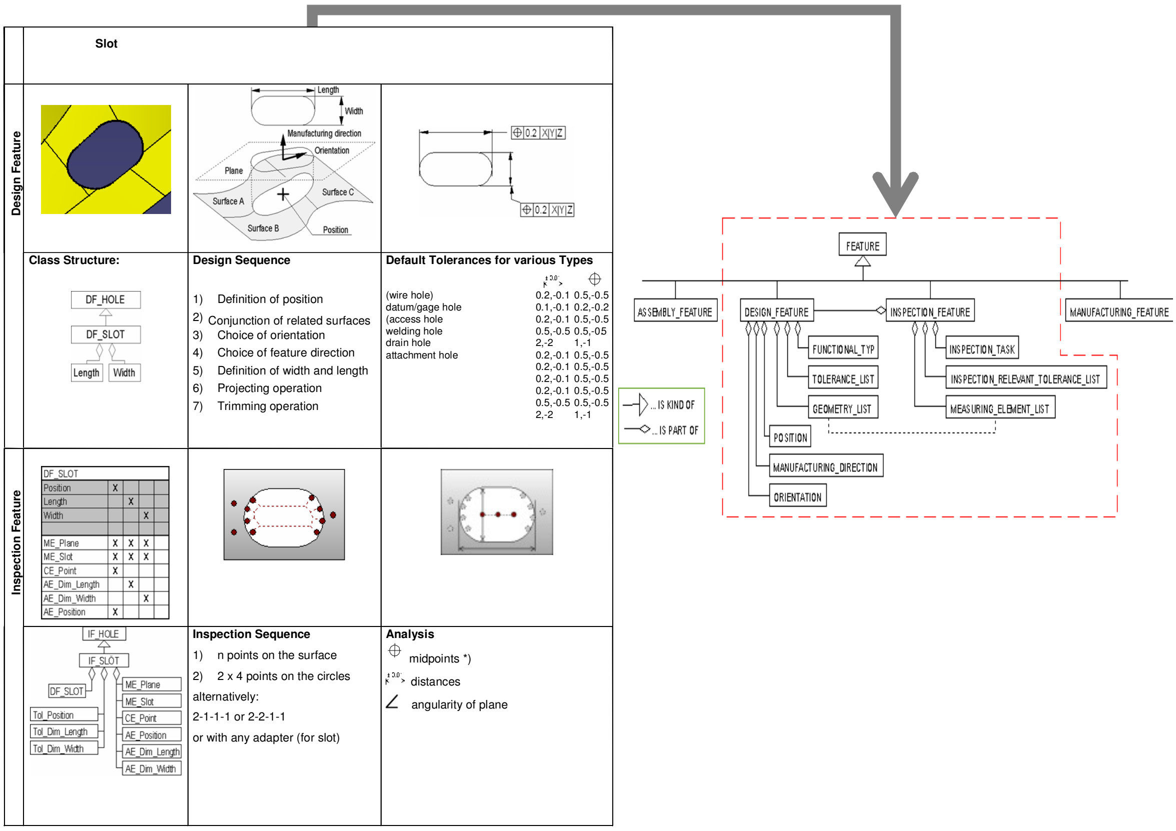


Figure 7-15: Feature decomposition rules for an inspection view of an intelligent feature.

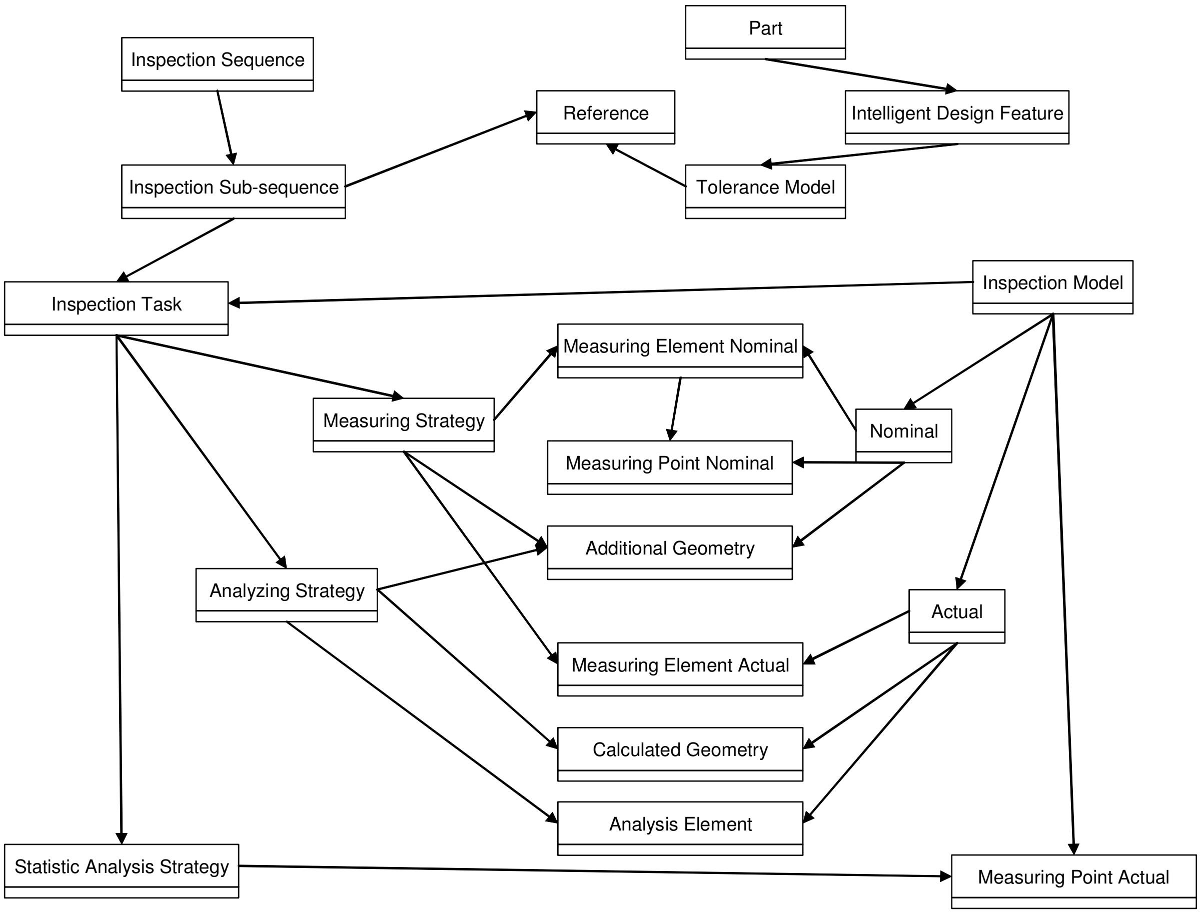


Figure 7-16: The integrated feature-based inspection model (IFIM).

7.3.4 Processing of measurement strategies

For the automatic generation of a measuring strategy for the individual intelligent features, the standard routines offered in the measuring programming systems are simply not sufficient. The chief aim is to derive suitable measuring methods in CAD underpinned by feature information. Depending on the system-oriented condition and as a function of the specific application field, two different approaches for the derivation of the measuring method are conceivable:

- Measuring method in an integrated CAD/CAM system
- Measuring method in a distributed system

Figure 7-17 illustrates this systematic approach, which finds application both in an integrated and in distributed environments.

This concept describes the measuring strategies externally on a neutral level, allowing design features to be inspected in a wide range of measuring systems. Yet, three elements are essential:

- A suitable specification language which fulfills the following requirements:

- a universal, higher object-oriented programming language which can easily be extended by measuring specific objects, and procedures.

- User friendly methods or functions (e.g., to define and select tracer positions, define CMM parameters, create and transform coordinate systems, and define measuring sequences and tolerances).
- A suitable feature interface to the CAD system and to the different measuring programming systems (e.g., Delmia-inspect, Silma, Holos, Faro).

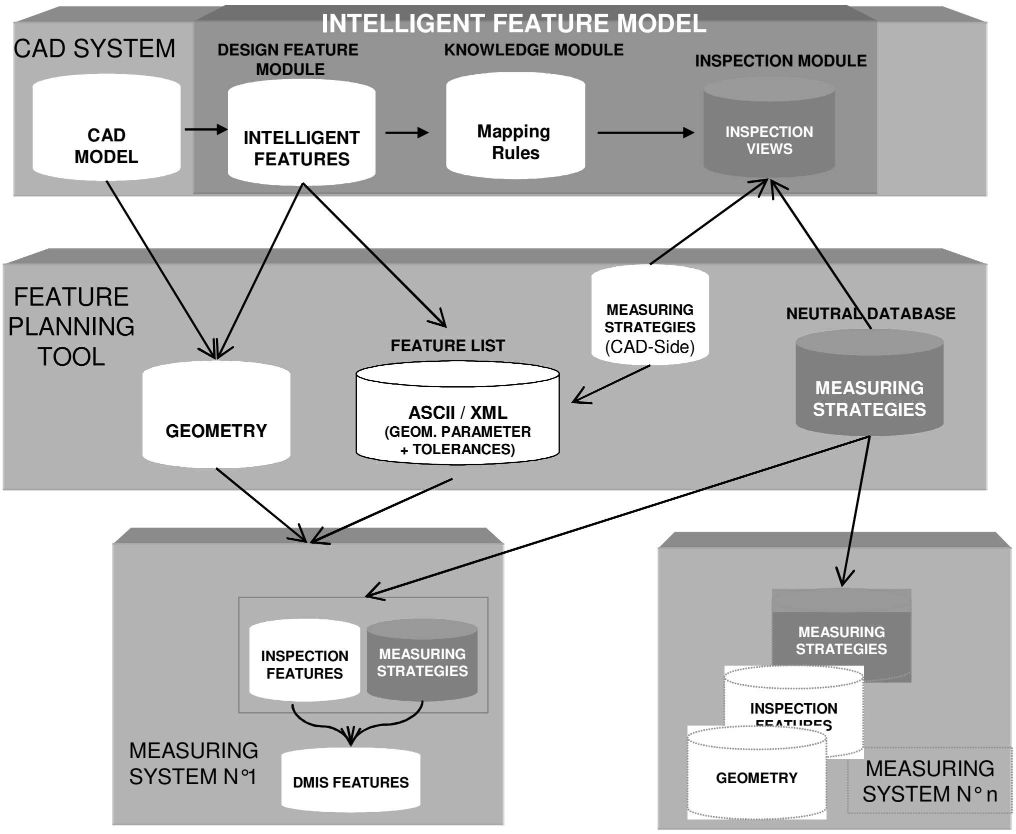


Figure 7-17: Concept for an external management of measurement strategies.

7.3.5 Application scenario

In the following, a short example is given to illustrate the new inspection process as proposed in this work. The starting point is the generation of design features in a CAD system. In this step, no inspection features are defined, solely references (middle point, punch direction, plane, etc.) which characterize the key elements for the inspect view, in addition to the main result of the feature itself. When using a single integrated system, the design feature is completed by necessary rules describing different measurement strategies contingent on the parameters (e.g., diameter, width). This is realized through the developed measuring planning tool and a knowledge module, which enables measuring strategies using the options of storing and describing intelligence and the management of these measuring strategies occurs via rules.

Figure 7-18 depicts a typical measurement strategy. Different measurement strategies as a function of the rule can be applied, depending on the change in the parameter specification of the radius of the hole.

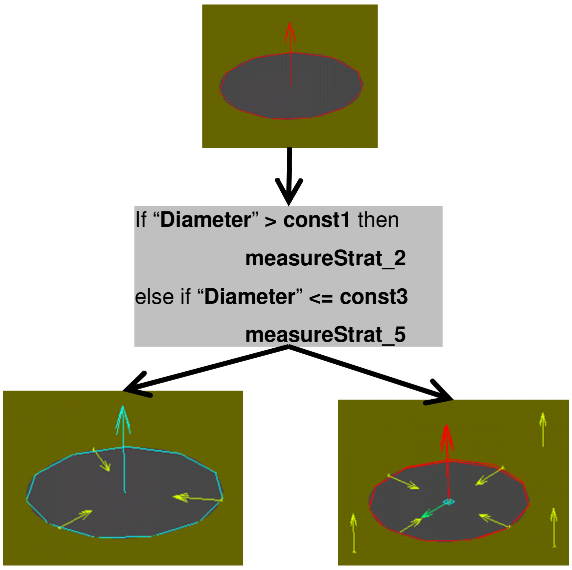


Figure 7-18: Example measurement strategy.

Figure 7-19 sketches the automation process of an integrated CAD/CAQ process chain. This concept contains the following indexing steps and/or requirements for integrated inspection planning and execution:

- Selection of the design feature that is to be examined; this leads to the definition of inspection view (decomposition).
- Definition of the quality criteria that are relevant for the examination of the functionality of the design feature and selection of a suitable evaluation method.
- Determination of the measuring elements that are to be measured for the examination of a particular inspection criterion.
- Selection of the measuring instruments (both CMM and sensors) to be employed for measuring a specific measuring element.
- Determination of the points of contact and the sensor path.
- Simulation and adjustment of the resulting measuring program.

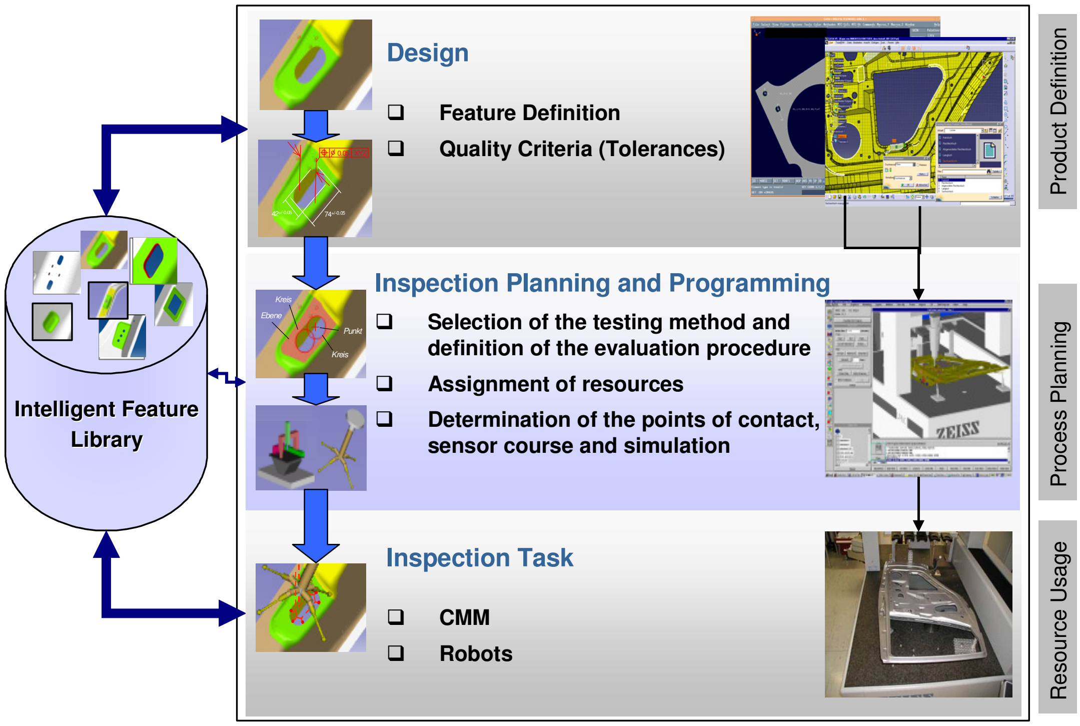


Figure 7-19: Integrated feature-based CAD/CAQ process chain.

7.3.6 Conclusion and benefits

This section has described an approach for a CAD/CAQ process chain based on intelligent features. Different information can be semi-automatically linked along the process chain: for example, between design and inspection planning.

The innovative method founded on intelligent features applied for the automation of the CA/-CAQ process chain yields substantial benefits: the storing and repeated instantiation of the design logic, including constraints and relations between the parameters, through a knowledge module. This leads to time optimization. The publication of parameters and appropriate geometric elements provides key information for downstream processes -- e.g., measuring planning and programming. This supports both the continuity of the CAD/CAQ process chain and change management

The extension of design features and the integrated feature-based inspection process model developed enable the automation of measuring planning and measuring programming. Thus, optimization of measuring programming time can be accelerated by up to 60%. Two further aspects are to be considered:

- Storage of process knowledge and experience in the form of enterprise-specific measurement strategies.
- Standardization of measuring processes through a neutral platform for the description and administration of the measuring strategies.

7.4 The stamping die manufacturing process

Shortening lead-time puts a great pressure on the developers of stamping dies and tools. The result is that both the die designer and die process method planner cannot wait until the surfaces from product design are completed before trying out their own die concepts.

It is a fact that the development of draw and stamping dies calls for a high measure of expertise and know-how. In the product creation process, there are a great number of conflicting requirements between the best design on the one hand and production on the other. While general engineering knowledge may suffice when designing components and panels for shallow presswork, deep drawing requires a much deeper understanding of the production process if costly mistakes are to be avoided. It is essential for the design intent to anticipate the problems posed by both the toolmaker and press worker before new shapes are released for sheet metal working.

The use of concurrent engineering in product and process development results in high planning maturity, so that, apart from costs, both quality and cycle times are optimized during tool development and preparation. The manufacturing concept and vehicle development are carried out in parallel while the launch phase is prepared and secured.

A key task in the development of a vehicle is therefore to clarify the manufacturing of the body parts in the earlier phase. In this sense, the definition of the manufacturing methods and the process operations are closely aligned with the production of the body parts in the press shop.

This section discusses a first approach toward linking product modeling and die modeling on the basis of intelligent feature technology and solution pattern. It then addresses how feature-based modeling is utilized for defining common features linked in the product and die geometry models. This concept thus integrates both the product design and manufacturing views.

7.4.1 The process chain for draw and die face design and tool production

The process chain of tool and die manufacturing represents the link between the main product development and line production (figure 7-20). This process chain involves the designer's collaboration in the sense that the die designer has to deduce the part to be constructed from the component part. In parallel with the development of a car door panel, for example, a tool or die needs to be specified, developed, and produced. This parallel process then undergoes multiple phases and various design modifications until the tool or die is produced.

After the initial product idea, various steps are carried out in sequence -- styling definition, body design, the building of prototypes, the definition of the manufacturing method, tool engineering, and production. Frequently, the forming simulation is only employed during die process planning. If the fact that manufacturing of a component will incur difficulty is not recognized before this point, then the alternatives for optimization are, to a great extent, limited. It is therefore much more efficient to influence the result through an early examination of the manufacturing of the body design (design for manufacturing). The goal here is to detect technical and design characteristic problems in upstream processes and to implement problem management if need be. In addition, this will ensure that, with the final release of product design, its manufacturing will be trouble-free. Thus, complex optimization loops can be clearly cut back during the tool trials.

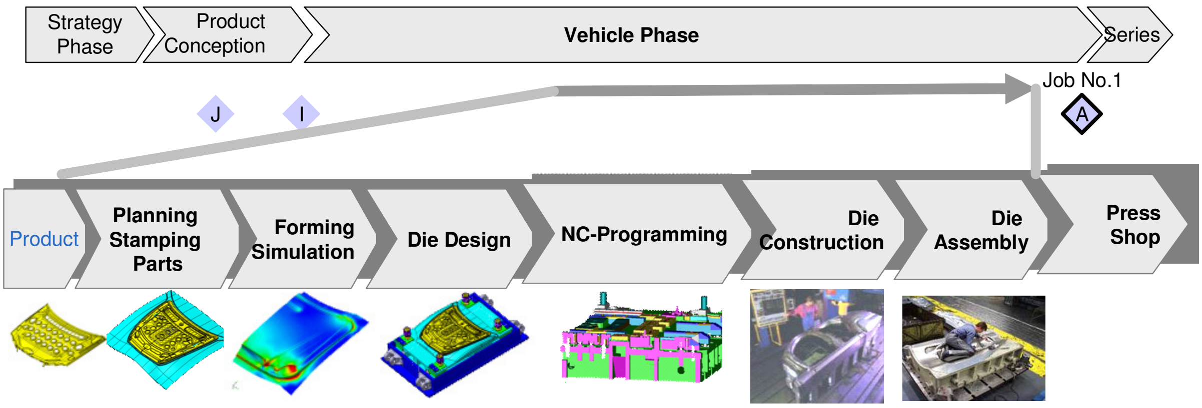


Figure 7-20: The stamping die manufacturing process chain.

Design changes needed after the final design -- typically due to the particular requirements of manufacturing or other processes -- add to both the time and cost of the overall product development. The philosophy of concurrent engineering counters this: concurrent engineering strives to integrate the different functions affected by product design decisions. This necessitates better communication of information between the different disciplines, also requiring CAD systems to capture all the aspects of information in the design such as intent, material, form, tolerances, and manufacturing processes. To improve die face and die structure design by reducing tooling lead-time, specific methods which allow a rapid derivation and associative of die faces are required. A promising candidate is feature technology, which shows high potential to replace the traditional engineering life-cycle, which is a sequential process where the decisions for engineering analysis, manufacturing systems, process planning, and production occur only after product design is nearly complete. This drawback lies chiefly in the fact that the design process does not provide "end-to-end information-technological support and linkage of product life-cycle phases into process chains" [Mbang et al. 02b].

In this context, an approach for a holistic stamping die manufacturing process chain based on intelligent features and solution patterns is sketched in this section. A corresponding intelligent feature library for product design, which considers the design-for-manufacture strategy, has been developed (see also chapter 6). Due to many of the requirements listed above, the usage of these intelligent or adaptive features allows us to describe the associativity between components, die geometry, and die structure and to manage modification changes in both directions concurrently. This enables early simulation for optimization.

7.4.2 Stamping die design process based on feature technology

The stamping die process typically consists of four main phases: manufacturing method planning (or stamping process planning), die face design, die structure design, and die manufacturing

In ***manufacturing method planning or stamping process planning***, rough process planning for developing a product is defined. The method and manufacturing concept begins with the first data available on a component. In this phase, the specific manufacturing operations are planned and the number of process steps in a press line and specifications for each die are determined: forming and cutting processes and their allocation to individual tools as well as possible manufacture of multiple parts are determined in the method concept. At this stage, a complete 3-D model is needed for each step in the method concept in order to simulate the forming process. However, subsequent die operations (cutting die, flanging, etc.) are only roughly planned. The results of this phase are utilized in die face design and in cost estimation.

Generally it is the method planner's task to assure the technical feasibility of a component and to specify the sequence of operations for the later manufacturing process. For this reason, manufacturing, quality, and cost goals are pursued with the following subordinate aspects in mind:

- Error-free geometry with a process window as broad as possible. Slight disturbances or deviations from the adjusted process parameters at the production plant may not affect the process result at all or only slightly.
- Fulfillment of the quality specifications such as adherence to the target geometry and the prevention of sink marks in addition to basic requirements such as cracks and free creases.
- Harmonization of the operational sequence in the production plant -- e.g., press line with simple or double-acting drawing press or multi-tappet transfer line. Important boundary conditions must be considered: for example, the number of process stages, whether the component position is to be changed or remain unchanged from process stage to process stage.
- Decrease in manufacturing costs through a reduced use of the material by the output plate and also through low tooling costs -- i.e., simple tools and minimized numbers of steps.

All these objectives are affected by the stamping die geometry. Basic data for the interpretation of drawing (stamping die) geometry and the operational sequence are the completed component geometry with the materials which are to be processed and with the relevant quality specifications.

7.4.3 Die face design

Forming of large auto parts typically involves a combination of stretch-forming and deep-drawing. To define producible car body parts for the deep-drawing process, the product shape geometry is supplemented by addendum shapes and a blank holder surface as portrayed in figure 7-21. The component must be supplemented in such a way that a drawable geometry can be realized.

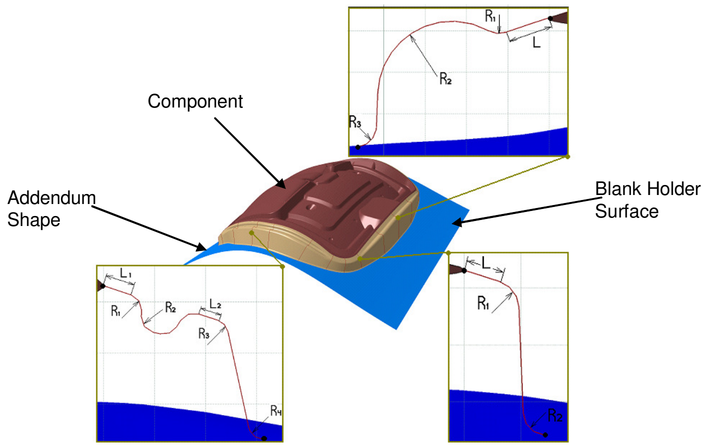


Figure 7-21: Stamping die face.

Addendum shape

The addendum shape is defined around the product shape. It should follow the characteristics of the product shape as smoothly as possible and be completable-- i.e., when the die face is closed, no folds may develop. Traditionally, one point is set interactively on the edge of the developed geometry and on the blank holder surface. Both points are connected by a curve. Using an addendum feature ensures that the resulting curve is a smooth curve on the blank holder surface.

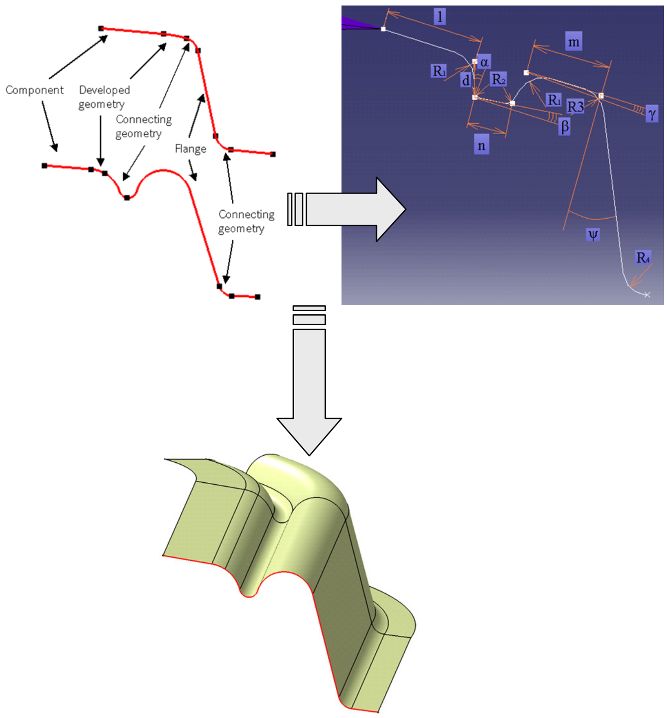


Figure 7-22: Specification of addendum features (profiles and shapes).

As this process is repeated very often, the usage of feature technology is an efficient way to avoid this routine work. Thus, an addendum feature calls for just one point on the edge curve of the developed component geometry or alternatively, depending on the type, additionally the punch opening profile. All these input points can be individually moved on the die face interactively; the edge curve is automatically carried. A result is either an addendum profile or an addendum surface composed of a defined number of profiles specified by the user. Each addendum profile also has connecting points as output. They can be used to define tangency conditions for the addendum shape. Figure 7-22 shows a specification of some addendum features.

7.4.4 Die structure design

Die structure design is divided into two phases: the conceptual design phase and the detailed design phase. Each phase has its own check items and approval conditions. Although die face design is usually performed by a single engineer, die structure design is effected by two or more engineers working simultaneously. Figure 7-23 an example of a die structure.

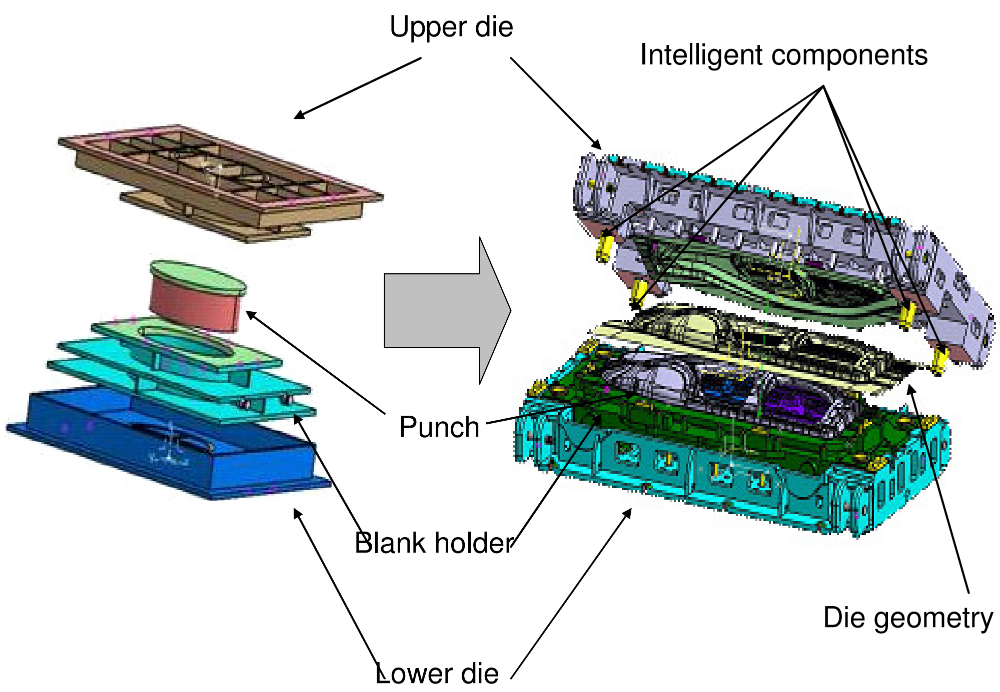


Figure 7-23: A complex draw die for the side wall (left) and its generic representation as template (right).

In this area, the die designer is doing at least the same degree of difficulty. The die is a complex product that should achieve request resulting from die manufacturing, die assembly, and press line issues. Kinematics and analysis are other important requirements as well. Additionally, the inputs for the die designer are the component from the product design and the die geometry -- i.e., the extension surfaces and curves of the component as well as the trim and flange lines. Therefore, the concept of intelligent features and feature-based templates is very useful here, as it is in product design.

Typically, to produce a part, engineers need many die operations (OP20 for draw die, OP30, OP40, and OP50 for cutting and flanging dies), in a die set. Each operation requires a die structure. Moreover, each set of dies is inside a press line.

Here, a generic description of a die acts as a feature-bases template or solution pattern. This template is detailed according to the function to be accomplished: trim, flange, pierce, etc. For each of these functions, a dedicated template is available. In this way, all the die structure is described by means of functional areas, a kind of modular construction system, as it is broken down.

Thanks to this systematization, the same template is used for different parts (fender, hoods, side panels, etc.) and is also reused over many car projects. Additionally, the die designer can now design by function, since he has all necessary intelligent features accessed through a library.

, Die and tool related intelligent features have the same behavior as features from product development, -- i.e., adaptivity according to the underlying environment. Here, they are divided into intelligent components (assemblies, for example, guiding units, sliders, etc.) and intelligent casting features (for example, hooks, and ribs).

Figure 7-24 below describes the adaptive behavior of such an intelligent component. As it is inserted in the tool assembly, the different parts are distributed automatically to their respective subassembly. This is done by association and naming convention.

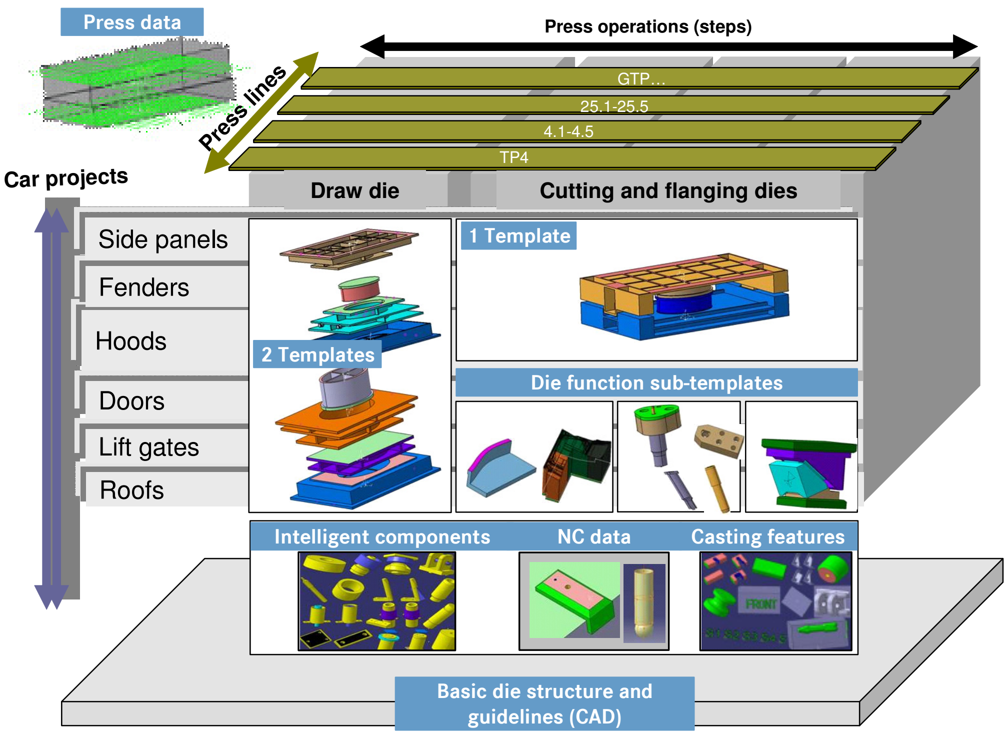


Figure 7-24: Systematization of dies and tools for the automotive industry by means of templates.

In addition, an intelligent component, as shown in figure 7-25, contains not only the shape of the component itself but also geometric elements representing some material to be added or removed (herafter called “Add/Remove geometries”): they have important downstream machining information such as milling area, drilling holes, etc.

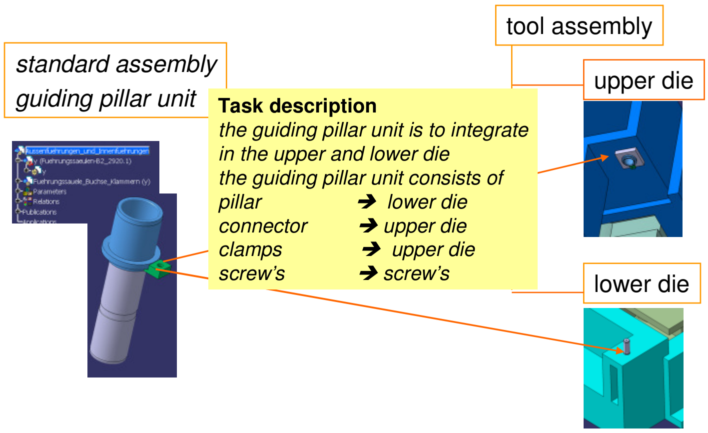


Figure 7-25: Example of an adaptive behavior of an intelligent component.

The intent of addition or removal of material is the description of the final machined plate or casting or the description of the rough plate/casting. It can also be used to describe plates/castings as they will be purchased, as opposed to plates/casting as they will be machined. To describe such a complex process, the syntax of naming add/removes in the components must be enriched and the structure of the receiving plate/casting needs to be enriched as well.

The definition of the machining information is described in terms of material to add or to remove, intended to affect various receiving die parts. When the user inserts a component in a die or tool, he can define some parts in which the Add/Remove geometries will be copied to and added or removed with a Boolean operation. The following figure 7-26 illustrates the basic mechanism. Add/remove geometries (milling areas and drilling holes, for example) are defined in intelligent components as positive elements. When these elements are copied in the die, the elements are subtracted. The result is a negative hole in the case of a drilling hole.

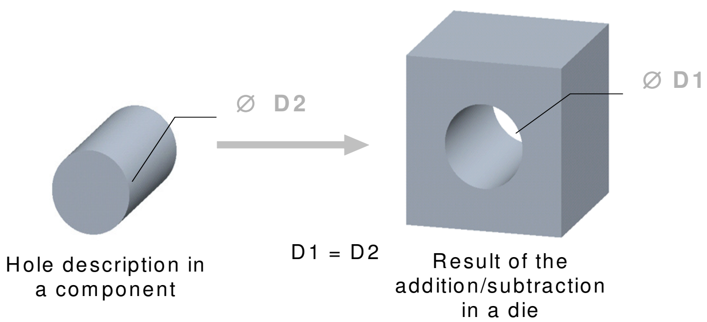


Figure 7-26: Example of an Add/Remove operation in die design.

In that respect, the user does not care about the downstream information. All the necessary information is integrated inside the intelligent component, as with intelligent features from product development. In NC-programming, the user just needs to read the data and apply the related machining process templates. Each machining process template grasps the templates inputs, because each element is correctly named.

7.4.5 Conclusion

A significant reduction in the development time of stamping die planning and design can be achieved by semi-automatic geometry definition using intelligent features and templates. This method reduces not only modeling delays but also increases design flexibility and facilitates change management. Here, a clear reduction in lead-time can take place with the additional help of advanced technologies such as virtual process planning (not described in this work).

7.5 Intelligent features for the welding process

Starting with the analysis of the joining process, this section discusses requirements and optimizing potentials for an automated welding process based on feature technology. Figure 7-27 shows the fastening process chain in the automotive industry with welding as an example.

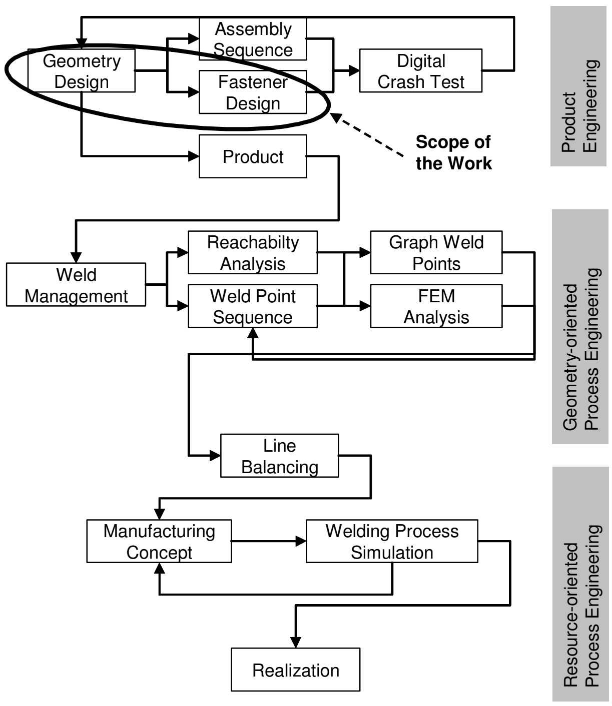


Figure 7-27: The fastening process chain.

The designer specifies the spot welds in the CAD model, using the experience gained in designing similar parts. Later, harmonization with process planning takes place. In a next step, this information is forwarded to the calculation department for crash and analysis. Here, important information is typically lost due to the break resulting from the interaction of different systems.

After simulation in process planning, the designer must verify the correctness of the spot weld definitions. This process is accompanied by intensive modifications. In general, it takes 1.5 years for this to be completed. Figure 7-28 illustrates this burning issue. A second considerable problem is the management of spot welds as depicted in figure 7-29.

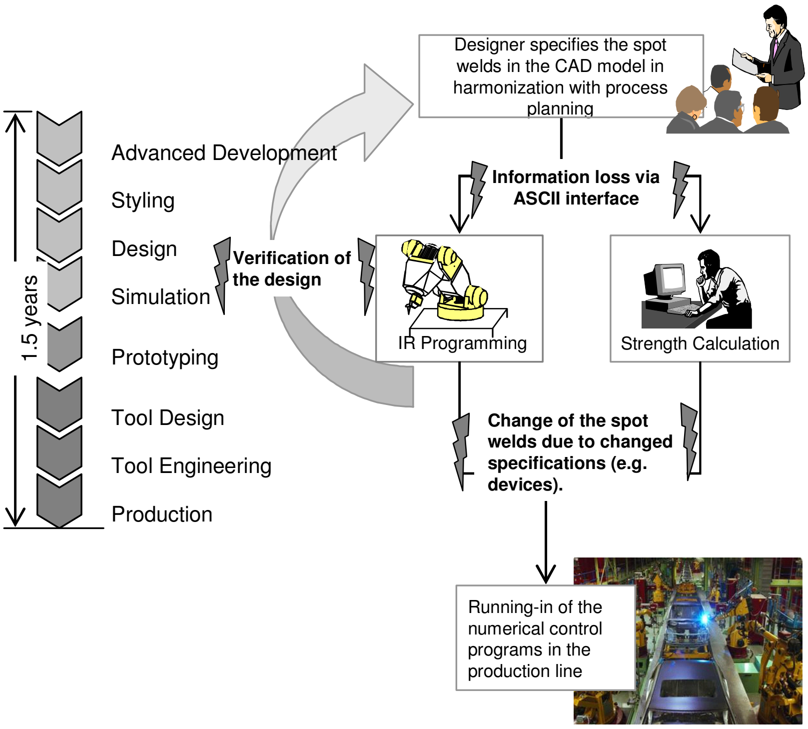


Figure 7-28: Correction cycle in weld planning.

The multiplicity of the different users of such component-spanning information and their different needs impose substantial requirements upon information technology. These requirements concern the administration and documentation of spot weld information (e.g., coordinates, welding current, kind of the weld) for production purposes and their availability in a digital format (e.g., for robot planning or crash simulation) as well as their modeling and functional context. In brief, what is needed is a uniform digital information model to which all users have access in order to extract and feed in their relevant data throughout the product development process.

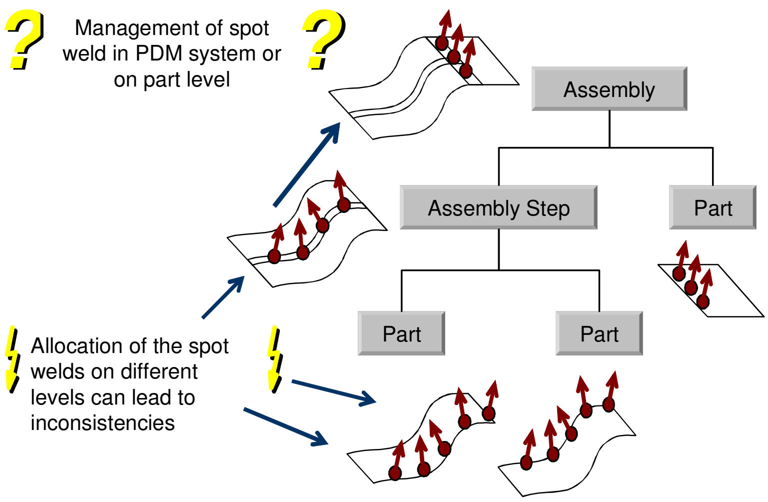


Figure 7-29: Spot-weld management.

A concept based on intelligent features is presented in the following subsections. Providing procedures to assist engineers in designing components and assemblies that are to be welded, it thus supplies the foundation necessary to automate many of the processes that would otherwise be done manually.

7.5.1 Requirements for an integrated welding process

All product designs are subject to approval by the engineering and manufacturing personnel responsible for an effective and efficient welding environment (e.g. flange length and width, accessibility, weld sequence). In fact, welding should be considered to obtain more complete information on the usage of a specific welding process before a design is finalized.

Complete welding information provided in the engineering release(s) specifies the overall requirements of weld elements. Welding symbols employed for this purpose enable the designer to efficiently and precisely specify the engineering requirements. The metals selected for a welded assembly, for example, either ferrous or nonferrous, must be of a suitable weldable quality for automotive applications. These metals do not require extraordinary welding means or controls and are suitable for high production rates. Welding of completely dissimilar metals should be avoided.

To outline an approach for fastening in the automotive industry, an integrated data model that can completely and unambiguously describe connection information and data needs to be established. In addition, processes and tools need to be in place to work with the connection data.

The considerable benefits expected are, in particular, consistency of the design, since the integrated data model should provide a framework which assures that advanced engineering, manufacturing, and process planning all have the same spot welds in their designs. Here, specific information can be displayed dependent on the required view. On the other hand, the necessary process automation for procedures that are otherwise done by hand (e.g., automatic weld robot programming) should be supplied. Once welds are unambiguously described, it should be possible to create an algorithm that is capable of automatically programming the weld robots in the assembly plants. Therefore, a single source of weld data is needed.

Furthermore, when describing the assembly data in a computer format, it is reasonable to work on methods that can automatically assess assembly feasibility. Various rules can be created and, based on the type of the assembly, the tools would be able to automatically assess feasibility. The underlying notion is that early integration of process knowledge in the design stage will not only radically reduce redesign costs but also accelerate design times. Moreover, some steps between design and production can be eliminated. In a way, this now meshes two aspects that often have been treated separately or sequentially: the product and the process. This is about integrating spot welding process knowledge in what have traditionally been product design tools, specific methods are required, such as feature technology. Hence, this work researches a feature-based solution for spot welding modeling to develop an intelligent solution that supports or automates the designer's routine task and contains relevant process information.

7.5.1.1 The flange design process

Flanges are an example for joining relevant features; they play a pivotal role in the welding of body-in-white parts. Flanges exist in different forms with different functions as elaborated in the following diagram [Weidlich 01].

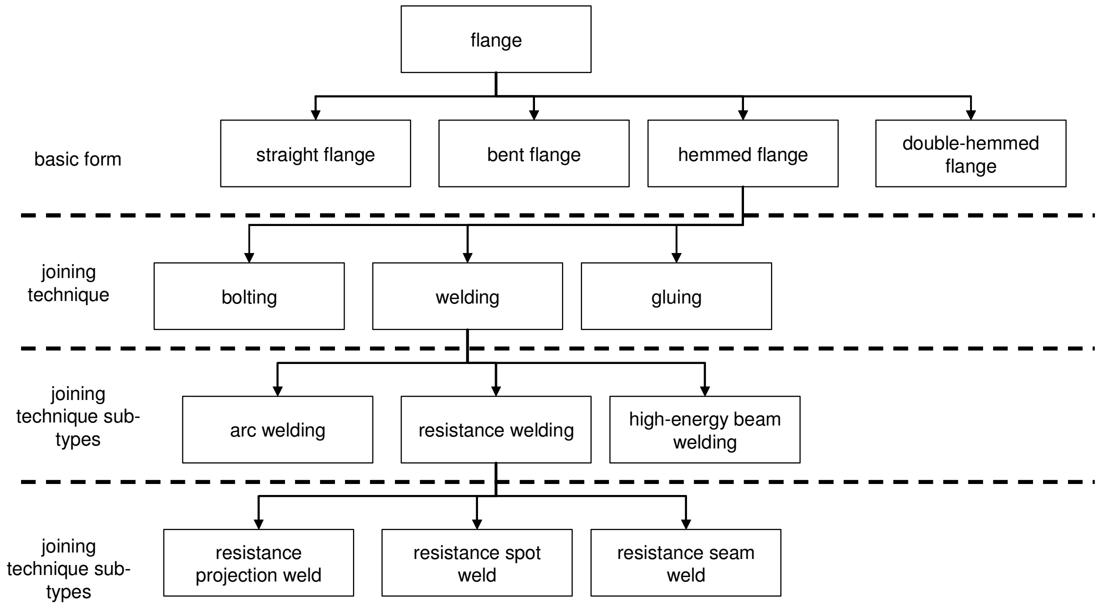


Figure 7-30: Rough hierarchy of the flanges.

Flange types

In general, a flange is an area of a part with the function of providing the contact surface between different parts. Usually this contact surface is utilized for the fastener process. By providing this contact surface, depending on the flange form used, a joint between the parts can initially be created. The geometry of a flange is contingent on the parts, their orientation to each other, their function, and the technique employed to join them. Different joining techniques place different demands on the flange. This results in a wide variety of flanges with different geometries according to their specific purpose. Not all parts can be joined with all types of flanges as this depends on their designated function. The flanges can be roughly divided into various basic flange forms, which can be further subdivided according to the joining technique employed (see figure 7-30). The basic flange forms have different geometries, whereas the sub-types of one basic flange form may be distinguished simply by differences in the parameter ranges allowed in the same parameterized geometry. The four basic forms mentioned in figure 7-30 are depicted in figure 7-31. The hierarchy illustrates that flanges of the lowest level are highly specialized features. For this reason, very often only the basic forms are stored as a parameterized geometry, called features. When applying these templates, the designer has to make sure that the design created follows the constraints of the desired joining technique.

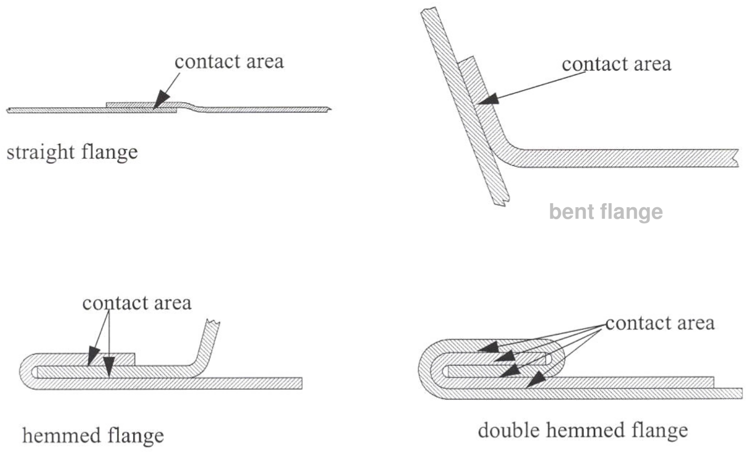


Figure 7-31: Cross-sections through some basic flange types.

The flange design process

The flange design process begins in the design phase of the product. Unfortunately, in this phase, most of the constraints regarding the manufacturing process have not yet been developed. Therefore, questions such as which technique is to be employed to join the parts have previously remained unanswered. When the designer creates a flange, it is clear that this contact area is for a special purpose. For example, the designer creates a flange for the resistance spot welding of two parts. The problem is that this knowledge is often based not merely on technical expertise but also on lessons learned from prior designs, and the procedure is not consistent with real requirements from downstream processes. The flange design process can be divided into two main steps:

- The creation of the flange attached to a part.
- The creation of relieves, due to geometry, function, and manufacturing constraints.

This process is affected by a number of changes. Before creating a flange, the designer first analyzes the functional requirements against the design intent. The choice regarding the method is made on the basis of the geometry of the parts involved in the welding and on the welding technique used. The guidelines for the designer’s final decision are the functions of the different parts, their geometries, and their orientation to each other, plus manufacturing constraints. An example illustrating the strong consideration of manufacturing requirements is given in the following: the joining of the door deck lid or daylight openings (see figure 7-32).

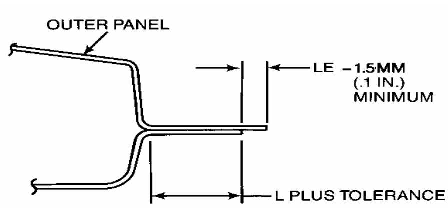


Figure 7-32: Manufacturing considerations for welding flanges.

According to general welding requirements, the preferred welding technique is resistance spot welding, but in a section of this design, resistance spot welding is not suitable for daylight openings, because welding marks occur on both parts, and all daylight openings are of styling relevance. The functional styling relevance implies that no customer-visible changes may be made to a part having this function. As shown in figure 7-32, both the outer panel and the inner part have to be equipped with a flange to achieve the desired contact surface. To avoid a visible joint, the flange of the outer panel has to be longer than the flange of the inner part.

If possible, the designer adds the flange to a part by using a feature (see figure 7-33). The feature contains a parameterized geometry, and the designer selects both the inputs for this geometry (the two parts to be flanged and the flange curve) and the values for the different parameters (e.g., the flange height). The designer needs knowledge about the manufacturing process at this point because the feature template does not necessarily prevent the designer from entering values which do not meet the relevant design standards (e.g., flange heights which are not suitable for the desired welding technique). If the designer decides to create a relieve, appropriate notch features might be utilized if they are provided. For the instantiation of the notch features, only the point and the edge are to be specified.

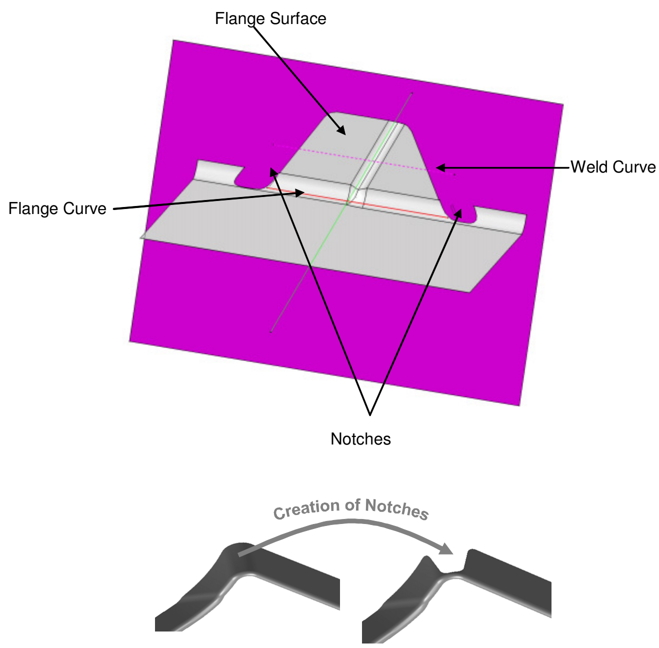


Figure 7-33: An example of an intelligent flange feature.

Creating relieves or notches

Notches or relieves are created for manufacturing reasons or for the functions of flanged parts.

The designer more or less manually checks the geometry of the flange for critical areas where relieves might be necessary. If a relief is needed at a certain point, the designer checks whether it would conflict with the function of the flange. Each relief decreases the stability of the flange by reducing the weldable area of the flange. Sometimes, therefore, a trade-off between manufacturing and design requirements becomes necessary.

For this evaluation, the designer has to have knowledge about the manufacturing process and the constraints connected to the different manufacturing steps. Each manufacturing step has its own requirements, and this can necessitate usage of a relief. Sometimes the designer cannot evaluate all the necessary relieves, as they are dependent on the overall manufacturing process, meaning that the designer needs feedback from manufacturing planning to put in additional relieves. An example for this is the strain-based relief. The strain is a function of binder pressures, which are very often evaluated in a stamping simulation performed by production planners.

7.5.2 Welding requirements

In accordance with the welding requirements set, the two parts are welded together. The preferred welding technique is resistance spot welding; however, depending on the surface finish and function, the welding technique used may vary. The welding technique has great influence on the geometry of the flange -- e.g., in the hemmed position. The following section discusses welding requirements in detail. In general, the following requirements are made for welding parts:

- The maximum ratio of sheet metal thickness.
- The minimum overlap length.
- The minimum welding spot spacing.
- The minimum flange length.
- The minimum width and access requirements.

An example of the requirement related to the maximum ratio of sheet metal thickness would be to make sure that the thickness ratio of adjacent sheets or of the two outside sheets does not exceed three to one (3:1). When the thickness ratio exceeds any of these requirements, the applicable manufacturing department is to be contacted for suitability in the manufacturing plant.

For a hemmed flange, the two outer sheets are of the same thickness t1, because they belong to the same part. According to the statement above, the other part thickness t2 can be smaller than 3 x t1.

The fact that the two outer sheets are of the same thickness is used to evaluate the minimum contact overlap length for a hemmed flange. For the sheet to be weldable, the flange height in the hemmed position should be greater than the minimum contact overlap length. Areas that do not fulfill this requirement cannot be welded with the resistance spot welding technique.

Further key requirements are the minimum welding spot spacing and the weldable flange length. Figure 7-34 shows specifications according to the minimum spacing and the relation to the thickness of the welded parts.

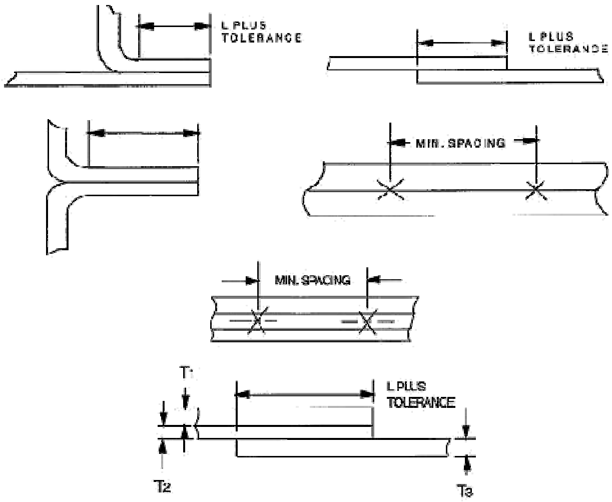


Figure 7-34: Minimum spacing for 2T and 3T.

An additional key criterion for the welding process is the reachability of the resources. The minimum weldable flange length has its origin in the width of the welding tip. An area smaller than the width of the welding tips might not be reachable with the welding tip and therefore cannot be weldable. But, depending on the geometry of the part, an area smaller than the welding tip width might still be reachable and therefore be weldable. Figure 7-35 shows the dependencies between the parameters of the welding tips and the parameters of the flanges.

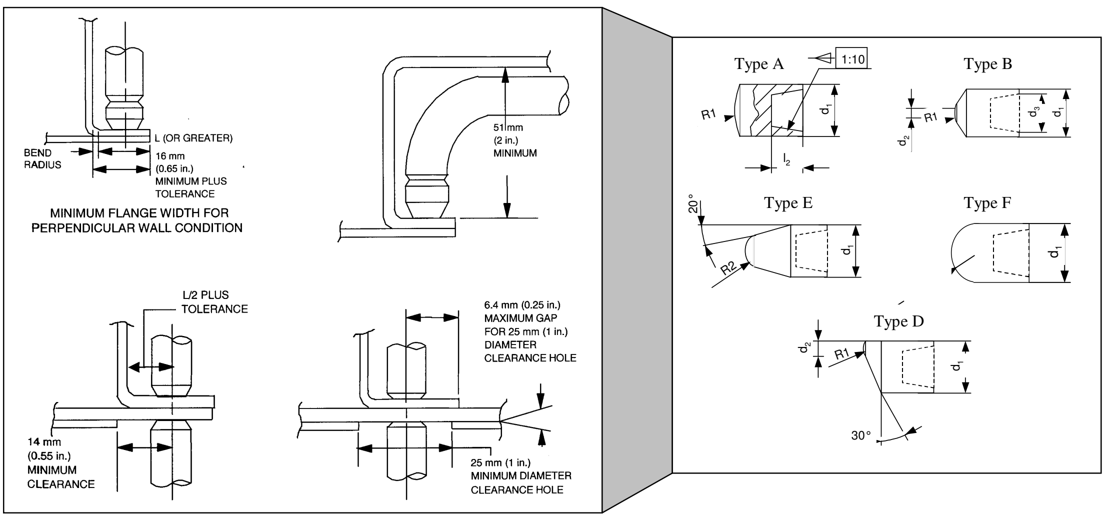


Figure 7-35: Reachability requirements.

Since it is not certain that an area smaller that the welding tip cannot be welded, the system is only able to draw the designer's attention to areas which might be critical. Critical areas are identified by measuring the distance between the beginning and end of a flange. If the distance is smaller than the minimum value, the designer is prompted for a decision.

7.5.3 The automation of the flange design process based on intelligent features

Today, there is no standard in welding components. Each enterprise has its own standards, and all design components and assemblies have to follow this standard. Furthermore, designers have different ways to generate spot welds. The results are inconsistencies and expensive modifications. The aim of this section is to show a method to provide the designer with an instrument to generate spot welds according to the underlying design, manufacturing, welding, and resource requirements described in the previous sections.

The concept developed is based on the so-called intelligent or adaptive features described in chapter 5, which support a system-guided process. The system is aware of the functions of the different parts or features of the parts, the design standards, and the manufacturing process, informing the designer if the design would conflict with the design standards for this particular manufacturing process. The prerequisite for this system intelligence is that all the relevant data are stored in computable form as rules and constraints.

The process described is based on the hierarchy of features, where a feature with all its views is divided into a set of features according to their appearance in the process chain. A flange incorporates different views -- e.g., a design, a manufacturing, an inspection, and a welding view. These views are mapped in such a way that the design feature flange, when observed from the production planner's perspective, turns into the manufacturing feature flange. Relevant information is mapped or linked from the manufacturing feature to the design feature.

The designer begins by selecting the two parts to be flanged together and a feature called “flange master”. The next step is the specification of the function of the parts to be welded. This step is essential, since the system captures all the relevant information from the parts and compares it to a set of conditions under which a certain flange is used. These conditions are linked with the feature library and are stored in the different flange features, their sub-features or the corresponding manufacturing features.

The system also suggests the part to which the flange is to be attached. This is done, for example, on the basis of the function of the parts involved in the welding process. In the case of a door, a hemmed flange would always be attached to the outer hull. A flange attached to the outer hull is hemmed from the outside to the inside so that it does not negatively impact the outer appearance of the car. Naturally, resistance spot welding would be prohibited for this particular joint.

The system analyzes the parts involved and calculates all the necessary parameters on its own. The bases of this analysis are the functions and the other properties of the parts involved as well as the properties of the selected flange form. The designer monitors the results and can change parameters if desired. The system then generates the geometry as per the parameterized geometry stored in the feature. The feature, together with its parameters and its properties (e.g., function), are stored in the part after instantiation.

In a further step, a link between the joined parts is created -- e.g., by creating an assembly feature. This link enables the designer and the system to monitor changes in all the parts concerned and their effects on the flange, since the system is now aware of the connection to other parts or features of other parts in the assembly context.

The next step is the creation of notches. Usually, the flange features developed in this thesis already contain notches. However, designers can specify if they wish to keep them, or the system automatically checks whether relieves are necessary, displays the reason, and suggests the shape and the position to the designer. The system performs this action by checking the feature flange for links to sub-features. Then it comparies the conditions under which these sub-features occur, the geometry (or function) of the flange, and the geometry (or function) of the part. After the designer accepts the creation and the parameters of a specific relief, the geometry of the flange is modified, and the sub-feature is added to the feature (and, as a consequence, to the part).

Due to the integrated engineering knowledge and rules contingent on standards, the manufacturing changes or even design specifications can be considered effectively. In this case, the designer is informed of this change and is asked if an update of the part is desired. If the designer accepts the change, the update is automatically performed. If changes that affect the flange are made to a joined part, the system informs the designer and suggests the commensurate changes that need to be made to the flange. Research is currently being done on a feature-based workflow which supports a system-guided change of features affected by the changes of features in other parts. The workflow informs the designer of changes in a certain feature which become necessary due to changes in a feature of another part. These two features are linked to each other by an assembly feature.

Dependency between the types of properties stored in the model

The dependencies discussed show that the flange (its form and its geometry and the fact that a flange is selected at all) is the result of the interaction of many different properties, constraints, and restrictions made on the flange, the joined parts, and the overall product. It also illustrates that there are some circular dependencies (e.g., function, form, and geometry) between different properties of the flange.

To provide the manufacturing information to the designer, design standards have been integrated into the features. These ensure, apart from the functionality and manufacturability, a cost-effective production. The design standards exist for many different manufacturing steps and are very comprehensive – that is, they cover many special cases. To create a part which fulfills these standards, the designer must be familiar with them. To achieve this familiarity, the designer needs a long period of vocational adjustment and constant efforts to remain up-to-date with the newest standards. However, all this knowledge can be provided by the features during instantiation.

Acquiring knowledge on how to create a product that can be produced at the lowest possible cost is not the main problem in modern, integrated product development. The chief problem is how to make the existing knowledge available to the designer, engineer, or manufacturing planner. One solution is the use of feature technology, as described in the following subsection.

7.5.4 Improved, feature-based spot welding design

The existing functionality in available software systems is not sufficient for the current needs of enhanced spot welding design. The weld design procedures today are slow, since the designer has to continually look up norms. Also, high redesign costs are incurred due to the influence of the process parameters in weld design and flange properties. The designer has to be supported by improved design functions combined with necessary spot welding process knowledge.

The aim of this example is to come up with a prototypical solution that computes and represents high-quality feature-based spot welds on the flange [Alday 03]. As mentioned, the experience and the standards in design of quality welds are reflected in norms. A good solution for spot-welding design should be able to automatically read these norms and obtain the values that correspond to each case.

As set out, a flange is a salient of the metal sheet on which the welding spots are to lie. The designer has to check standards related documents in order to determine which geometric parameters the flange must satisfy. Furthermore, some parameters not only depend on sheet characteristics but are also contingent on process decisions such as the electrode type chosen. Now, all this knowledge is integrated into the flange feature and the interface provided for flange instantiation. This interface facilitates the modeling of flanges in sheet metal parts. With only three shapes as input, a flange can be computed and integrated into the model. At the same time the model contains many published parameters that reflect information of several types. While some of these parameters (for example, those related to sheet material) can be useful in computing the spot welds, the computation of the weld may show that some geometric parameters of the flange were not adequate for the process. In this case, it is very easy to change the value of the published parameter afterwards, and the flange geometry is updated automatically.

Welding spots are more than just simple points. In accordance with norms, the distance between contiguous points is a function of the thickness of the sheets to weld – that is, the number of points is not proportional to the flange length and has be computed for each case. Thus the weld would have to be defined point-to-point. As a consequence, the geometry to instantiate is not always the same, or, in other words, the number of features varies for each weld.

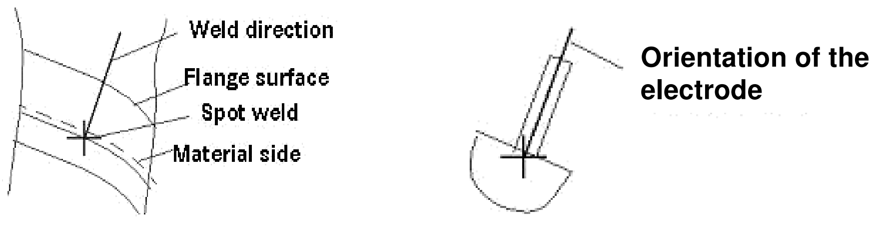


Figure 7-36: Specification of a spot weld.

The welding spot must be placed on a weld curve, which is part of the flange feature. At the same time, each spot weld must include a specific direction (see figure 7-36). The reason for this specification is that industrial robots must know in which direction the welding electrode should approach the point, both in order to avoid a collision with the part and to perform the weld with the electrodes in perpendicular direction to the flange to ensure the desired quality.

In addition, between consecutive spot welds of the weld on a flange, a concrete minimal distance must be maintained, and this varies for each case. Figure 7-37 shows the interface developed for this purpose. Moreover, we wish to integrate the process parameters in this feature. Apart from the traditional feature concept, we are seeking knowledge integration.

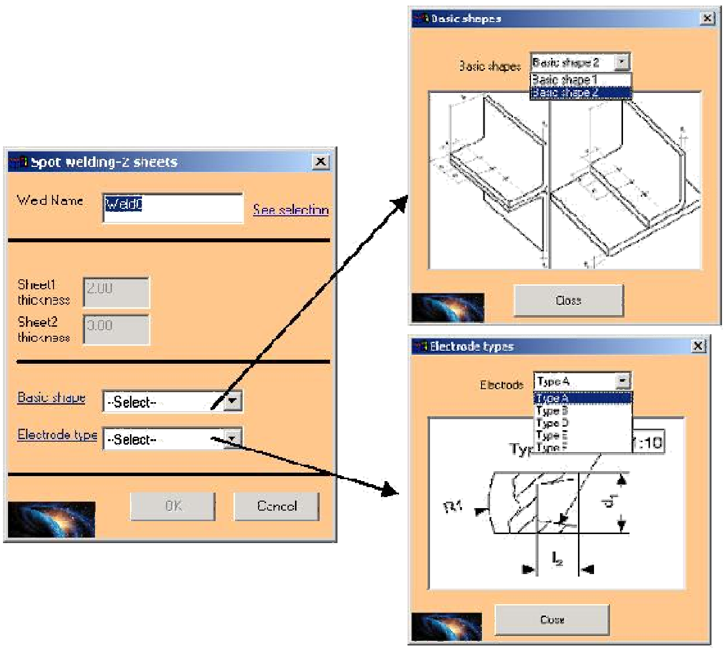


Figure 7-37: Definition of spot welds on a flange surface.

In this case, knowledge integration means to be able to design a weld with quality. The experience and the rules to do so are reflected in standards. The following example illustrates a rule integrated into the intelligent feature template:

“When the gauge being welded falls between the table’s thickness values, use the thinner thickness to select the contact overlaps and weld spacing.”

Figure 7-38 below depicts the necessary inputs and outputs for creating weld spot features, while figure 7-39 portrays their instantiation.

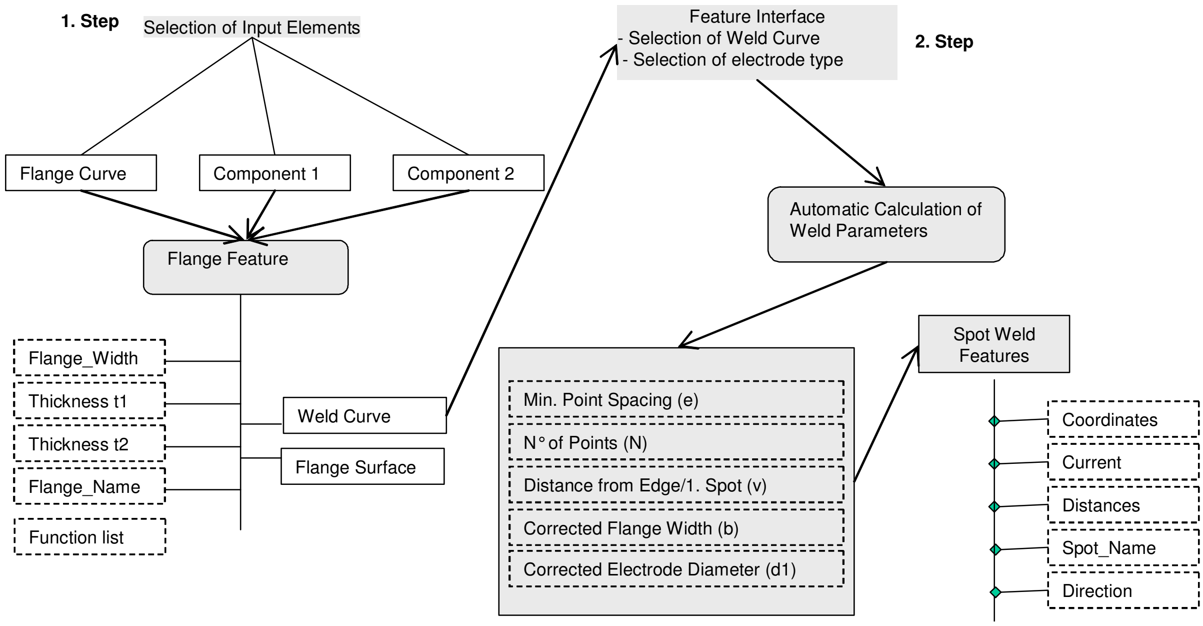


Figure 7-38: Inputs and outputs for spot weld.

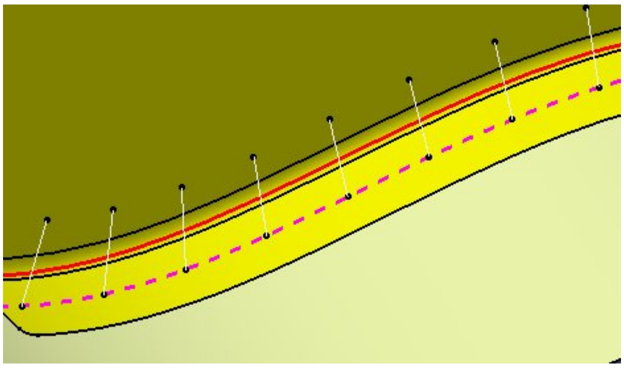


Figure 7-39: Instantiated spot weld features on the flange feature.

In addition to geometric information (point location, vector direction), the norm provides a wealth of other information: standards, process category, process type, feature type, definition robustness, regulation, geometry flag, inspection flag, manufacturing code, material, and diameter. Furthermore, process parameters need to be integrated into the feature. These are, for example, the electric current, the weld time, the electrode, and the force that the welding device must have. All these welding parameters need to be controlled effectively to produce a quality weld. The industrial robots are the machines that steer this process.

An XML file containing all spot weld-related information (coordinates, process information, etc.) can be created each time by the process planner according to the desired view (analysis or assembly). This avoids an expensive data storage strategy while allowing the process planner to carry out modification through the list. The modifications can be fed back to the CAD system to reconstruct the changed spot weld parameters. This supports effective change management and promotes consistency in CAD, CAE, and manufacturing departments, since all these organizations work from the same data.

In this sense, the weld spots can be automatically computed in an XML file and automatically converted into a robot programming language. Current CAD systems have an integrated robot simulation tool. It receives the programming code and moves a virtual robot identically to a real one. In this simulator, the process planner can quickly check and analyze the interaction between robot and car body. If this simulation is satisfactory, the programs are ready to be fed to the robots in the production factory.

To summarize, the solution provided presents a number of benefits. Any specific norm can be integrated and updated. For example, the point diameters are computed according to norms. All spot welds are computed at the same time, with an adequate distance between them. Currently, each point has to be computed separately. Before creating the spot welding, information about the flange feature can be read and specific information retrieved for the location of the spot welding. In addition, during evaluation, the designer can be informed about non-compliance with the norm. Furthermore, all spot welds are linked associatively to the weld curve and flange. If the parameters of the flange change, the spot welds are redistributed along the weld curve.

7.5.5 Conclusion

A method for designing car body components that are to be welded, especially flange areas, has been introduced. In the different sections of this work, a solution for improved spot welding design was discussed and evaluated. First the basic knowledge and standards for spot welding design were analyzed. These are reflected in norms. Each norm is concerned with different variables, which must be understood before a solution can be worked out.

Concepts for linking the specific knowledge and experience of the norms for process improvement and knowledge integration were realized. The current approach supports the work of the designer in spot welding design. Necessary process knowledge is provided through intelligent and feature-based modeling techniques. The functionality of the fastener concept developed enables the user to define, modify, visualize, and manage welding joints (e.g., welding point’s seams).

PART IV

IMPLEMENTATION: FEATURE-KNOWLEDGE ASSEMBLY DESIGN - FAD

Chapter 8

8 Development of an integrated vehicle conceptual engineering framework based on feature-knowledge assembly design

During the last few years, many tools that aim at supporting engineers during their decision-making activities have come to light and have been typically introduced in research. The common focus of these tools lies in simulation tools and virtual prototyping. Yet no tool provides efficient decision support that in any way matches the way designers and process planners work or takes into account the integration of product development, process planning, and resource allocation. The available tools for tackling these problems are much too complex or are different from the standard tools, and they not able to find acceptance with the users. In this chapter, we focus on a prototype software tool, which uses the intelligent feature and solution pattern (feature-based template) approaches as well as knowledge-driven engineering in order to provide a high end-to-end design and process-planning environment tailored to the needs of designers and process planners in the automotive industry. These approaches are combined under the term Feature-Knowledge Assembly Design (FAD). FAD combines the realization concepts shown in the previous chapter.

8.1 Introduction

The ability to design and evaluate alternative solutions in a short time is a crucial issue in the product development process. Today, doing this job is extremely time-consuming and often repetitive work. In addition, the knowledge about similar steps cannot be used in a tailored, computed way.

To provide such capabilities, the system should incorporate all the design and process knowledge acquired in the past (best practices). This knowledge has to be formalized and made available in the form of solution patterns (feature-based templates or even intelligent features), thereby providing the necessary mapping into appropriate product functions and engineering tasks.

As stated, the design converts the results of the interdisciplinary tuning (tolerances, welding, manufacturing, planning) in order to determine geometry. This knowledge flows into the design. Design decisions can therefore result in unintended consequences that have a propagation effect across multiple product life-cycle phases. Hence, in the context of an integrated environment, there are a number of questions, which must be answered by users:

- Who needs which function (context, situationally) and when?
- How can the complexity of methods be reduced (acceptance of new technologies, automation of design and engineering tasks, standardization)?
- How can we consider variety and perform requirement- and specification-driven engineering in a tailored way?

- How can guidelines, standards, and methods be fully integrated into the different engineering processes efficiently (I would like to be able to say only what I would like to do, and not have to outline how it is to be done)?
- What about abstraction, generalization, and facilitation of the work and user support: are methodical procedures required?
- Should availability, actuality (maintaining knowledge) not be uncoupled from other processes?
- Do factors such as comprehensibleness, dependencies, influences, and sensibleness need to be considered?
- Is supplier integration or privacy a factor?
- Are fulfillment of the specification and control mechanisms to be done via functional models and functional structures?
- What has to be taken into account with respect to constantness (CAx/EDM integration) and documentation (how do I get from the specification to the geometry or to the process?)
- How do we carry out design and process synthesis?

Although there are good software programs on the market that enable vehicles to be developed more efficiently than in the past, there is a strong need to focus on concrete engineering tasks and automate them. Often engineers become confused by the abundance of available programs and the complexity of the methods at their disposal. Each company has to customize its processes, because all these perfectly adequate tools are only aids in designing one's own processes. Yet focusing on one's own processes also means providing engineers with dedicated tools and assisting them in their work -- i.e., in capturing and reusing their own knowledge and experience according to corporate standards and processes.

Engineers need additional tools to support them in considering the consequences of their decisions on the overall product life-cycle, starting with conceptual design and detail design and ending withprocess planning, stamping, and assembly. A key requirement is the full integration of these tools into the daily working environment of the designers and process planners. The notion of Feature-Knowledge Assembly Design (FAD) is described in the following sections. It bridges the gap between feature-based (not merely oriented) and knowledge-driven engineering.

8.2 Feature-Knowledge Assembly Design (FAD): concept and architecture

FAD is an advanced technology geared for the vehicle creation process. It offers advanced tools for vehicle design and process synthesis. The guiding idea is to provide a backbone throughout the design process, maintaining consistency and keeping links between all the views and aspects of the component or assembly to be manufactured. It was created to assist designers in developing products according to the design methodology (design support, provide design suggestions) and to assist process planners in associatively automating their tasks. The underlying aspect of innovation is centered on an agreed and holistic method and around a specific question:

- How can a component be designed so that it is manufacturing process-secure and quality-assured? Better, how do we get the right design the first time?

This conceptual design covers the entire product creation process from the initial requirements to functional specification and product modeling down to simulation. It aims at working on the entity level most easily understood by engineers: intelligent features and feature-based templates.

8.2.1 Concept

The underlying idea of FAD is to provide a framework concept for the development of a vehicle modeling system based on a customized design methodology. The system aids designers in evaluating a proposed design and provides the comprehensive IT technical support of design activities in the different phases of product modeling: requirement modeling, function modeling, principle modeling, and shape modeling. Here, the views center on the different phases of the product's emergence, in particular the design phase. This concept enforces design discipline on the one hand and allows users to explore different design alternatives on the other. The result is a boost in innovation.

The key to automating packaging, manufacturability, and measurability evaluation is to have a component representation scheme which is suitable for representing all these views. Hence, a vehicle structure as depicted in figure 8-1 lets the designer describe any component while keeping the links between component neighbors according to the concept introduced by Pahl and Beitz[Pahl/Beitz 97].

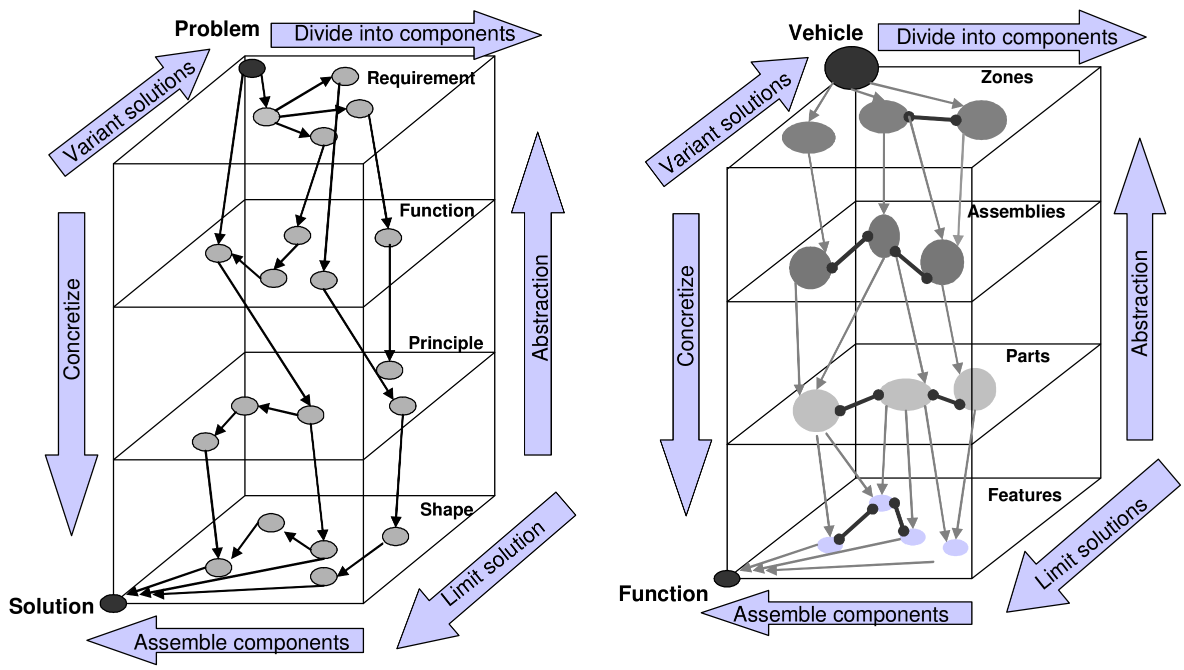


Figure 8-1: Modeling principle of FAD and the vehicle model structure used.

Furthermore, FAD provides users with tools to reuse generalized knowledge throughout the organization. Features and part and assembly templates as well as embedding knowledge process templates enable designers and process planners to easily reuse existing geometry and process solutions. Here, best practices are paramount as they provide the agreed and necessary design standardization framework.

To work on the advanced entity level, a number of objects (handlers) are incorporated in FAD: technological objects, behavioral models, and intelligent user interfaces:

Technological objects are objects defined on a high level with embedded knowledge about their processing as per the respective upstream or downstream processes. They are employed to define and drive object parameters, relationships, inheritance, and their behavior, whereas behavioral models are related tasks usually performed on technological objects.

The knowledge expressed by the ***behavioral models*** accords the users guidance and automation through engineering task procedures related to the specific technological object. It takes care of prerequisite steps and subsequent follow-ups. Object behavioral modeling embodies design task automation, which more or less comprises the activities that designers and process planners can do manually or have done manually in the past.

FAD distinguishes between behavior for design tasks and behavior for engineering tasks:

- *Behavioral modeling for design* aims at capturing creation activities and patterns related to corporate knowledge and engineering expertise. This is mainly assured by intelligent feature and template description.
- *Behavioral modeling for engineering* aims at simulating products as they would behave in reality, taking into account all the desired effects and constraints, test or validation procedures, for example. In this way, inspection planning can be simulated automatically for a given component or assembly. Intelligent process templates assure this.

The foundation for the above are the trends described earlier: parametric and associative design, relational modeling, knowledge integration, and intelligent feature technology as an integrating methodology. Figure 8-2 illustrates this basis in more detail.

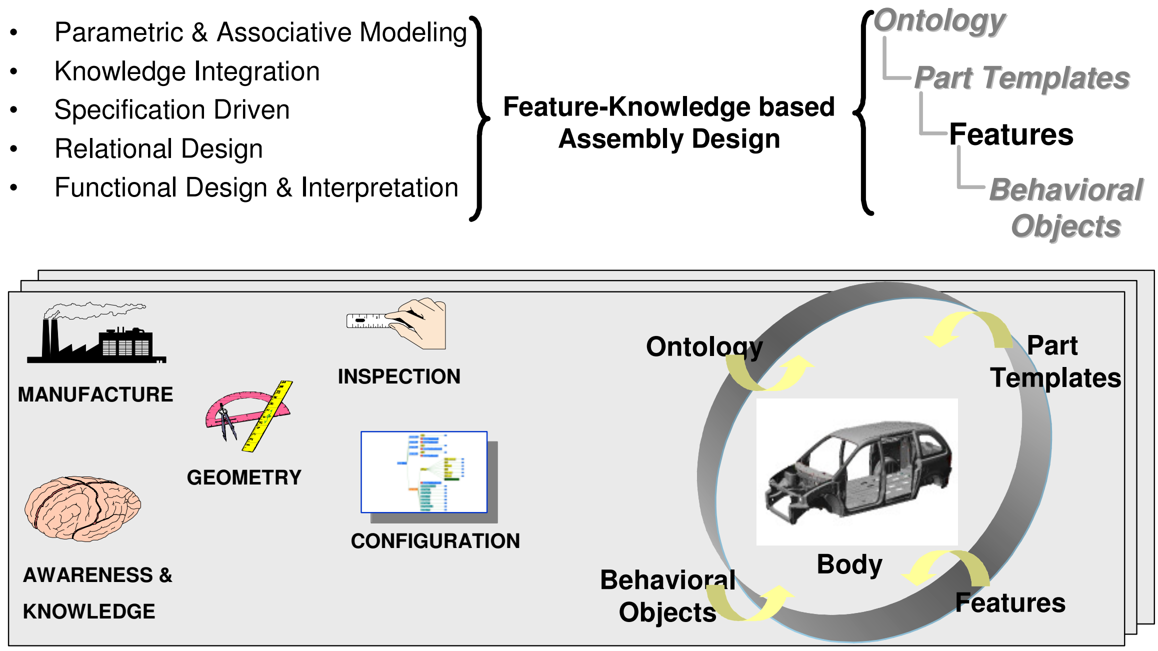


Figure 8-2: Base foundation of FAD (Feature-Knowledge Assembly Design).

The FAD concept uses following technologies:

- Features and part template libraries for faster and robust design-for-X
- Process templates library for applying procedures in process planning.
- Application development interfaces (C++ APIs) to implement behavioral aspects and functional dependencies.
- Vehicle model structure to handle the product hierarchy graph.

In summary, FAD is a concept that extends the capability of existing systems and is dedicated to automotive design and automotive process planning. However, this concept can be extended to other manufacturing areas, as the technology employed here is neutral. Figure 8-3 illustrates the holistic approach of this concept.

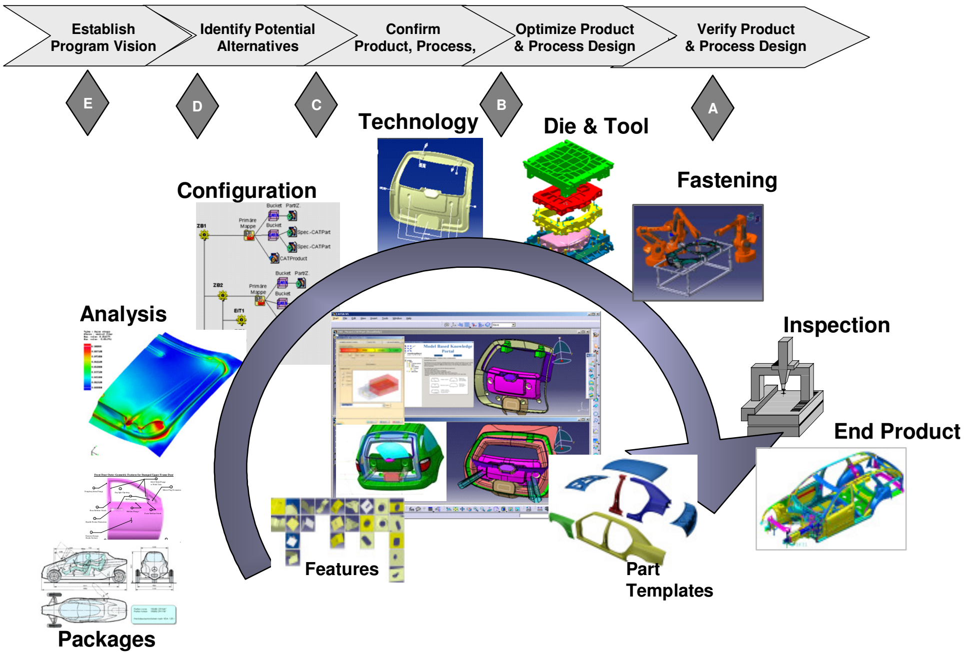


Figure 8-3: Holistic approach of FAD.

8.2.2 Architecture of FAD

The chief characteristic of the FAD architecture, intelligent feature and feature-based templates, is the usage of a suitable language for the representation of design and manufacturing knowledge, processing of components with defined interfaces, and management of information in a semantic net. Figure 8-4 portrays the underlying architecture in a simplified manner.

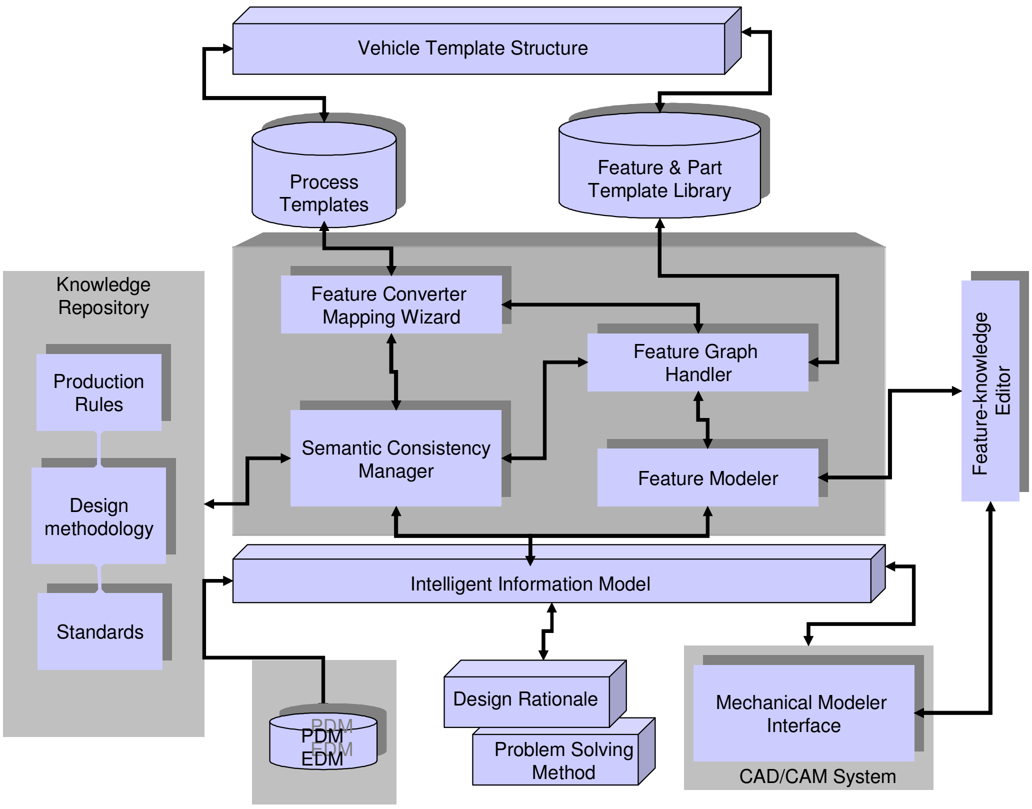


Figure 8-4: Basic architecture of FAD.

Key components are:

- The *semantic consistency manager* aims at supporting the definition, evaluation, and satisfaction of functional constraints. The feature data has to preserve the engineering significance. It also supports the definition of constraints to help the designer in defining the intelligent features (not to design them as the design of new features is performed using the basic functionality of the CAD system). These constraints are then evaluated to ensure the correctness of the feature. Various complex and time-consuming tasks allow these constraints to be evaluated off-line, for example, by using links to knowledge portals. In any event, this consistency management is triggered by the user. Engineering significance is supported through insertion of new features into the model, deletion, and parametric modification of existing features (as a consequence of feature interaction). It is based on semantic nets, a diagram of object-oriented representations, whereby the knots represent objects and edge relations.
- The *feature modeler* provides functionality for the management and maintenance of the feature library of user-defined features and their processing methods.
- The *feature template relation graph* describes and manages component semantics and geometric constraints between the features and the part templates as well as the

downstream process. Thus it provides a backbone to maintain the consistency of the feature interaction.

- The *feature converter* maps design features to the desired process templates, be it machining or inspection process templates.
- The *user interface, or feature-knowledge editor*, is responsible for the communication of the FAD with the CAD system. It supports the collection of all feature and template data in the process by obtaining all the data necessary to accomplish the design of a complete component.
- *Production rules* are one of the oldest and most common forms of knowledge representation in expert systems, since experts regulate and readily formulate their knowledge in the form of rules. Rules consist of a precondition (rule context) and one or more actions for the definition of truth content (implication or induction) or for the description of an activity. Rules are oriented toward the paradigms of logic, and predicate logic in particular.

8.2.3 Functions on the application level

FAD is a prototype of an assisted component design and manufacturing tool. It is a designer's assistant: the designer is led by the design process, and the system can intervene independently if necessary in the form of warnings and suggestions. The overall goal is to have a system in which designers can intuitively (in the designer's language) design by features and interactively and automatically have manufacturability and measurability indications as well as cost estimation for the part by providing context-sensitive design or process knowledge. Figure 8-5 illustrates the working principle from the design view.

This prototype is therefore designed to help designers and planners look at a component model from either a design, inspection, or manufacturing perspective. It provides functions for analyzing a component model and identifying logically related geometric entities as features for design or process planning, depending on the engineering role. Other entities can be defined by recognition as features either automatically or interactively.

Furthermore, additional functions allow the design features to be incorporated in or linked with embedded modules (feature-based tolerancing and feature-based measuring).This ability to automate the engineering process and to meet the engineer's needs is what distinguishes this software prototype from other tools.

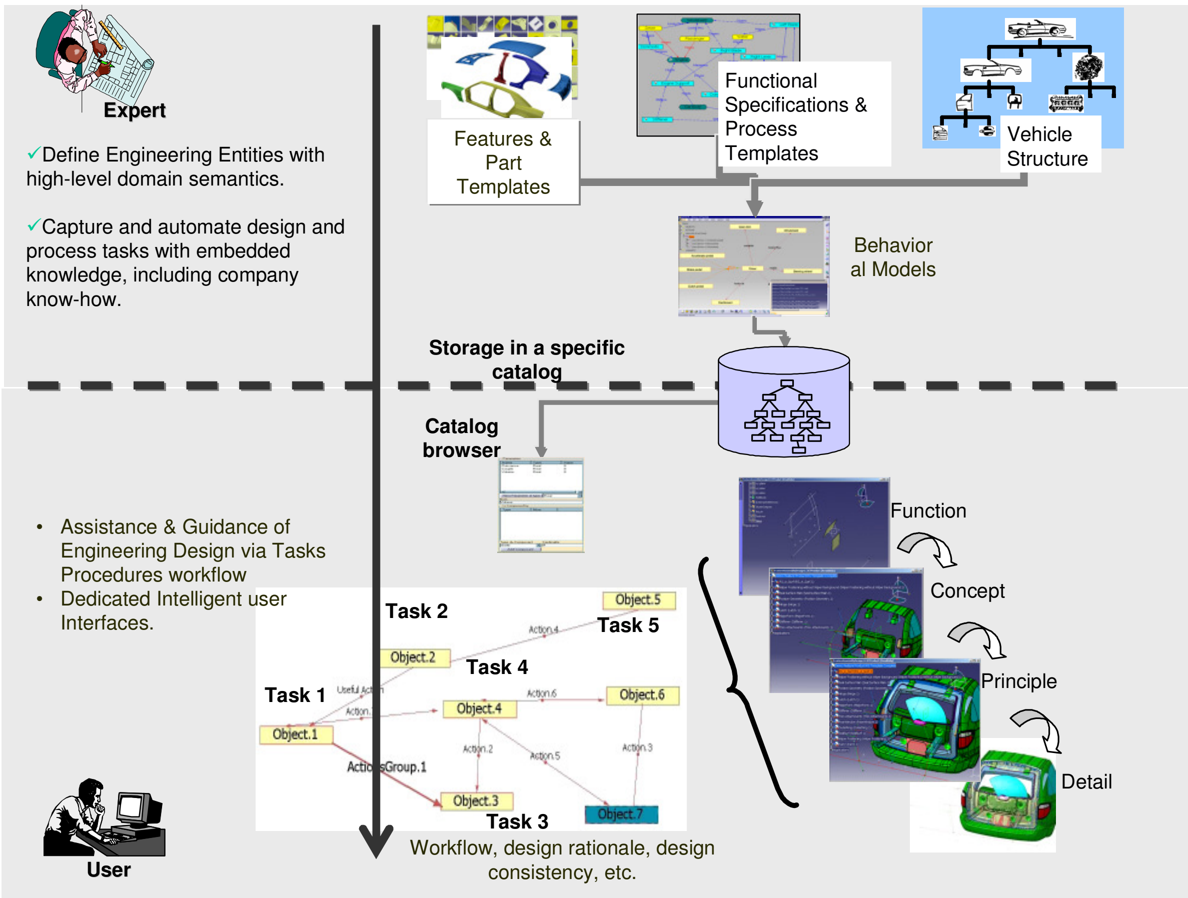


Figure 8-5: Working principle.

FAD supports the designer through the direct determination of characteristics from the desired properties, keeps the appropriate dimensioning standards ready for application, and applies them automatically if necessary. It can save dependencies between characteristics and properties for design features and evaluate them automatically as far as possible to make the definition of the characteristics and the associated consequences transparent.

In fact, the user interacts with the system in order to generate alternative solutions. First, the system guides the designer in applying the feature-based methodology when designing a component. At any desired time, the user can perform design checks to test design consistency. The user can also allow the system to do this automatically after each design validation. The system also gives feedback on the manufacturability, packaging, or measurability of each evaluation solution. In a further step, the system supports engineers by planning manufacturing or inspection tasks. At all times, the associativity is maintained bi-directionally.

8.3 A holistic scenario example

In the following section, we will discuss a holistic example as set out in figure 8-6. To demonstrate the validity of this approach, FAD has been integrated into CATIA V5.

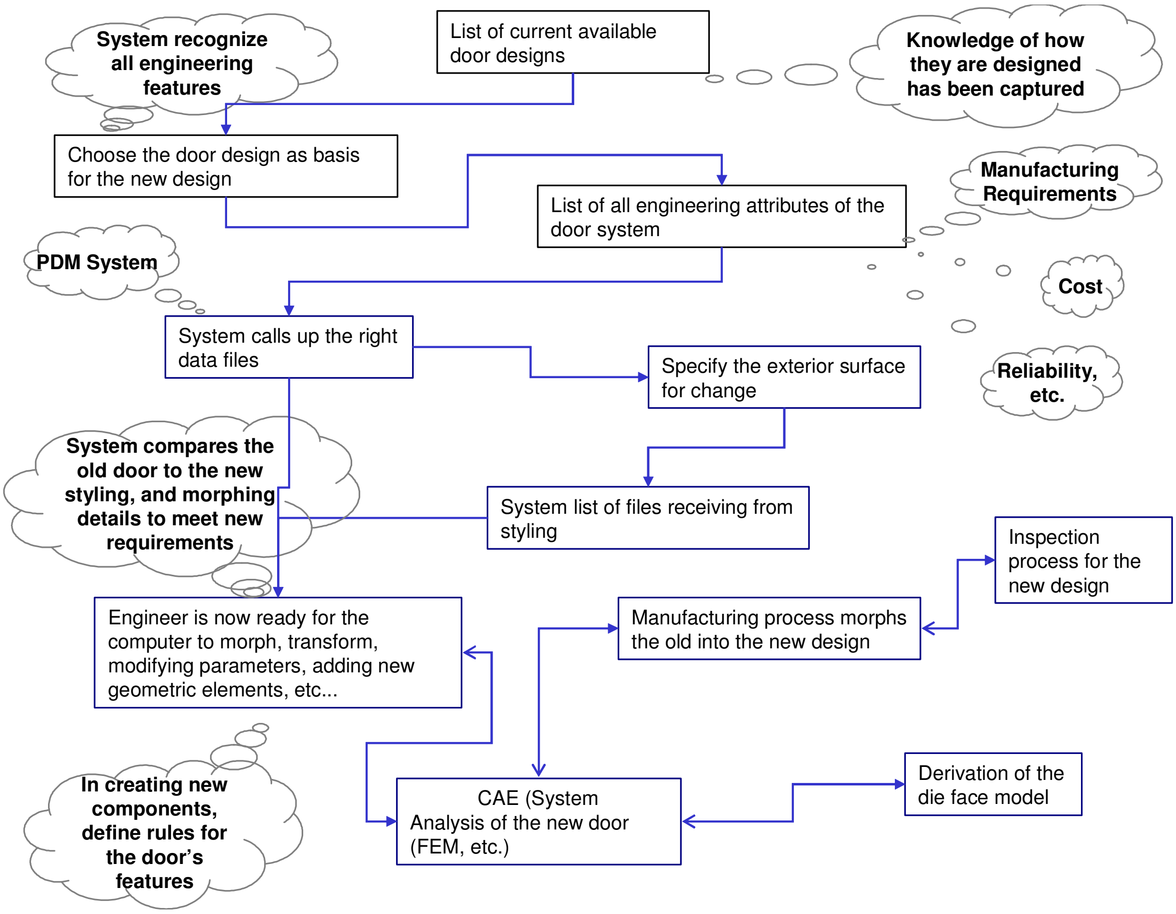


Figure 8-6: Holistic scenario example.

For this example, we will assume that a lift gate inner panel is to be designed and manufactured for a family vehicle. Figure 8-7 illustrates the starting panel for the definition of the part type.

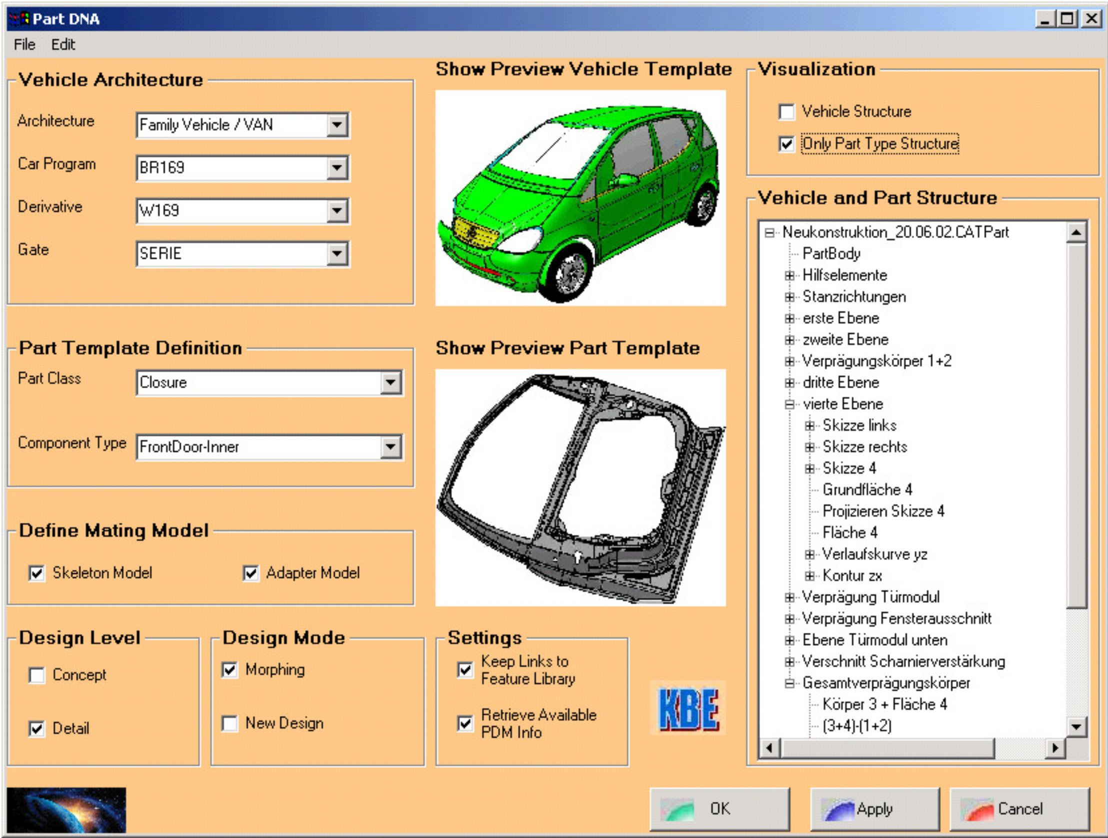


Figure 8-7: Specification of the part to be designed.

Now, the engineer can query the system for its list of currently available lift gate designs. For each of these lift gates, the system contains the knowledge of how they are designed, manufactured, and inspected, as has previously been captured.

Before the system can manipulate the geometry, the engineer must first choose which lift gate template to use as the foundation for the new design. This is a crucial step that calls for technical knowledge, since the basic architecture of the legacy lift gate template must be in line with the new lift gate's performance requirements.

The selection made leads to an automatic retrieval of the template and the necessary adapter models for the part. These template and adapter structures are captured knowledge about the basic architecture of a lift gate. At the same time, the system retrieves the corresponding list of preferred intelligent features that are to be used to create the part: for example, a weld flange is recognized as a weld flange, subject to all of the rules which define this feature.

This selection is also done with a thorough understanding of all engineering attributes of the lift gate system: cost and investment statistics (if available), manufacturing requirements, reliability, inspection requirements, and structural performance.

After a suitable lift gate template has been selected as a basis, the supplementary vehicle environment is defined within the view panel of the feature knowledge editor maintenance window (figure 8-8). This panel has various functions. The first area -- the vehicle development system timeline (the row) -- defines and controls the representation of the part creation and allows the relevant details the timeline associated to the selected row to be displayed, according to the role of the operator. A template will contain all the information needed to create a part properly, including process information. For this reason, the operator is only able to view the information of immediate interest.

The second area, the zone, reads the styling information of the vehicle and attaches other constraints and inputs for the part to the styling geometry. To develop a completely new design with new styling, the engineer specifies the exterior surface to be changed. The system then responds with a list of computer files received from styling. Each file contains exterior surface information created by the stylists. After the engineer specifies styling information for the part, the system calls up the correct data file and asks which parameter the engineer wishes to change. Now, the engineer can modify the template structure or the adapter model by changing the parameters or concept curves and surfaces.

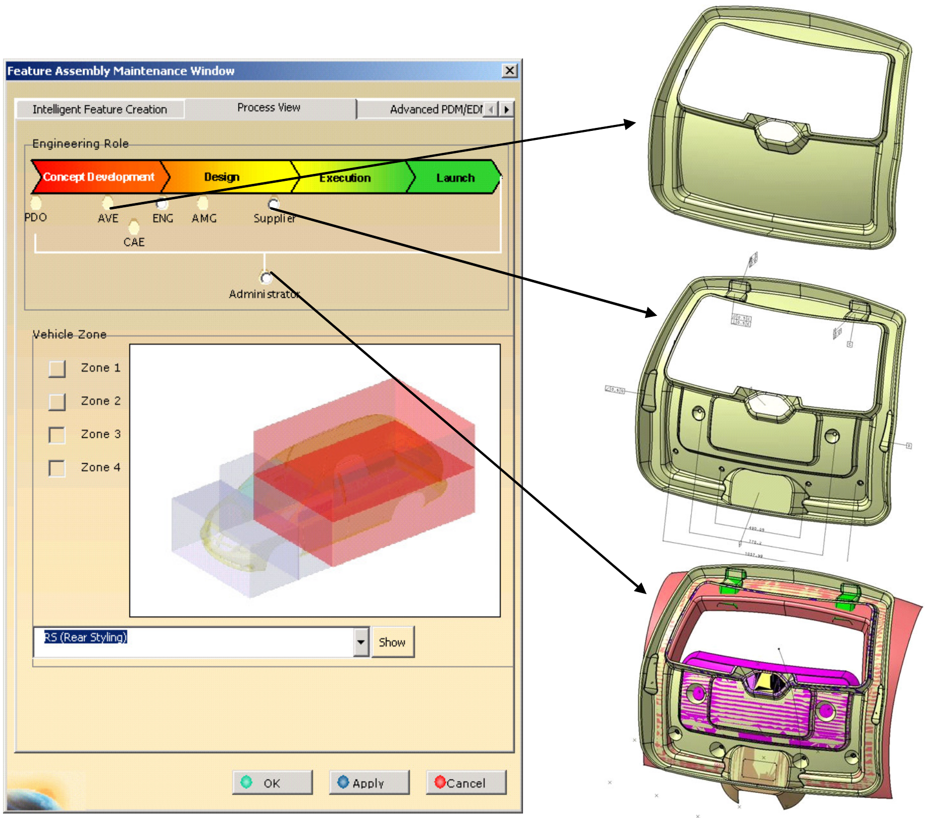


Figure 8-8: Vehicle development system timeline: Management of views related to the current operator (engineering role).

When a suitable design has been chosen, the template structure is adapted to the new situation as per the specified requirements. The work that the system is now doing is the equivalent of many weeks of work with current standard CAD systems. It compares the old lift gate to the new styled lift gate and morphs functional models of the previous design to meet the new requirements.

After this step, vehicle zones can be activated to show additional environmental information.

The vehicle environment is now defined. Additional information is mapped from the PDM system of choice. This knowledge is imported to the part in order to set manufacturing parameters for the creation of the model. With this link, potential manufacturing complications can be detected or new manufacturing parameters can be applied to show geometry and cost impacts associated with the change.

The list of engineering intelligent features is now ready for selection and populated with the list of preferred intelligent features necessary for the creation of the lift gate inner panel (figure 8-9). The list is divided into two categories: intelligent features and free defined features

The first category, intelligent features which define the basic part, consists of the free-form surface features connecting the styled part (here called formation features). The second list, free features, represents all the detail specifications of the part (beads, flanges, bosses, etc.). Intelligent features are those which do not necessarily contribute to the main shape but are defined from a previous panel based on a summary part. Intelligent features can be added, removed, or edited by the basic operator. They can be simply applied to the 3-D workspace. Due to their intelligence and an underlying formalism, they are able to adapt themselves to the new template model.

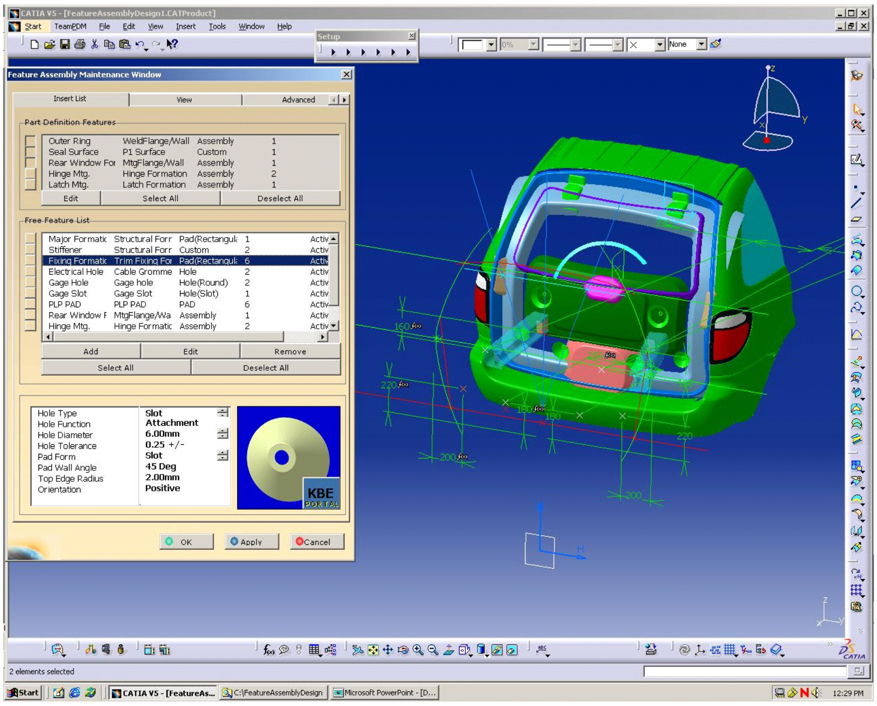


Figure 8-9: Automatic retrieval of preferred engineering features.

Working with a vehicle development system timeline, increased detail is added as the design progresses. At the beginning of the program, we may not require all the features needed to create a lift gate inner panel. For example, an AVE engineer may only require a window opening, the outer ring, and the P1 surface (only formation features). As design VDS progresses, a detail engineer will require all the details: features are selected and the mean surface is added, as we will see later. The result is a flexible, tailored design that meets all the requirements for that particular environment. As the intelligent features are developed, they will contain all the items discussed previously: knowledge, technology, process, and links to advanced knowledge portals.

The engineer is now ready to morph, or transform, the legacy lift gate inner panel template into the new design. When a feature is activated, it automatically adapts to the environment. This is a core activity of the intelligent feature-based approach. At this point, the features are independent of the final part. They modify the appearance according to the environment and may be joined to other features to form a study or assembly feature, which is not constrained when joining the final part. This promotes flexibility. If there are further links of features which do not affect others, identification and diagnosis also become more focused and efficient.

As we are in the “admin” row by default, all the features are activated; yet for all the other rows, features within the list are activated for convenience. Further capabilities are available to operators at all levels for all the free features. Additional features are enabled through the feature edition panel. In this example, we define a wiper formation and, for speed, we select a predefined assembly feature. An alternative would be to select the individual features and to group (constraint) them into an assembly feature.

Selection of the assembly feature shows the micro-template structure. The activation of this assembly feature will instantiate the formation feature, and a functional study of the wiper position will determine the position input for the formation to be instantiated. Feature information that is necessary as minimum input for the instantiation is included during this step.

Access to knowledge portals is possible at any time in the design work. In the case at hand, the area of interest is the rear wiper formation model. Propagation of this knowledge into the CAD model will instantiate rules into the wiper and will check the rules for this study. When the minimum input is mapped, automatic instantiation of the features is possible, and the wiper formation positions itself on the basis of the functional study features contained within it.

The designer can create new features at any time and add them to the list. In creating the necessary data files, the engineers must define rules for these new lift gate’s features. The required lengths of flanges, the draft angles, and the optimum method to determine corner transitions, for example, have to be written as rules to be followed when creating the new design. Engineers can also modify other parameters, using their experience and knowledge of the performance requirements. Knowledge is built into the intelligent features and formulas are applied. Formulas are used to table a particular feature to meet certain requirements. Additional process information can be embedded into a feature as well.

As an example, we take a trim fixing formation. This is an assembly feature consisting of a hole feature and a pad feature. In addition, the function of the assembly feature is an attachment hole. Therefore, the manufacturing tolerances must be plus/minus a certain range. The magnitude of the range is dependent on the hole size, and the hole size is dependent on the part to be attached to it. More features are now driven by the type and function of the feature.

After these steps, the part is now functionally complete with the exception of the mean joining surface. Traditionally, the mean surface was the one to be created first. By the end of the creation process, the mean surface could have been created at any time in order to join all the features (trim of fillet operations), thus duplicating the model size each time. FAD technology reverses this process by creating the mean surface at the end of the part creation process. This is made possible by embedding control points into the formation features. The result is a cloud of points which are used as input for the creation of the mean surface.

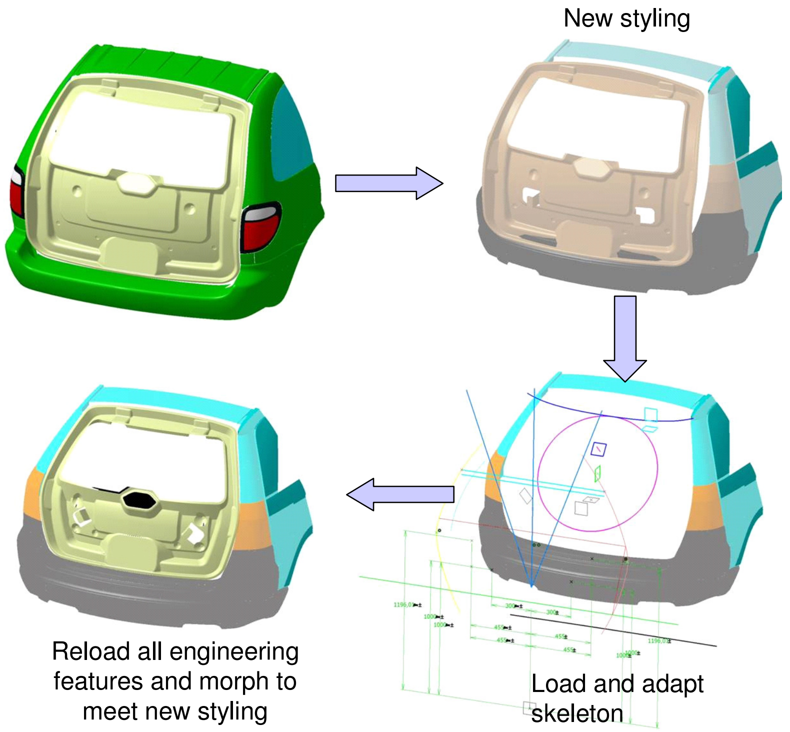


Figure 8-10: Change scenario based on new styling data.

The features are then assembled to the surface. Details such as fillet radii are not necessary as they are defined by the manufacturing method chosen as explained earlier and by knowledge in the features. This is a parallel rather than a linear process. This final operation does not need to be history-based, since all the knowledge has been captured up to this point. Generating a result that is not history-based solves potential security issues, thereby allowing proprietary knowledge to be protected.

Figure 8-10 portrays one of the most powerful functions of FAD. At any time in the design, the new component can be morphed to new styling. The main components used here are the mating model and the control points as outputs of the formation features (i.e. those that contribute to the main form of the component).

When the system analysis of the new design is complete, the system integrates the functions of computer-aided design, engineering, and manufacturing. After a legacy design template has been morphed into a new one, the manufacturing process for the predecessor design can be morphed into the new one for the new design. To do so, the geometry is analyzed once again. After analyzing the geometry, the engineering features recognized are listed on the side. This list is expanded into a list of the corresponding manufacturing or inspection steps involved in producing each feature. The user clicks on one of the process planning commands, in this case an inspection planning command. The system automatically analyzes the component model and identifies available features based on the shape of the feature and how the features are related to each other. Additionally, the user can click on the feature recognition command to recognize all the geometric elements that can be defined as a feature based on the part's geometry and topology and according to the specification made in the feature library. Essentially, the user responds to a series of queries in a dialog box until the system has enough information to define the area as a feature.

So once FAD has recognized the engineering features, they are listed by work plane in a feature tree, following the order in which they were recognized. Interactively recognized features are also inserted in the tree. These features can then be linked to planning routines (measurement strategies and the corresponding cutting tools) stored in a database. The database includes manufacturing parameters such as speeds and feeds that match the different planning tasks or inspection parameters such as the number of measuring points.

The user can have default values applied, or the system can reflect engineering preferences based on related process templates. Connecting features to proven manufacturing and inspection operations is the genius of feature knowledge-based engineering.

After the inspection view has been defined, for example, the user interactively identifies lists of inspection operations step-by-step. This list can then be arranged to form the appropriate inspection sequence, creating a complete inspection plan. Other inspection parameters can also be associated with inspection features at this point.

FAD then generates the inspection process model, which enables planners to see how the inspection plan will progress step-wise until the final operation. At any time, planners can change the sequence of operations, and the system will automatically create a new inspection plan.

The next step is, in the case of a manufacturing process, to generate the tool paths based on the set of operations already established. Coordinate values for the required axis positions and motions are automatically derived from the design feature geometry. Here, it is important to note that the design feature and the manufacturing or inspection process template are associative. When the geometry of the design feature or even of the part model is modified, changes to the process template result in corresponding changes in process operations, manufacturing parameters, measuring elements, and tool paths.

8.4 Conclusion and benefits

Implementing a durable best-in-class product creation strategy call for continuous, systematic improvements, which collectively address all the engineering disciplines across the overall product life-cycle. FAD is the first step toward implementing such a strategy. The key advantages of this concept are manifold:

- It transforms intellectual property (IP) from idea to profits. The knowledge is owned by the company.
- It manages the IP life cycle and offers the possibility of extending the capacity in order to manage the overall product development process, thus enabling faster specification of products and part requirements.
- It allows quality to be addressed right from the start. Intelligent features and engineering templates are provided to capture IP and make them available to inspection staffs. Process checks can be planned and verified in advanced of use.

Furthermore, it yields three key benefits:

- Capture and reuse of the design intent (features and part templates), thus extending existing CAD functions.
- Implementation and automation of design and engineering tasks (process templates).
- Performance of diagnosis mechanisms.
- Evaluation of design-for-manufacturability and measurability, which can be extended for cost estimation purposes

Chapter 9

9 Conclusion, discussion and outlook

This chapter aims at reviewing and summarizing the work and provides an outlook for further developments. Section 9.1 contains a summary of the work and an evaluation of the essential results and conclusions. Section 9.2 provides a future perspective, starting with possible further developments and extensions of FAD. This provides related recommendations and proposals on how the topic can be extended. Possible new and innovation research areas are derived, and related academic and industrial action fields are recommended.

9.1 Conclusion, potential and benefits

This dissertation work introduces a new approach for the improvement of the product creation process in the automotive industry. The key aspect is the integration of product, process planning, and resources allocation. First of all, a theoretical approach to the design process based on a clear definition of product characteristics and product properties has been discussed in chapter 4, section 5.5.2.

Result 1: *An extension of existing theoretical approaches, axiomatic design and property driven, towards an integrated product and process modeling has been described.*

The underlying expression, an integrated product and process relation matrix, is described in equation (5.8). It enables product designers and process planners to understand the relationship between the intended functions of a product and the means by which they are achieved. As it is a mathematical definition, it can easily be transferred into software.

With this mathematical understanding of the product creation process, a structuring method based on feature technology has been proposed, in order to clearly define and handle product characteristics and product properties. An in-depth view was provided to illustrate the new concept, called intelligent features and intelligent templates, generally called solution patterns.

Result 2: *A novel conception approach is developed to realize and drive the integration of product development, its process planning, and the allocation of resources and tools to produce it.*

Product characteristics are expressed by generic entities and constraints to fulfill certain functional product properties that, at the end, define the behavior of the product.

In this sense, a new concept, engineering solution patterns, whose occurrence are intelligent features and templates, has been proposed to integrate product design, process planning, and resource allocation in the automotive engineering. While an intelligent feature is a functional area of a part with strong process relevance according to its manufacturability, templates represent more of a solution pattern representing best practices -- how a part has been successfully designed and manufactured. Both are reusable, parameterized and structured elements with embedded process and resource information. With this new approach, the rapid evaluation of ideas and concepts early in the development process and the identification of important “delighter” downstream features are achieved, as the vehicle concept is refined.

Result 3*: This work has described concepts that ensure a strategically best executable vehicle concept based on architectural, technological, functional, and as geometrical associativity.*

The pattern information is grouped in functional, physical, and process information, each of which describes the necessary requirements for the solution patterns (templates), as follows:

- The *functional view* enables modeling and assessment of functions and sub-functions with their respective properties.
- The *physical view* enables the use of CAx techniques to show interdependencies.
- The *process view* provides criteria to measure the concept against manufacturability, quality assurance, market, customer, etc.

As the main objective of this thesis was to provide new concepts for the integration of product design, process planning, and resource allocation in automotive engineering, a systematization of product functional characteristics (features) was developed, thereby enabling the development of a reference model for an integrated product and process design.

Result 4: *A feature library for body-in-white entities (holes, bosses, flanges, etc.) has been developed and structuring graph has been proposed to link product features and templates with their process counterparts.*

Intelligent features enable designers of a CAx system to retrieve and to use -- depending on the perspective -- all the relevant information that is necessary for their task. They also enable the system to perform automated or system-guided operations based on the information stored. From the very beginning of the design phase, manufacturing requirements can be checked by the system when key parameters or attributes and the designer is informed about possible manufacturing conflicts. In some cases, a certain design can even be blocked by the system. Repetitive loops between engineering, design, and manufacturing planning can therefore be reduced.

Therefore, the concept of intelligent feature is critical because it is the logical link to knowledge-based engineering. Design features such as holes and flanges are defined by the inspection and manufacturing steps commonly followed to manufacture or to inspect them. The manufacturing knowledge (how to manufacture and inspect a hole) is embedded inside the intelligent feature.

The feature-based part template incorporates the intelligence that contains vehicle engineering concept information, body design, process planning, and stamping and manufacturing environments. Intelligence is one of the key attributes but not the only one: interoperability, usability, and adaptability all contribute to a balanced feature part template. Hence, the intensive use of intelligent features leads to reduced development costs by minimizing loops. Both CAx vendors and the automotive industry are currently investing extensive research effort in the implementation of intelligent features in modern CAx systems. This thesis demonstrates the first applications in this area.

The feasibility of the these principles and system concepts that provide practical guidance for both product designers and process planners has been developed in the areas of styling, product design, quality assurance, welding, and stamping die. This concept has been validated in chapter 8 in a new framework for automotive conceptual engineering, called Feature-Knowledge Assembly Design (FAD).

Result 5*: A software prototype, Feature-Knowledge Assembly Design, based on intelligent features and product and process templates, has been developed.*

FAD provides procedures to assist engineers in designing components and assemblies and links them with process planning, thus supplying the foundation necessary to automate the engineering process that otherwise would have to be done manually.

Advantages of this approach are better support for creativity, emotional design, modularity and flexibility, efficiency, higher performance and quality of work, increased re-uses and collaborative thinking and working. It also allows the user to “play” with given variants of the solution patterns (templates) to create new variants based on their requirements for their “delights”.

9.2 Discussion on organizational and educational impact

Naturally, the changes that result from a consistently implemented solution pattern-based product creation process, in the sense of PPR integration, also affect the organization. Such a new process is only successful with appropriate organizational changes. Amon other things, the new systems produces new tasks and roles for the users, for example, template developer and template user.

The following conditions are very important for the successful implementation of solution patterns:

- The solution pattern creation must be centralized and must be generic for a wide range of the primary product. Likewise, it must be ensured that technological advancements are considered in the standards as well as in the solution patterns.
- The solution paterns must always correspond to the current state of the art as well as permit new product innovations. Likewise, realizations at the end of a vehicle project must be evaluated and considered for improvement.
- The solution patterns, therefore, must be submitted to a continuous improvement process. so, too, there are methodical and process related effects for the series design.

Figure 9-1 shows an example of the template creation process and one of its organizational approaches. Mandatory for template definition is a clearly defined and formulated standard or best practice: The template is just the realization of this standard in a CAx format. Accordingly, there must a dedicated team (Centre of Excellence), which has the ability to generalize and has a broad view of the product creation process. It is very important to ensure that the product creation process is not stopped if the templates are not working. That is why these three points are important:

- Template creator is embedded within the process.
- Template creation does not trigger the process.
- Template developers makes final release during the process.

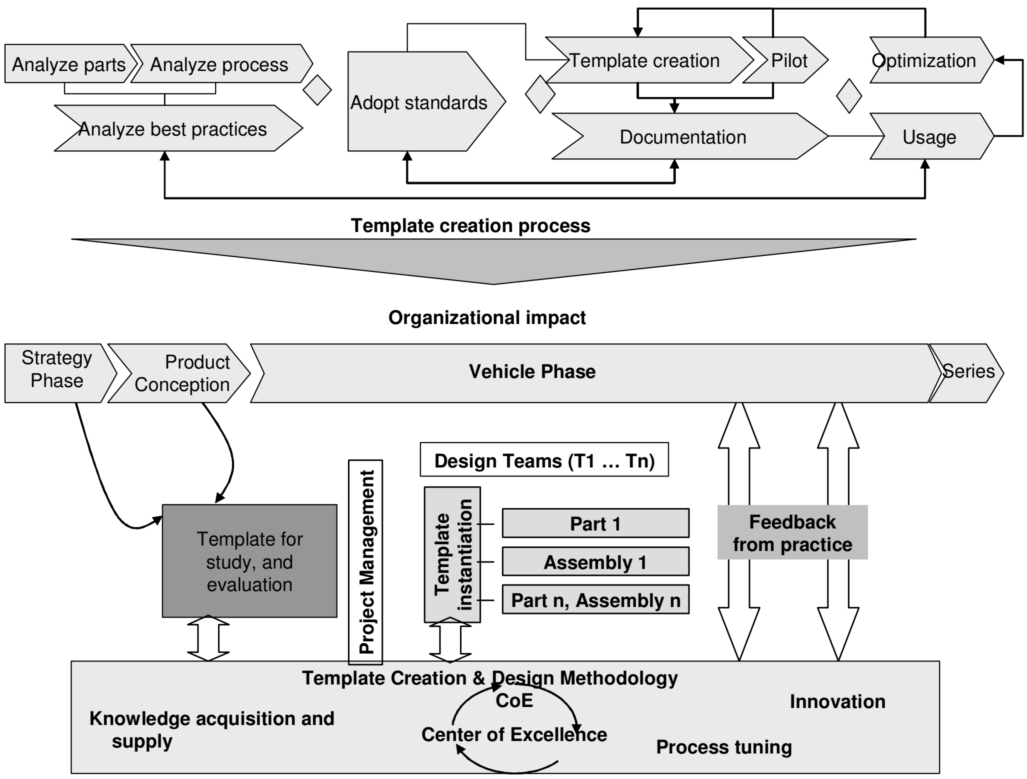


Figure 9-1: An example of the template creation process and the embedding into an organization structure.

Templates represent information is represented that is processed by the users during their work. The templates' information interacts with in already existing mental models in the long-term memory of the users. The templates's information must be optimally mapped with the existing mental models of the designers. However, there is often a gap between template developers and users (figure 9-2).

To fit of mental models with information from the templates, it is important that:

- Data is never processed independently of the foreknowledge.
- Discrepancy between foreknowledge and templates leads to high cognitive expenditure and has a negative influence upon the acceptance of templates the use of templates.

In this sense, the cognitive ergonomics of the developed templates must consider mental factors of designers.

The term cognition (Latin: *cognoscere*, "to know") is used in several loosely related ways to refer to a faculty for the human-like processing of information, applying knowledge, and changing preferences. The term "cognition" is also used in a wider sense to mean the act of knowing or knowledge, and may be interpreted in a social or cultural sense to describe the emergent development of knowledge and concepts within a group that culminate in both thought and action [Wiki].

Ergonomics (or human factors) is, however, the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and is the profession that applies theory, principles, data, and methods to design in order to optimize human well-being and overall system performance [IEA00]

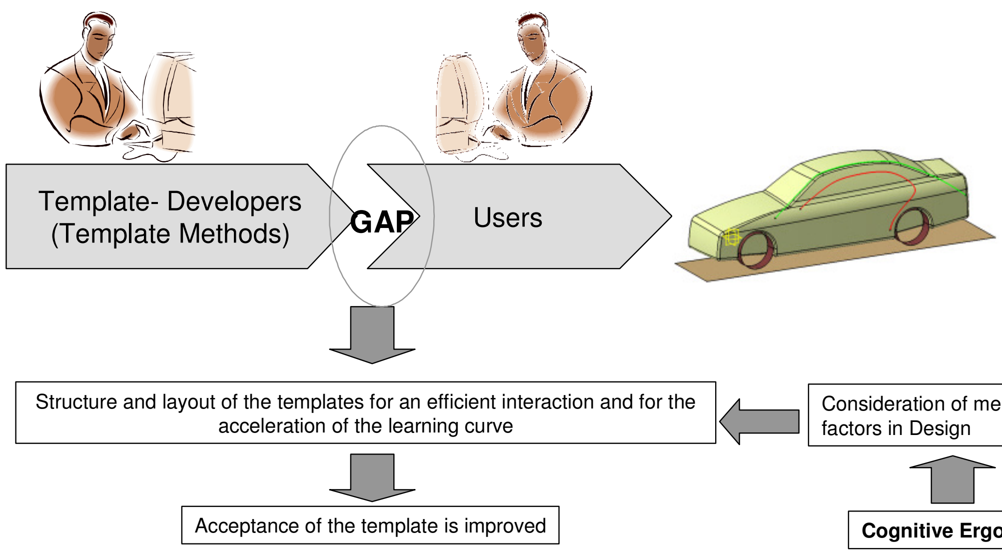


Figure 9-2: Cognitive ergonomics as means of increasing user acceptance.

Therefore, **Cognitive Ergonomics** studies cognition in work settings to optimize human well-being and system performance. But how to bring management is strategic inputs, user acceptance, and template performance together?

Figure 9-3 sketches an approach that has been successfully put into practice. It describes the relationship between the steps towards templates (development road) and reflects the degree of freedom (bottleneck road) of users accordingly to the potential to be used (potentials road). For each step, a dedicated training program is mandatory, considering aspects of cognitive ergonomics.

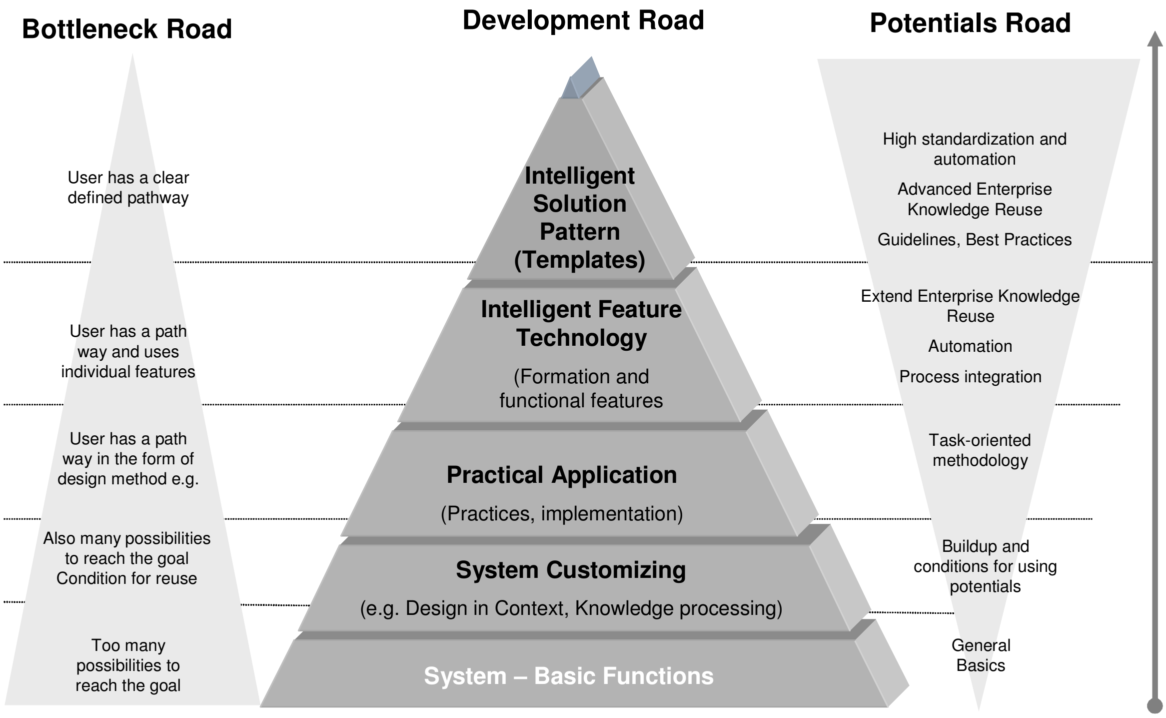


Figure 9-3: Relationship between method development, potentials, and freedom of users.

For users, it is apparent that intelligent features as well as solution patterns are a kind of “black box”. While they used to design step by step, they now receive a tool for their job, which, in extreme cases, consists of combining the different modules together. The development of such modules is quite complex. However, their usage must be simple. This is achieved by introducing design decision support mechanisms inside intelligent features and solution patterns. Figure 9-4 shows the relationship between design complexity and design methods, with or without decision support, which is here related to any kind of knowledge support.

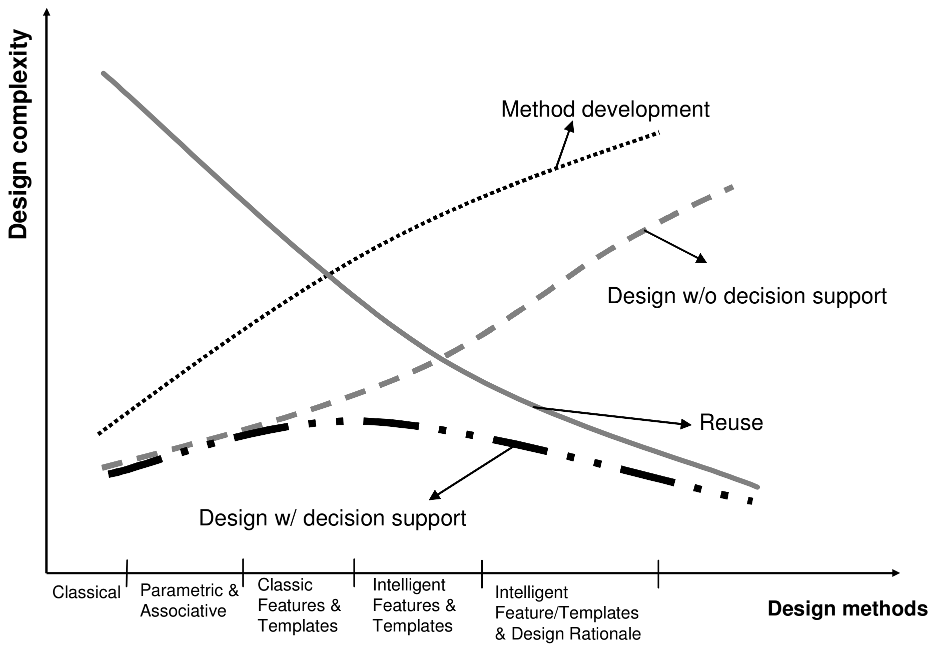


Figure 9-4: relation of design complexity and design methods.

New team structures: Integrated Product Creation Teams (IPCT)

It is apparent that this novel approach has a great impact on team structures. During this work, different studies have been done and mapped with current research in industrial engineering and management in terms of evaluating organizational structures in the context of PPR integration. As a result, organizational architectures are of critical importance for the improved performance of product creation processes in terms of creativity, quality and speed. Today, streamlining those processes is of vital importance for survival in a global and turbulent marketplace. However, the most commonly used solution, the matrix structure, does not support this effort sufficiently.

Instead, a new configuration is emerging: an organizational arrangement consisting of several temporary, integrated product creation team (IPCT) organizations, one for each product creation project, to be drawn from a sustainable pool of professionals representing multiple competencies. This novel, dynamic organizational architecture is clarified in terms of its opportunities for improved creativity, quality and speed.

Integrated product creation teams are cross-functional teams that are formed for the specific purpose of delivering a product. This is important to assure that the innovation is optimized and that the knowledge gained during a project is passed to the next one. IPCT members should have complementary skills and be committed to a common purpose, performance objectives, and approach for which they hold themselves mutually accountable. IPCTs are the means through which PPR Integration is best implemented. Members of an integrated product creation team represent design, engineering, manufacturing, and support functions, and organizations which are critical to developing, procuring, and supporting the product.

All functional disciplines influencing the product throughout its lifetime should be represented on the team. Having these functions represented concurrently permits teams to consider more and broader alternatives quickly and, in a broader context, enables faster and better decisions.

The expectation among the team members becomes high, too. Once on a team, the role of an IPCT member changes from that of a member of a particular functional organization, who focuses on a given discipline, to that of a team member, who focuses on a product and its associated processes. Each individual should offer his/her expertise to the team as well as understand and respect the expertise available from other members of the team. Team members work together to achieve the team's objectives.

Five criteria are important for a successful IPCT member, of which one, and only one, is a thorough grounding in technical disciplines and systems. The other four essential qualities he described by Olling [Olling 99] are:

- An understanding of global issues
- A well defined personal sense of ethics
- The ability to communicate well at all levels
- The ability and willingness to particpate in such IPCT teams

(Inter)Cultural remarks

Another critical observation in this context are differences in culture, process, management, and organization observed in large companies. Often, this requires change in thinking. The Following differences have been observed during this project’s realization in an international context between US and European partners:

- Acceptance of best practices in the design departments and by management
    - US: best practices are defined and commonly accepted. Management trusts feasibilities based on best practices.
    - EU: Each product has reasons to “optimize“ best practices.
- Different understanding of “standards“:
    - US: Many standards are used for a wide range of product lines.
    - EU: Different standards are used for each vehicle type.
- Efficient processes and methods:
    - US: The most efficient process is used for each individual task.
    - EU: Tendency to standardize processes and methods regardless of individual advantages or disadvantages.

Hence, the successful implementation of such an approach depends how well intercultural aspects have been taken into account: There should be a clear and common understanding of the expectations and the way of thinking of different team members.

New vehicle creation process

On the whole, the author suggests that in order to take full advantage to the benefits provided by this approach, companies should change the current standard product creation process that are currently characterized by:

- Strict design reviews
- Gates for decision making
- Functional development teams

While product creation process remains linear and sequential, it will not support effective change management. The author proposes a new concept sketched in Figure 9-5.

The key characteristics of this new adaptive and flexible lean product creation process are:

- Possibility to generate many alternatives and studies during product synthesis. To do so, the underlying principle must be based on solution patterns and their capability to be adaptive.
- All options are kept open longer until all aspects of market, regulation, technology, and manufacturing conditions are proven for feasibility before going to the next step.

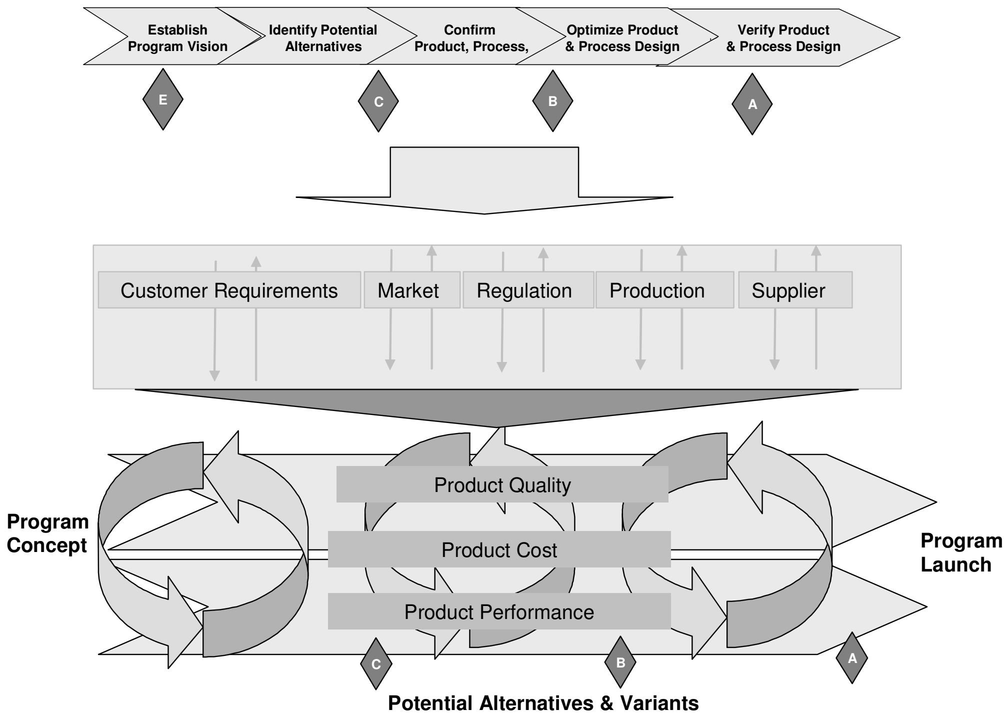


Figure 9-5: New product creation process for the automotive industry.

It is mandatory to observe conditions for successful management of the enterprise knowledge in terms of:

- ***Culture***: an open organizational culture energizing to the knowledge exchange (a "knowledge-friendly culture").
- ***Organization***: organizational structures and conditions, allowing real exchange of knowledge.
- ***Technique***: efficient information and communication systems focused on the requirements of the respective enterprise for the support of knowledge management.

To conclude, the following table gives an overview of critical characteristics for implementing integrated product, process, and resources:

Key Characteristics	Comments
Downstream/Product Life-Cycle	• Primary PPR integration objective is to identify and satisfy each downstream process step's needs better and faster. Downstream needs determine the nature of the product and its associated processes. • Early integration of production and resource elements results in lower costs through fewer changes/less rework later in the creation process.
Concurrent Development of Products and Modeling of Processes	• Processes that are used to manage, develop, verify, test, deploy, operate as well as support, train people, and eventually dispose of the product should be planned early in product design.
Early, Continuous Life-Cycle Planning	• Early product life-cycle planning provides a foundation for the various phases of its development and should include downstream organizational functions and suppliers. • Key software functions, engineering activities, and milestones should be defined to track, understand, and effectively manage progress towards production targets, allocation of resources, and the impact of problems, resource constraints, and changes in requirements. • Product and process modeling and performance must remain balanced to optimize product life-cycle affordability and production objectives.
Robust Design and Improved Process Capability	• Promote the use of advanced design and modeling technologies such as intelligent features and solution patterns that will result in comprehensive software that achieves high quality and is robust for all domains, and promotes continuous product creation process improvement. • Users should be integrated from the beginning. It is essential that

	formulate their expectations and anxieties. On the other hand, it is also essential to consider their expertise.
Integrated and Multidisciplinary Teamwork	• Multidisciplinary teamwork is a critical factor in the integrated and concurrent development of a product and its processes in order to achieve product and program objectives. • Team members must fully understand their roles, support the roles of all other team members, and understand the constraints under which the team operates.
Seamless Management Tools	• Establish a framework that relates products/processes/resources at all levels to demonstrate dependencies and interrelationships. • An established management system should relate requirements, planning, resource allocation, and program execution and tracking over the product life-cycle.

Table 9-1: Key characteristics of Product, Process, and Resources Integration

9.3 Main benefits

The approach presented here results in new potentials for cooperation and parallel treatment of dependent components in the sense of concurrent engineering by several technical designers. It leads to the coupling of the processes by consistent passing on of data, decision alternatives, and changes and thus promotes a constant process chain within the body development phase.

The initial assessments of this concept at DaimlerChrysler demonstrated that there is a potential for reduction in the design time needed for new designs of up to 45% and for variant design of up to 80%. The parametric-associative body modeling on the basis of intelligent features therefore leads to an efficient and significant decrease in development expenditure and the number of change loops. The comprehensibleness and reusability of the design knowledge and a more effective adjustment, for example, at design and package changes in other model variants, are accomplished through this methodology.

A further benefit is an increase in productivity and process security achieved through knowledge and experience integration in the CAx development process by the observance of process-specific rules and firm standards and their examination. With the partly automated digital planning of product, process, and resources on the basis of intelligent body features, not only does user acceptance increase, but also maximum process transparency is achieved.

The main advantages from a research point of view are summed up below:

- Explicit illustration of function, technological data, structure information, and other data by the reference of characteristics with objects, which are necessary in the process of the product emergence.

- Possibility for downstream processes to extract necessary information directly by evaluation of the model.
- Avoidance of redundant development steps and redundancy with the production of model information via a uniform product model.
- Improved communication between different phases of the product life-cycle.
- Design consistency and process reliability.

9.4 Outlook

The integration of life-cycle vehicle creation across enterprise is the biggest challenge for automotive companies and the hallmark of successful business development in the 21st century. It is defined as the seamless, real-time integration of the entire value chain, geared toward delivering customized solutions and experiences in a timely and cost-effective manner.

Lean production per se is becoming less of an issue for the automotive industry. Today and in the near future, car companies will more and more need factories that are completely flexible, able to switch from making one model to another to meet fluctuating demand, as well as engineers and designers able to work in a fully collaborative environment, eliminating duplications and overlaps. The underlying idea is to tie product development, marketing, and manufacturing more closely together.

In this context, a plethora of niche models needs to be designed and launched to the market to attract particular groups of consumers, and to renew the models rapidly enough to keep interest fresh. Thus, the emerging concept of the "build to order car" is considered a strategic vision for the product creation process in the future.

Although there is as yet no automatic car-create button, and there will surely never be a command that can produce (manufacture) a car just by clicking on a button, it is surprising how this futuristic prediction is already a reality in specific process steps of passenger car production. While these individual concepts are, in fact, not yet fully perfected and some advanced aspects are only in the pipeline, it is astonishing how much is actually happening in the world of automotive manufacturing. And it is the concept of product, process, and resources integration based on intelligent feature technology as well as feature-based templates -- a coupling of feature-based modeling and knowledge-driven engineering-- which is one of cores of these breakthroughs.

With the inclusion of the specification-driven methods and design rationale, it is possible to accomplish a rapid evaluation of variant products and production processes, thereby yielding earlier statements about feasibility. Specification-driven design and planning leads purposefully to the description of the product specification and the derivation of geometric solutions, the integration of computations, and the maintenance of the relationship between specification and the geometry derived.

Future IT trends

Today, all our efforts focus on digital engineering. The vision and future of CAD/CAM systems is logically directed toward virtual engineering. Figure 9-5 illustrates the evolution of CAD/CAM systems and the expected maturity into practice in the automotive industry. In virtual engineering, there will be largely configuration and modification tasks: new styling will be applied, customers will be able to configure their products themselves, and designers could simply paste new features and part templates. They will be able to manipulate designs, and all the changes will be directly reflected in geometry, using intelligent objects and templates developed today in the area of digital engineering.

Virtual models will be used to capture product, process, and resource knowledge, and to develop and optimize of product concepts, designs, and manufacturing tools. At any time in the design process, the embedded intelligence will provide more flexibility, and consequences will be constantly monitored: performance, quality, and cost will be directly evaluated against the underlying customer and functional requirements.

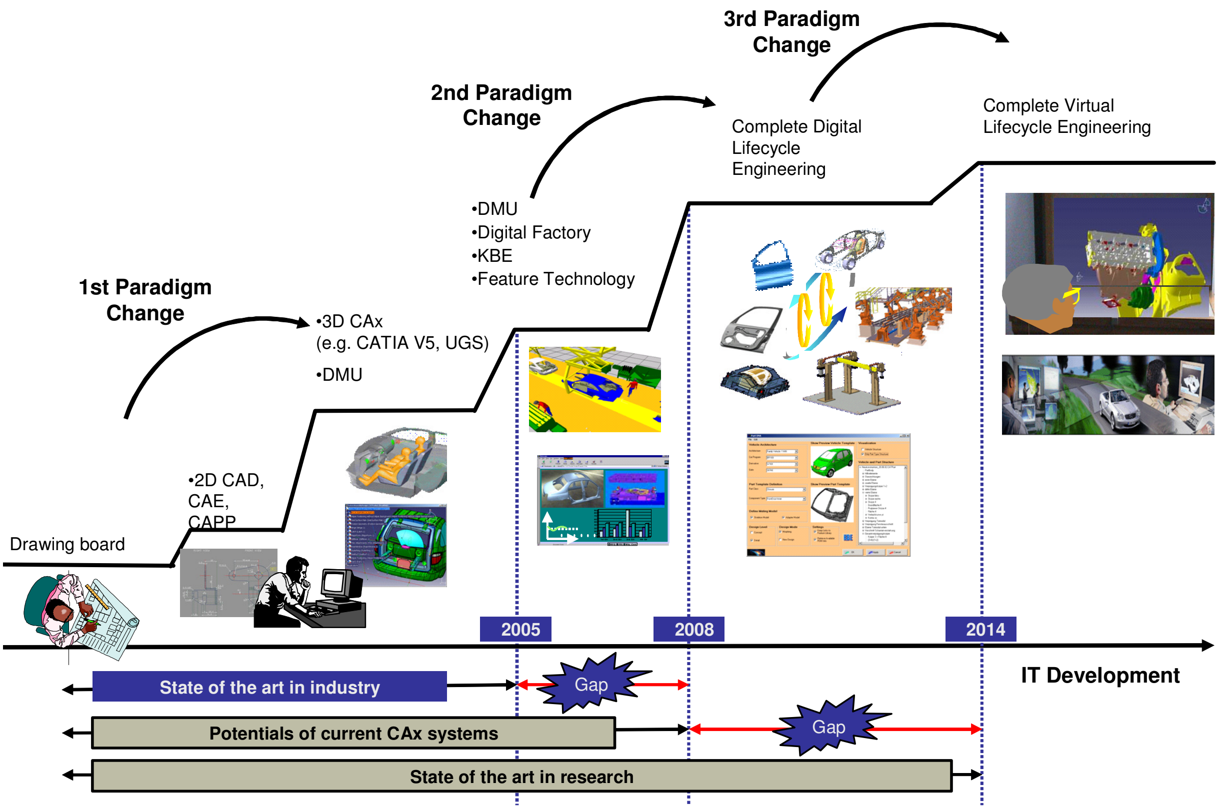


Figure 9-6: Evolution of CAD/CAM systems and their expected maturity in practice in the automotive industry.

In particular, using the solution patterns (templates), the implement of the "virtual vehicle" concept as a computer-based, realistic representation of the total vehicle will be possible, including all associated functions during the entire product life-cycle, which offers equivalent opportunities to customers, OEMs and suppliers, to manipulate and evaluate the future (physically not existing) vehicle with respect to all relevant properties in an intuitive, realistic way.

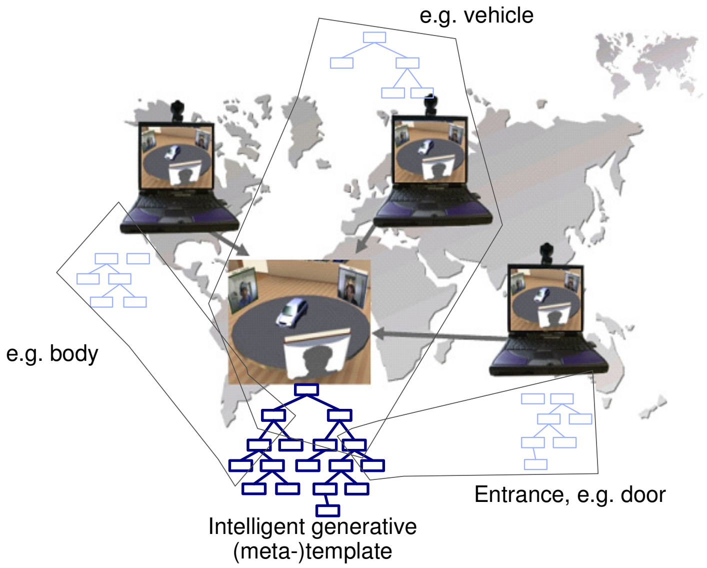


Figure 9-7: Real-time collaboration in future product creation processes.

Internet technology will provide the necessary platform for real-time interactivity in the collaborative process and accordingly support the real collaboration of individuals in their professional role, thus enhancing creativity and productivity, and presenting the challenge of moving from a corporate integration to global enterprise collaboration, as shown in figure 9-7

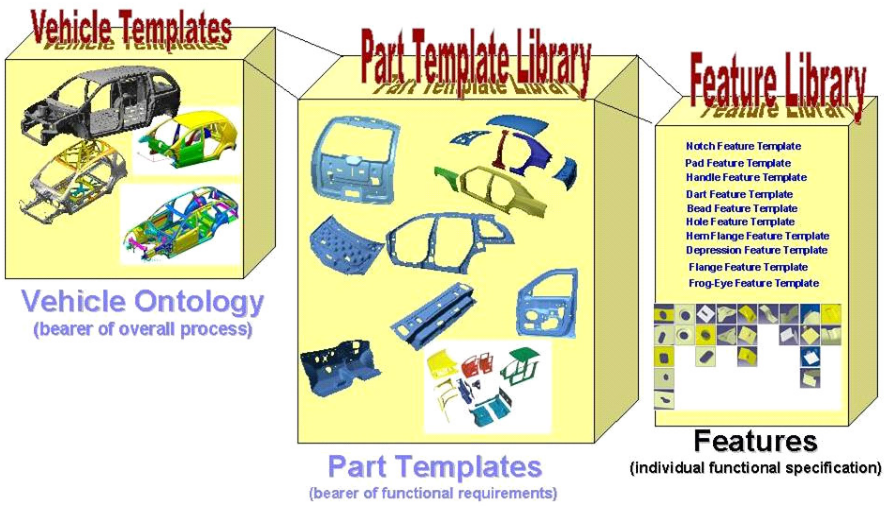


Figure 9-8: Features for the BiW process.

To reach this vision, it will be necessary to describe all the necessary dependencies of a vehicle as a generative vehicle template (figure 9-8) based on the description of vehicle ontology.

This vehicle template will be employed as a foundation for other platforms or car programs. At this time, we will be close to the vision of the automatic car-create-button. Yet, even if we are able to digitally design or to generate a complete vehicle by command in the digital or even in the virtual factory, we will never be able to produce it automatically. However, just the fact that we are working on this vision of the “100% virtual car” is exciting enough. For new opportunities will arise to fulfill the four trends mentioned at the beginning of this work: individualization, socialization, globalization, and virtualization.

Furthermore, in-depth work will be done in the area of problem-solving methods or cost estimations. Other implementations targeting the capture of knowledge on the fly, the integration of mechanics, electronics, and software (mechatronics concepts), and the embedding of artificial intelligence in order to perform tasks in manufacturing will be possible.

Future academic research fields

The next step after vehicle templates will be the consideration of a vehicle as a “living product” which, as in nature, comes into existence through “genetic material or DNA”. It is “born”, “grows”, and reaches the necessary maturity for production. It stays “alive” when delivered to the customer and will “die” at the end of its life [Ovtcharova 04].

Following the biological paradigm, one of the critical factors for success is the consolidated, efficient, and adaptable representation of all necessary and sufficient requirements and constraints for the development of a new generation of vehicles: vehicle DNA.

- A “living” vehicle possesses a “biological genetic history” and can be “born” with desired properties.
- The generic history implies very well known properties as well as new properties required by customers or corresponding to technological innovations.
- The vehicle “DNA” is the basis for the development of a highly flexible (associative) vehicle concept which includes architectural, functional, technological, and geometric relationships and satisfies different customer requirements.

Here it is not enough to simply merge existing specifications and solution patterns into one document; the “DNA” must be designed through collaborative thinking of experts and the use of best practices (heuristic knowledge). In other words, the DNA should be considered a “genetic material” at the beginning of the vehicle program, containing both the vehicle elements and their relationships.

Modifying the genetic code leads to the brand specific product. From a biological point of view, this is comparable to the evolution of high organisms (humans) in the early stages of mankind to humans in the present. Figure 9-9 shows the evolution of the vehicle creation process and the different research fields as well as the expected outputs.

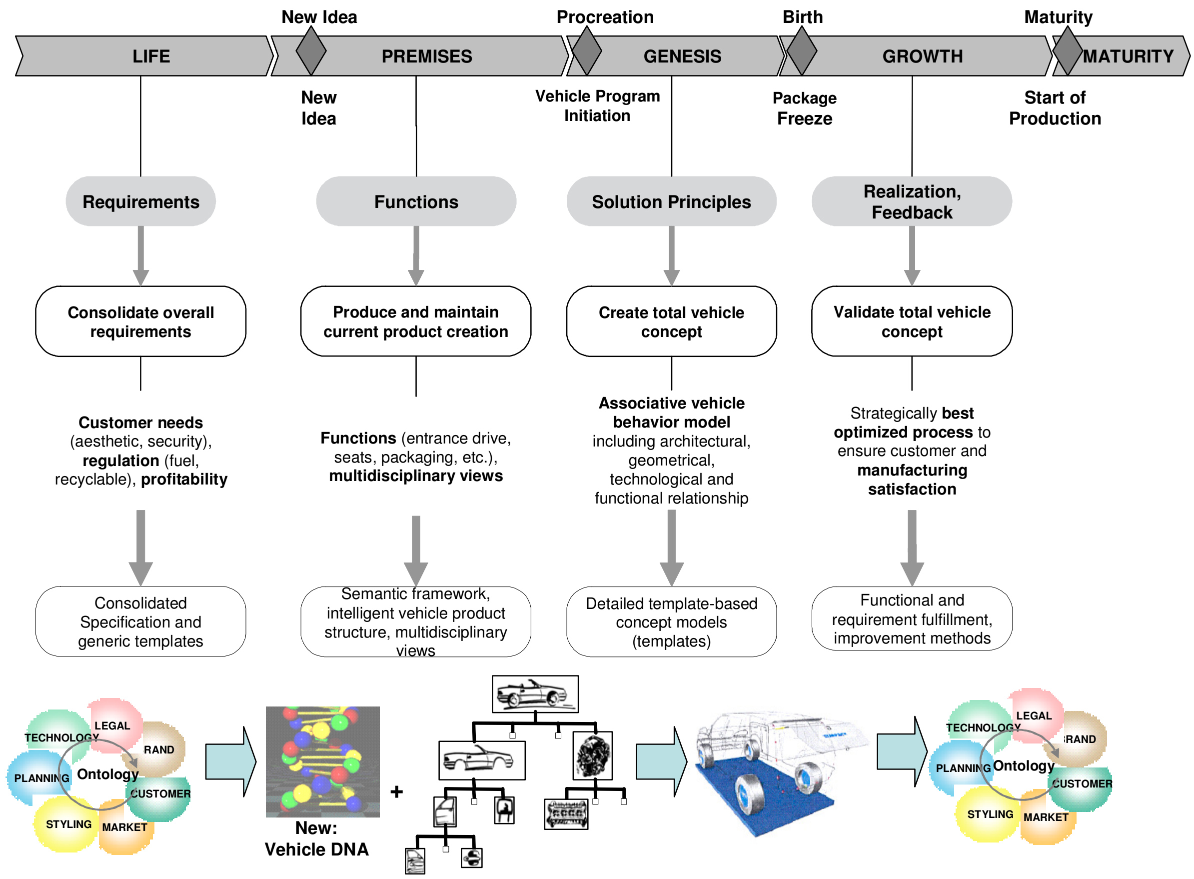


Figure 9-9: Future research efforts based on “vehicle DNA”

Chapter 10

10 Literature

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11 Appendix

A - Criteria for state of the art of FENet

FENet was a Thematic Network, funded by the European Commission for four years from August 2001. The network sought to coordinate activities within Europe aimed at improving both the quality of industrial applications of finite element (FE) technology and the level of confidence that can be placed in the computed results.

The FE technology used in various industrial sectors was examined from the perspective of both the State of Practice and the State of the Art. Here, the State of Practice refers to the degree of uptake of a technology by industry -- it is in effect a reflection of the maturity of the industrial usage. State of the Art refers to the degree to which a technology has been developed to meet a perceived need.

Three measures were used to qualify the situation in the various industry sectors: Technology Readiness Level (TRL) quantifies the availability of the required technology (0 not available, 9 fully developed). Maturity Level (ML) (in this work as Level of Practice – LoP) quantifies the extent to which the technology has been adopted (0 not adopted, 9 fully utilized) and Priority Level quantifies the importance of the technology to the industry sector (0 not needed, 9 business critical). The reports also considered such issues as areas for research, business drivers, and the barriers to further uptake of the technology.

TRL	Definition for engineering analysis method/tool	Life-cycle stage
TRL 0	No basic principles observed and reported	No basic technology research
TRL 1	Basic principles observed and reported	Basic technology research
TRL 2	Concept and application of method/algorithm(s) formulated	Research to prove feasibility
TRL 3	Proof of concept demonstrated for critical aspects of method/algorithm(s)	
TRL 4	Method/prototype tool validated on simple representative test cases	Technology development
TRL 5	Method/prototype tool validated on comprehensive representative test cases	Technology demonstration
TRL 6	Method/prototype tool demonstrated on representative real-world analysis problems – implemented functionality complete – performance/interfacing solved in principle	
TRL 7	Method/prototype tool validated on representative real world analysis problems – implemented functionality complete	Method/tool development
TRL 8	Robust method/tool, routinely used in industrial product development environments – with adequate software problem han-	Method/tool operation

	dling, distribution, user documentation, and support	
TRL 9	TRL 8, plus method/tool fully integrated in the industrial product development processes	

Table 11-1: Technology Readiness Level (TRL) indicates the state of the art or technological maturity.

LoP	**Level of Practice**
LoP 0	No use
LoP 1	Information received
LoP 2	Evaluation temporary licence
LoP 3	First approaches
LoP 4	Occasional use
LoP 5	Periodic use
LoP 6	Currently used within the most important activities
LoP 7	Currently used within all the activities
LoP 8	Essential for the correct workflow
LoP 9	Necessary for the design sign-off

Table 11-2: Level of Practice (LoP) gives a measure of industrial maturity.

PLI	**Priority Level Index**
LoP 0	No need at all
LoP 1	The need is only a feeling (it could be useful)
LoP 2	Random need
LoP 3	First support to traditional design process, not necessary for decision phase
LoP 4	Necessary for innovative projects
LoP 5	Necessary for strategic projects
LoP 6	Daily need
LoP 7	Important
LoP 8	Very important
LoP 9	Essential, the work cannot be done without it

Table 11-3: Priority level Index (PLI) indicates the relevance for industry.

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