Tailored Data Exchange Processes for Automotive Body Development

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„The slaves of today are not driven with whips, but with schedules.”

(John Steinbeck, 1902-1968, US-American writer)

Abstract

Due to continuously changing boundary conditions in the automotive industry, development processes must be constantly optimized and enhanced. Besides propulsion systems and automated driving technologies, vehicle body development (BIW – Body-In-White), which covers the full range of styling integration, aerodynamics, structural design, materials and joining technologies, represents an essential field of research. Among others, development goals include body stiffness and durability, optimized crash behavior and the reduction of body weight to reduce driving resistance and thus lower fuel consumption and exhaust emissions.

The reduction of body mass and further of the total vehicle weight can be achieved by various opportunities. In this context, the so-called “multi-material body design”, which focuses on the use of different materials and material combinations, plays a crucial role. In addition to the achievable reduction of weight, “multi-material body design” is able to provide the advantage of cost-savings at the same time.

The implementation of several materials and material combinations also means that different types of joining technologies must be adapted to the increasingly applied “multi-material body design” solutions. This means that new challenges arise in both, the area of creation, administration and management of joining technology data as well as the area of data and metadata exchange between the different involved disciplines and systems of computer-aided design (CAD), engineering (CAE) and manufacturing (CAM).

The aforementioned data exchange process between the individual CAx disciplines poses new challenges for the various applied disciplines and the concerned engineers. At the same time, new possibilities arise to optimize the development processes by implementation of innovations with the target to reduce data engineering and data management effort as well as development duration. Furthermore, optimized development processes and data exchange have the potential to reduce development costs.

The presented thesis deals with data management processes between different CAx environments, whereby the main focus is put on the data exchange between design (CAD) and calculation (CAE) as well as on design and manufacturing (CAM). Since joining technology is becoming increasingly important in the automotive industry, joining technology data play a significant role in data management, especially in BIW development.

Furthermore, an approach of an efficient data exchange model, which is tailored to the requirements of the automotive industry is provided. The changes in the used types of joining technology and their metadata as well as an optimization of the data exchange options are considered. Furthermore, this approach offers an optimized data exchange process, which can significantly reduce the development time of vehicles.

Kurzfassung

Aufgrund stetig ändernder Randbedingungen in der Automobilindustrie müssen auch die Entwicklungsprozesse ständig optimiert bzw. verändert werden. Neben der Antriebstechnik und den Automatisierungssystemen stellt die Karosserieentwicklung (BIW – Body-In-White), die unter anderem den gesamten Bereich der Werkstoff- und Fügetechnik umfasst, ein wichtiges Forschungsfeld dar. Zu den Entwicklungszielen gehören beispielsweise Karosseriesteifigkeit und Langlebigkeit, optimiertes Crashverhalten und die Reduzierung des Karosseriegewichts zur Verringerung der Fahrwiderstände. Mit einer Verringerung des Fahrzeuggesamtgewichts ergeben sich in weiterer Folge auch Reduzierungen im Kraftstoffverbrauch und in den Abgasemissionen.

Die Reduktion der Karosseriemasse und folglich des gesamten Fahrzeuggewichts kann dabei mittels verschiedener Maßnahmen erreicht werden. Eine wesentliche Rolle spielt dabei, das sogenannte „multi-material body design”. Bei diesem steht die Verwendung unterschiedlicher Materialien bzw. Materialkombinationen im Vordergrund, um neben potenzieller Gewichtseinsparung Kosteneinsparungen realisieren zu können.

Die Einführung von verschiedenen Materialkombinationen hat zur Folge, dass Fügetechnologien an die entsprechenden multimateriellen Konstruktionslösungen angepasst werden müssen. In diesem Zusammenhang treten neue Herausforderungen in beiden Bereichen, der Erstellung und Verwaltung von Daten der Fügetechnik, sowie im Austausch dieser Daten und Metadaten zwischen verschiedenen Disziplinen und Systemen der computergestützten Konstruktion (CAD), Simulation (CAE) und Produktion (CAM), auf.

Der Datenaustauschprozess zwischen den einzelnen CAx Disziplinen wirft neue Herausforderungen für die verschiedenen Disziplinen und involvierten Ingenieure auf. Gleichzeitig ergeben sich damit aber auch neue Möglichkeiten, den Entwicklungsprozess mittels Innovationen und geeigneter Maßnahmen so weit zu optimieren, dass sowohl der Aufwand zum Datenmanagement als auch die gesamte Entwicklungszeit eines Fahrzeuges wesentlich verringert werden können.

Die vorliegende Arbeit beschäftigt sich in erster Linie mit dem Datenaustauschprozess zwischen den verschiedenen CAx Umgebungen. Hierbei liegt das Hauptaugenmerk auf dem Datenaustausch zwischen den beiden Disziplinen der Konstruktion (CAD) und Berechnung/Produktion (CAE/CAM). Da die Fügetechnik in der Automobilindustrie eine immer wichtigere Rolle einnimmt, besitzen Verbindungstechnikdaten einen zentralen Stellenwert im Datenaustauschprozess ein.

Des Weiteren wird ein Ansatz eines effizienten Datenaustauschmodells, welches auf die Anforderungen der Fahrzeugindustrie zugeschnitten ist, geliefert. Dabei werden sowohl die Änderungen im Bereich der verwendeten Typen von Fügetechnik und deren Metadaten, als auch eine Optimierung der Datenaustauschoptionen berücksichtigt. Des Weiteren bietet dieser Ansatz einen optimierten Datenaustauschprozess, welcher die Entwicklungszeit von Fahrzeugen wesentlich verringern kann.

Statutory declaration

I declare that I have authored this thesis independently, that I have not used other than the declared sources/resources, and that I have explicitly marked all material, which has been quoted either literally or by content from the used sources.

Graz, 15.01.2019

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Alexander Kreis

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List of Abbreviations

0D	Zero-Dimensional
1D	One-Dimensional
2D	Two-Dimensional
3D	Three-Dimensional
AP	Application Protocol
API	Application Programming Interface
approx.	approximately
AR	Augmented Reality
BIW	Body-In-White
BoM	Bill of Material
BREP	Boundary REPresentation
CA	Computer-Aided
CAD	Computer-Aided Design
CAE	Computer-Aided Engineering
CAM	Computer-Aided Manufacturing
CAS	Computer-Aided Styling
CATIA V5	Computer Aided Three-Dimensional Interactive Application V5
CAx	Computer-Aided x (where x serves as placeholder)
CC	Concept Confirmation
cf.	confer/compare
CFD	Computational Fluid Dynamics
CFRP	Carbon Fiber Reinforced Plastic
CGR	CATIA Graphical Representation
cm	centimeter
CO_2	Carbon dioxide
COG	Center Of Gravity
COM	Carry Over Module
COP	Carry Over Parts
CSG	Constructive Solid Geometry
dB	Decibel
DB	Data Base
DBMS	Database Management System
DF	Data Freeze
DIN	Deutsche Industrie Norm (German Industry Standard)
DMU	Digital Mock-Up
e.g.	exempli gratia
EOP	End Of Production
etc.	et cetera
F	Force
FC	Functional Confirmation
FDS	Flow Drill Screw
FEM	Finite Element Method
Fig.	Figure
g	gram
GFRP	Glass Fiber Reinforced Plastic
GUI	Graphical User Interface
i.e.	id est
IGES	Standard for the Exchange of Product Model Data
IS-BIW	Input Stop Body-In-White

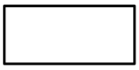
IT	Information Technology
JT	Jupiter Tessellation
KBE	Knowledge-Based Engineering
km	kilometer(s)
kN	kilonewton
l	liter(s)
LOD	Level Of Detail
LS	Launch Sign Off
m	meter
MBS	Multi-Body Simulation
MIG	Metal Inert-Gas
mm	millimeter
mpg	miles per gallon
MS	Microsoft
N	Newton
nm	nanometer
no	number
NURBS	Non-Uniform Rational B-Splines
OEM	Original Equipment Manufacturer
pcs	pieces
PDM	Product Data Management
PDMS	Product Data Management System(s)
PF	Package Freeze
PLC	Product Lifecycle Collaboration
PLM	Product Lifecycle Management
PMI	Product Manufacturing Information
PP	Pilot Production
PPS	Preliminary Product Specification
PS	Process Stability
PSM	Product Structure Management
PTO	Production Try Out
PV	Product Vision
SE	Simultaneous Engineering
SMC	Sheet Molding Compound
SOP	Start Of Production
SPR	Self-Pierce Rivets
STEP	Standard of The Exchange of Product model data
STL	Surface Tessellation Language
SUV	Sport Utility Vehicle
TA	Target Agreement
Tab.	Table
TIG	Tungsten Inert-Gas
USA	United States of America
VPD	Virtual Product Development
VR	Virtual Reality
VRML	Virtual Reality Modeling Language
xlsx	Excel spreadsheet
xMCF	extended Master Connection File
XML	eXtensible Markup Language

Formula Symbols

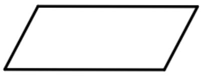
ρ_x	Density of the material x
$\rho_{aluminum}$	Density of aluminum
ρ_{CFRP}	Density of Carbon Fiber Reinforced Plastic
$\rho_{magnesium}$	Density of magnesium
ρ_{steel}	Density of steel
E_x	Modulus of elasticity of material x
$E_{aluminum}$	Modulus of elasticity of aluminum
E_{steel}	Modulus of elasticity of steel

Flow Chart Key

This flow chart key serves as a reference for all process-charts and diagrams, which are used in this thesis.



…tool, system, environment, exchange drive



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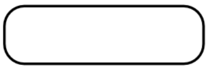

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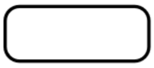

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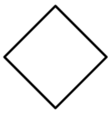

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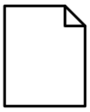

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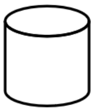
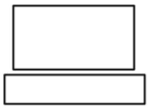
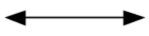


…data base, product data management system



…remote machine to access other company environments

…one-direction



…bi-direction

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1. Introduction

1.1. Motivation and Initial Situation

In recent years, the automotive industry has been faced with numerous new challenges. This continuing trend, combined with today's growing globalization, is increasing the pressure on automotive manufacturers and suppliers. From ecological, economic and technical points of view it has become increasingly important to save costs and time in the entire vehicle development process in order to remain competitive on the market.

An important starting point for achieving a continuous optimization includes the decrease of the total development time of vehicles. In the past, two essential factors – simultaneous engineering and the introduction of various CAx (Computer-aided x – where x serves as placeholder) tools to support engineers throughout the entire development process and beyond – led to this reduction [55]. The trend towards shorter development time has continued over several decades and the target of further improvements plays an important role in all considerations of this thesis.

The introduction of CAx tools and systems not only shortened the development time but also confronts the engineers with new challenges. One of these challenges includes the configuration of data exchange processes between different CAx disciplines. In this context, several factors such as exchange formats, process adaptability, task assignment, different boundary conditions and optimization measures must be considered. In the field of automotive body design, the reduction of the vehicle mass has a massive impact on the required optimization of data exchange processes. The reason for this is that mass reduction calls for new technological approaches (e.g. new joining technologies) that are increasingly integrated into the development processes.

In this thesis, the term "BIW" (Body-In White) refers to the assembled unpainted car body sheet metals of the basic bodywork [85]. These car body sheet metals include all panels of the body structure (e.g. A-pillar, B-pillar, C-pillar, ring panel, quarter panel, drip rails, roof frame …). Another term used in literature is the so-called “closed BIW”, which contains the mentioned BIW components and all closures (e.g. hoods, bonnets, doors) as well as roof structures (e.g. roof, headers, bows) [9], [85]. In view of production engineering, the BIW represents the manufactured level before components and systems are added (e.g. engine, chassis, external components and interior trim) [117]. Fig. 1 shows an overview of a closed BIW structure including its components [104].

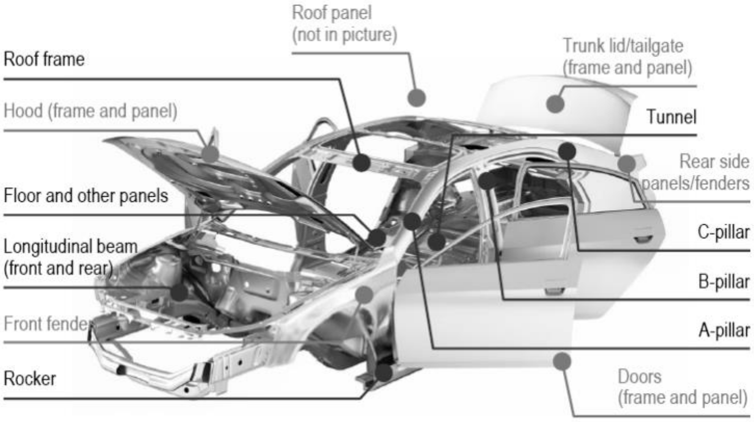


Fig. 1 - Closed BIW including all components [102]

However, the term "body" serves as an overall term for the bodywork of a vehicle, including, among other things, BIW components, movable parts (e.g. doors, hood, flaps…), external components (e.g. bumpers, mirrors, lamps, windshield…) and interior trim (e.g. seats, instrument panel, safety belts…) [85].

An increasingly important aspect for automobile manufacturers and suppliers is the production of climate-friendly vehicles. To achieve this goal, manufacturers rely on a wide variety of strategies, such as more efficient engines or increased efficiency in aerodynamics, driving resistance optimization and friction minimization. Another approach involves the optimization of body development. The reduction of the vehicle body weight and thus of the overall vehicle weight plays a decisive role here. In average, an automotive BIW contributes up to 50% to the weight reduction potential [9].

Body mass reduction is motivated by the increasingly strengthened exhaust emission targets in different markets worldwide. Exemplary, the European Commission has set a goal of reducing the CO_2 emissions to 95 grams per kilometer (g/km) by 2021 as an average value for vehicle fleets [89]. There are similar approaches in the North American, Chinese and Japanese markets [89].

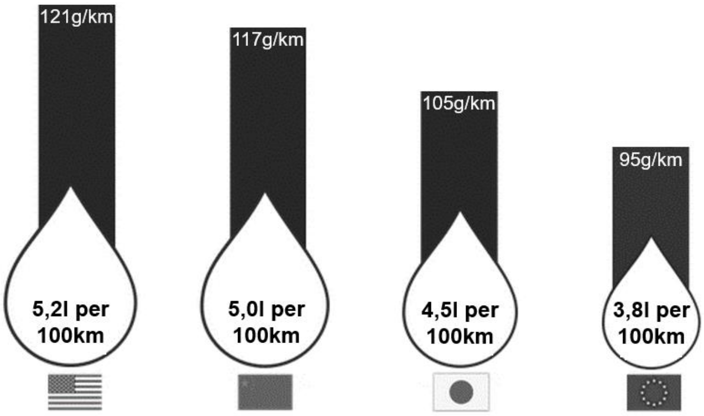


Fig. 2 - Comparison of international CO_2 targets [68]

Fig. 2 gives an overview of the mid-term targets to be achieved by 2020 (Europe 2021). These targets show a reduction of CO_2 emissions down to 121 g/km in the United States of America (USA), 117 g/km in China and 105 g/km in Japan. Besides the reduction of CO_2 emissions, the Japanese legislation is pursuing the approach that the target fuel efficiency for gasoline-powered vehicles should be at least 20.3 kilometers per liter, while the North American approach (valid in 2025) requires new passenger cars and light trucks to be able to drive at least 54.5 miles per gallon (mpg), which is equivalent to 23.2 kilometers per liter of fuel [68], [89], [128].

A reduction of body mass can be achieved, for example, by means of lightweight design, which has gained in importance due to the increasing number of applied components in a BIW structure [9]. Several methods for lightweight design, such as structural lightweight design [66], material approaches, etc., are available for this purpose. Fig. 3 shows the potential of weight reduction of automotive bodies considering the fulfillment of all stability, comfort and safety requirements, like BIW stiffness and durability or the behavior of bodies in crash cases [39], [56].

Nowadays, aluminum is a common solution to replace standard steel with a weight reduction potential of approx. 40%. Magnesium and carbon fiber have an additional weight reduction potential of about five to 20% compared to aluminum. Carbon fiber shows the largest potential with more than 50% body mass reduction. On the other hand, the material costs for aluminum and carbon fiber, which are much higher than those for steel, must be considered (c.f. section 3.4.2). However, the cost calculation must not only include the material, but also other costs such as investment cost for production facilities, manufacturing costs, joining technology, etc. Investment costs in particular play a major role alongside material costs. If the acquisition costs for tools are considered, pure steel bodies are economically desirable, especially for production sizes of more than 100.000 pieces per year [39], [43], [56], [74], [123].

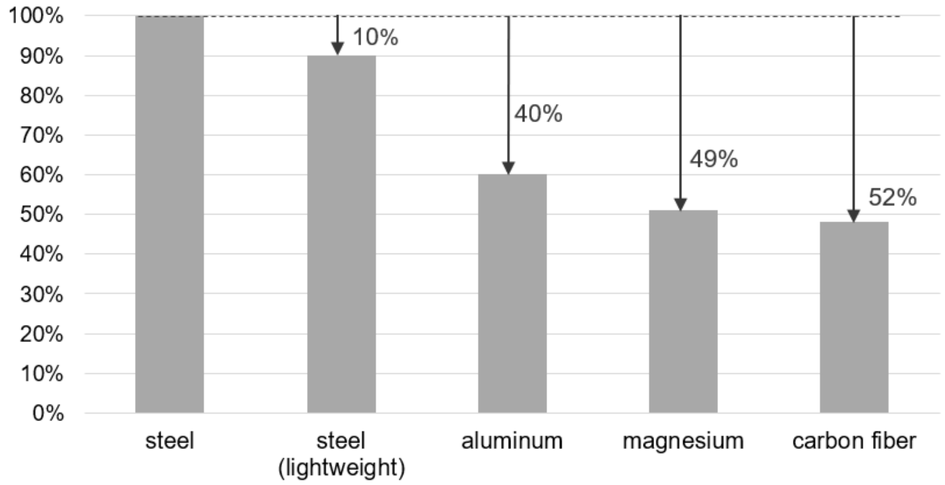


Fig. 3 - Lightweight design possibilities due to material change [39], [74]

If the production volume is lower, aluminum bodies are particularly worthwhile. In addition to the advantage of weight savings, these also offer a reduction in investment costs. Besides the higher material costs, the higher costs for assembly and joining technology compared to steel bodies are a counter to this [39], [43], [56], [74], [123]. Components made of magnesium or carbon fiber are used primarily in higher priced vehicles (e.g. sports cars). But modern electric cars can also have a carbon fiber body, either partially or completely. This means that, above all, driving resistances that are weight-dependent can be reduced, which leads to an increase of the driving range [8], [11], [56], [81].

In addition to car bodies, which are made of a single material (e.g. aluminum or steel bodies), the use of so-called “multi-material” car body design is increasingly widespread. Multi-material car bodies are body types with a mixed material design. This means that at least two different materials are used in one body. Exemplary, the entire vehicle body is made of aluminum and the engine hood, which is a large component, is made of carbon fiber due to weight saving reasons. This mixed material body design combines the advantages of weight reduction potential without causing costs to explode [39], [56], [74].

In the following, exemplary BIW design solutions of mass production cars give an insight into the development trends in terms of body materials and multi-material applications. In the early 1980s, FIAT started with the development and production of the then new FIAT Uno. The entire vehicle body was designed and manufactured exclusively out of steel. At that time, this corresponded to the state of the art with regard to design and manufacturing (including the entire field of joining technology) of vehicle bodies. The components of the steel body were solely joint by around 2.700 spot welds, whereby nearly all, except around 20, were welded by robots. No other type of joining technology was used to fix the entire body [88]. Since the entire vehicle was made of steel and all joining technology elements were spot welds, there was a low level of complexity in terms of design, simulation, manufacturing and data exchange throughout the entire BIW development, including joining technology.

In recent years, multi-material body design became a common approach in the automotive industry to reduce the weight. Fig. 4 gives an overview of the BIW materials applied by different car manufacturers today. They all use different kinds of steel as well as different kinds of aluminum and different kinds of synthetic materials (summarized as SMC (Sheet Molding Compound)).

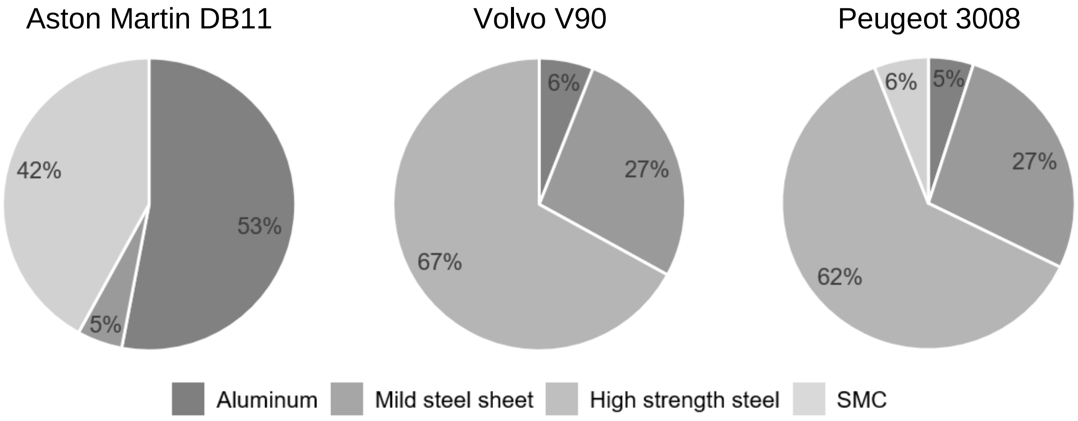


Fig. 4 - Comparison of BIW materials of different mass production cars [86], [99], [101]

This diversity of different types of materials (cf. Fig. 4) leads to an increase in the variety of joining technologies [37], [56]. But not only the number of different types of joining is increasing (cf. Tab. 4 in section 3.4.3) also the data (e.g. meta-information, parameters, etc.), which are needed to describe these types, become more complex. Fig. 5 shows an extract of different types of joining technologies used in modern aluminum bodies.

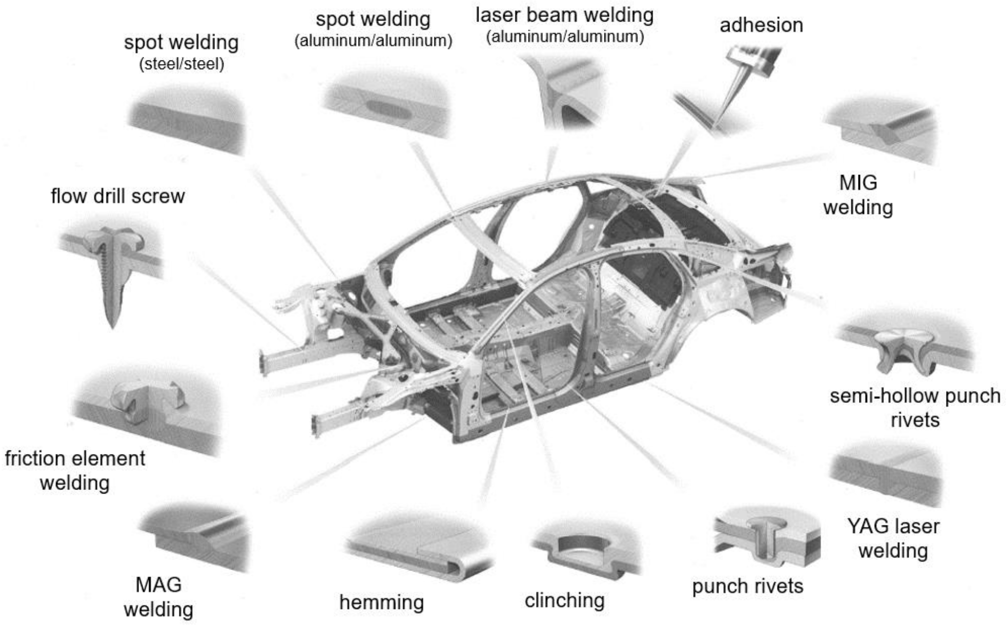


Fig. 5 - Extract of different joining technologies (BIW Audi A8) [47]

With an increasing number of – partially novel – joining technologies, this leads to a considerably higher complexity of development and manufacturing processes of modern vehicles. This, in turn, leads to higher complexity in the area of data exchange processes between the different applied CAx environments during the development processes. It is, therefore, of great importance to support the engineers with suitable measures. One of these measures includes the introduction of an optimized data exchange process between the different disciplines of CAx.

1.2. Problem Statement

The aforementioned variety of variants with regard to body design and the associated increasing complexity in the field of joining technology leads to new challenges in data exchange processes. The focus of this work is put on data exchange processes between CAD environments and diverse involved CAx environments, such as CAE (Computer-aided Engineering) or CAM (Computer-aided Manufacturing). In this thesis, the term “environment” describes a collection of all tools, systems and methods involved in the corresponding development processes.

The data exchange of all joining technology-relevant information is massively influenced by the increasing number of joining technology elements in vehicle bodies. But also, the introduction of new types of joining technology and the adaption to the variety of variants with regard to the applied materials in body design have an impact. In particular, the introduction of new types of joining technology leads to an increase of metadata. This additional information is indispensable to describe all parameters (e.g. geometric dimensions, materials, manufacturing data) of the applied technology.

The mentioned metadata are decisive for the exchange of joining technology data that contain all information regarding the joining technology elements, e.g. type of joining, coordinates, adjacent sheets, diameter, etc. Since many sections of the development process of a vehicle are performed in a digital way, the individual process phases are supported by CAx systems. According to [55], a development process is divided into the following process phases – “definition phase”, “concept phase”, “pre-development phase”, “series development phase” and “pre-series & series production phase” – which are explained in more detail in the sub-chapters 3.2 and 3.3. The creation of joining technology data usually takes place in CAD environments. CAD tools are used in the development process for the first time in the pre-development phase (geometrical integration). In earlier phases, such as concept phase (e.g. packaging, styling), CAS (Computer-aided Styling) and reduced parametrized CAD tools are mainly used. In this very early phases, no joining technology-relevant data are created and processed [55], [124].

Since there are no uniform standards for the creation and proceeding of joining technology models, every automotive manufacturer has defined their own methods to generate the corresponding CAD data. These methods vary in a broad range (no off-the-shelf tools available), which leads to a gap in the data exchange processes within the involved CAx environments.

The already mentioned gap in the data exchange process between various CAx environments refers to different data exchange strategies. These strategies differ in terms of parameter and metadata structures, data exchange file formats and the information content of data. While data exchange file formats in the field of geometry data (contain all information of the components, e.g. geometric dimensions of sheets, material, center of gravity, name or label of parts…) are limited through a few standards and boundary conditions, the situation is more complex in the field of joining technology. Here, a variety of transfer file formats are used, which leads to inefficient data management. In this context, a uniform data exchange format has a high potential to optimize the data exchange process of joining technology data.

While in CAD environments an exact representation (e.g. geometry, material, dimensions…) of the joining technology elements is created, other CAx environments require only a fractional part of this information. This also means that not all information that has been created in CAD is to be used further in the specific simulation and manufacturing engineering processes. Tab. 1 shows an example of parameters that are necessary to fully describe a spot weld in the respective CAx environment. This table only shows parameter that are relevant for joining technology data.

CAD	*CAE*	*CAM*
Parts to be connected Geometrical depiction Coordinates Diameter Height Weight Normal direction	Parts to be connected Coordinates Diameter	Parts to be connected Coordinates Diameter Normal direction

Tab. 1 - Comparison of necessary parameters for a spot weld in different CAx environments

As visible in the example, a high amount of information is needed to create a certain joining technology element (e.g. spot weld) in CAD. Of these many parameters, only three – parts to be connected, coordinates and diameter – are needed in the CAE environment. These three parameters are necessary to deliver information for specific simulation tasks, e.g. durability & crash simulation. Even in the CAM environment, only the four parameters – parts to be connected, coordinates, diameter and normal direction – are necessary to process all CAM-related tasks, e.g. space analyses, creation of a suitable joining sequence. All other parameters, which have been created in the CAD environment are used for further processes, e.g. the weight specification of a joining technology element, which is important for the calculation of the total vehicle weight. Of course, CAE and CAM simulations require additional parameters, e.g. sheet material, geometric dimensions, etc., that are delivered by separate data exchange processes.

In addition to the different data exchange strategies, each automobile manufacturer defines different boundary conditions for the creation, management, export and exchange of CAD-based (joining technology) data. For car manufacturers and suppliers, the tools and methods for the creation of joining technology are to be provided accordingly, which demands the integration of existing solutions and the development of new tools.

The great effort for the preparation of data in the target environments (e.g. CAE, CAM) represents a time-consuming aspect. Due to different requirements of manufacturers (different exchange strategies, different file formats, etc.) and different requirements in target environments (e.g. data structure) dissimilar pre-processing steps, such as the restructuring of data or separation of required and unneeded information, are necessary. Since this is not a uniform procedure, the time required to perform these tasks increases with rising data complexity. In addition to an enlarged elapsed time of the development process, this also leads to an increased number of man-hours involved. The preparation time in the target environments can be significantly reduced by a clean structuring of the data and a simultaneous minimization of the data volume.

Due to the multitude of possibilities for creating and exchanging joining technology data and the wide variety of requirements, data management faces new challenges. There is no uniform standard in the field of joining data exchange. Consequently, new approaches have to be implemented that are able to handle the different data exchange file formats effectively. In order to make this possible, suitable interfaces must be developed that allow efficient data transfer without losing the required information.

1.3. Structure of this Thesis

The presented doctoral thesis is divided into five main sections – respectively seven chapters – which build on each other (Fig. 6). This thesis starts with the section “Introduction” which includes motivation, problem statement and goals of the research works. The section “State-of-the-Art” includes the chapters “CAx in the Automotive Industry“ and “Automotive Body Design“.

After the introduction to the topic and the section “State-of-the-Art”, the section “Conception”, includes the chapters “Investigations of Data Management“ and “Boundary Conditions for the Development of a Tailored Data Exchange Process”. The fourth section includes the implementation of the developed approach into selected projects in the automotive industry. This “Implementation” section includes the definition of actual boundary conditions, requirements and the application of the approach (chapter “Application of the Approach“). Finally, the thesis is concluded in the section “Discussion”, respectively the chapter “Discussion of Results“, in which a summary and discussion of the results, expected benefits, as well as challenges and regimentations of the approach are elaborated.

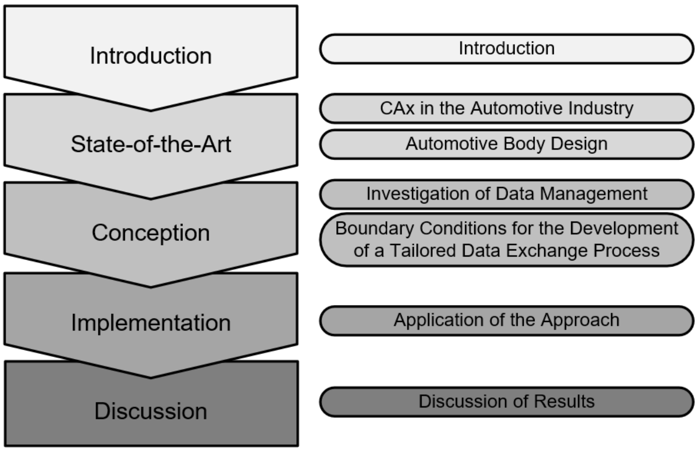


Fig. 6 - Structure of this thesis

Section “Introduction”

This section serves as a starting point and introduces the reader to the topics of the thesis. The first part includes the motivation and the initial situation that led to this work. Then an overview is given of the problem statements, which are considered in this work. The results of this work and the expected objectives are described at the end of this section.

Section “State-of-the-Art”
After the introduction to the topic of this thesis, an introduction of CAx systems in the automotive industry is given. In a further step, the requirements of the individual disciplines are explained to be considered independently of each other. After their individual consideration, the interactions of these disciplines, including their interaction with PDMS (Product Data Management Systems), are analyzed. After the importance of CAx environments in automotive development has been demonstrated, the chapter “Automotive Body Design” explains the processes of BIW design, including but not limited to BIW types and materials used in modern cars. In addition, a brief historical review of body design in the automotive industry is given.

Section “Conception”
The focus is put on the data exchange processes of joining technology and potential measures to optimize these processes. In addition, the created methods, strategies and tools that are necessary to support the optimized data exchange processes are presented here. Besides, an analysis of requirements and boundary conditions for optimized data exchange processes is carried out in order to implement the workflow accordingly. Furthermore, the different data exchange formats for the data exchange of geometry and joining technology data, as well as the possibilities to exchange data within several CAx environments are considered and elaborated.

Section “Implementation”
In this section, the results developed in the conception phase are applied to selected practical projects of an industrial partner. In this way, the results and the optimized data exchange processes, including all necessary tools are validated with regard to the specific requirements. Furthermore, it is shown that the optimized data exchange processes are able to be applied to various projects in the automotive industry.

Section “Discussion”
In the discussion part, the research findings are reflected and discussed. After the summary, a discussion is initiated on all the results and objectives achieved, as well as the advantages and limitations of the presented approaches. In addition, an outlook is given on necessary future efforts to support the industry in their data exchange processes between different CAx environments.

1.4. Goals of the Thesis

The project underlying the present doctoral thesis was carried out in cooperation with the industrial partner and automotive supplier MAGNA STEYR Fahrzeugtechnik AG & Co KG in Graz [77]. Therefore, all results obtained in the course of this work are made available to the industrial partner and implemented into ongoing development processes.

The terms “external” and “internal” (and possible variations) are often used in this work in relation to data management, to describe the constellation of CAx environments participating in the data exchange processes. When it is defined as an “internal data exchange process”, it means that only CAx environments of one company are integrated. Exemplary, all exchange tasks take place in the automotive supplier's internally placed CAx environments. Using the term “external data exchange processes” means that are at least two CAx environments are involved that are located in two or more different companies. Exemplary, the data created in the CAD environment of an OEM (Original Equipment Manufacturer – from the viewpoint of a supplier it is equivalent to the customer) is transferred to the internal target environment of the automotive supplier (e.g. CAE, CAM).

As mentioned in the introduction, the automotive industry is subject to massive changes in the field of BIW development. These changes include different aspects, such as multi-material design or new types of joining technology, and do not only influence the individual computer-aided disciplines applied in the development processes, but also face the involved engineers with new challenges in terms of managing computer-generated data. Other changing boundary conditions in the automotive industry include new companies that enter the market (e.g. Asian OEMs), a lack of uniform standards for data exchange and thus new challenges in data management at Tier 1 supplier companies.

The above-mentioned issues lead to gaps in the data exchange processes, especially between the customer-specific and the supplier-internal environment as well as within company-internal data management. In order to counteract these changing boundary conditions, the gaps in data management between purely internal and between internal and external exchange processes must be closed. This leads to the following research question treated in this Ph.D. thesis:

> *“What measures must be taken to close the existing gaps in data exchange processes between different CAx environments, considering all boundary conditions and requirements of joining technology development in the automotive industry?”*

In order to answer this research question, a detailed analysis of the boundary conditions is carried out first in which both internal and external data management and exchange processes are investigated. The main focus is put on demonstrating the possibilities of data transfer optimization and the involved methods and tools, e.g. CAx tools, PDM (Product Data Management) systems, that are used during the entire development processes. Furthermore, an investigation of the data exchange formats used in the automotive industry is carried out. These steps serve as a basis to create a uniform data exchange process, which is applicable in a broad variation of automotive development projects.

Besides the data exchange formats, the development data structures of different OEMs are analyzed. The analyzed data exchange formats and data structures serve as a basis to create appropriate interfaces to optimize data management and exchange processes. This is particularly important to ensure that no unwanted loss of information arises during data exchange, but the data are to be reduced and tailored according to the specific requirements of the target environments. For this reason, an analysis is performed to determine, which specific information is required for the considered different CAx environments.

As mentioned above, the main focus of this work is put on the exchange of joining technology data in automotive BIW development. In this way, specific metadata of joining technology data and standards are considered in the exemplary presented industrial applications of the created methods. Nevertheless, the introduced methods and strategies have the potential to improve other applications of data exchange in a broad area of automotive development processes.

2. CAx in the Automotive Industry

This chapter gives an introduction to the virtual processes and systems currently used in automotive development, focusing on the applied CAx systems and tools. Firstly, an overview of the tools introduced over the last decades is given. In addition, the interaction of systems necessary for data exchange between several CAx environments is described. This chapter concludes with an overview of VPD (Virtual Product Development) widely used in the automotive industry today and its optimization potential regarding the entire range of development processes.

2.1. Introduction

In today's increasingly globalized economy, which involves distributed engineering as well as the associated cost reduction potentials, the introduction of different computer-aided systems represents one important step to remain competitive in the market [75]. Due to increased effectiveness, the introduction of these systems during recent decades has been an important step to reduce the average development time of a car from seven to almost two years [55], [70].

The term CAx is the hypernym for all computer-aided tools, such as CAD, CAE, CAS, CAM, etc., whereby x is used as a placeholder. Other important systems that have to be considered are PDMS, which play a crucial role in storing and managing data throughout the entire development process (cf. sub-chapter 4.1). This sub-chapter starts with an introduction to the historical development of various CAx systems with a focus on the automotive industry. Particularly in the area of VPD, all IT-related processes play a decisive role in optimizing the development processes and supporting the engineers.

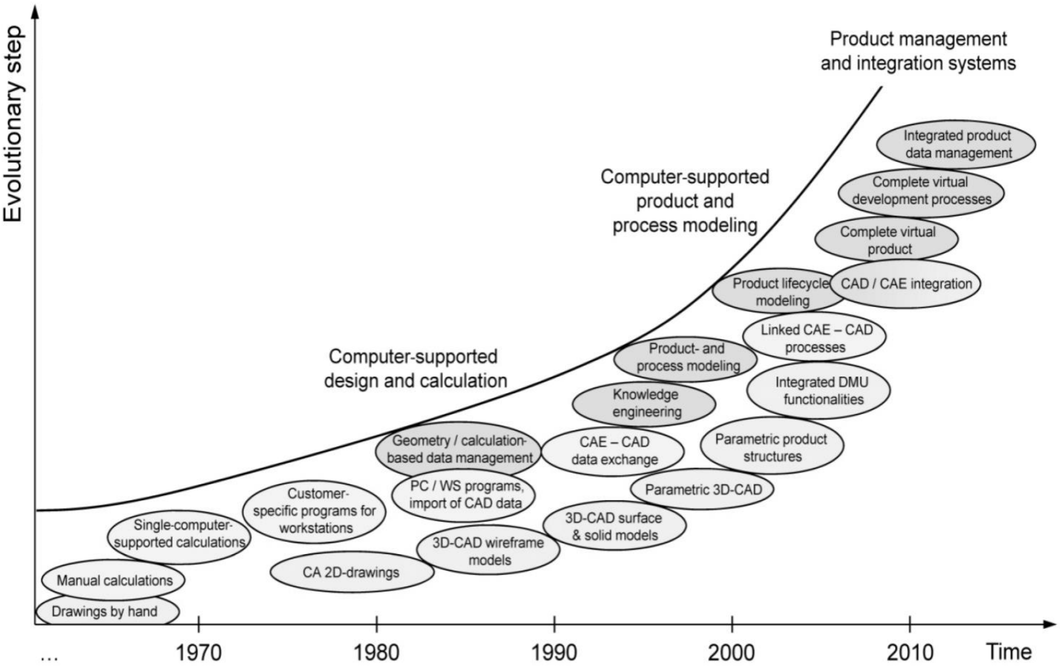


Fig. 7 - Historical review of CAx systems development [55]

As shown in Fig. 7, the first applications to support product development processes through the use of CAx systems emerged in the 1960s. Since this time, the number of different computer-aided tools in vehicle development is increasing. In the middle 70s of the past century, the first commercial 2D-CAD drawing programs were introduced. The main task of these 2D-based programs was to support the engineers with simple two-dimensional functionalities, like sketches. In the late 80s and early 90s, a change from 2D-CAD drawing programs to 3D-CAD modeling programs took place [43]. This change was the start of modern computer-aided engineering and changed the mindset from 2D-drawings to 3D-based CAD model work. This modification towards 3D-models had many benefits, such as an effective visualization of the models or supported processing possibilities in case of model changes. Furthermore, it was possible to integrate production-related knowledge into the models and to support assembly processes with the help of assembly-related information. Since the introduction of these systems, the issue of effective data exchange between the various disciplines has also arisen. Furthermore, an integration of the different computer-aided environments into the data and information exchange processes had to be established. Therefore, it was and still is important to find suitable ways to exchange data between the different disciplines, whereby unwanted data and information losses at the interfaces have to be avoided [35], [83], [134].

As already mentioned, the introduction of different CAx environments led to a cost reduction in development processes. This cost reduction can be justified above all by faster detection of faults and the associated earlier elimination of corresponding errors. In addition, the probability of detecting an error or a source of an error is much higher than without using CAx methods.

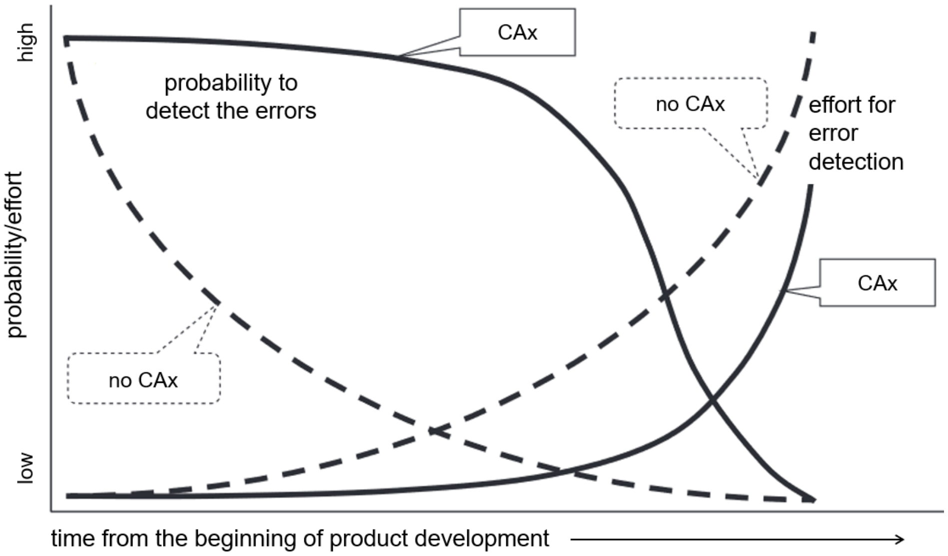


Fig. 8 - Probability and effort to detect errors in the development process [126]

Fig. 8 shows a comparison of the probability of error detection and the effort required for error detection during a product development process of both CAx supported and CAx independent environments. It can be seen that the effort required for error detection in CAx-based development environments is lower than in non-CAx supported ones. The curves for the probability of error detection show the opposite behavior.

This means that the possibility to detect an error with the help of CAx systems is much higher. In addition, it is shown that especially in the early stages of product development, the possible costs reduction is very high while the costs for changes are low (cf. Fig. 9). For this reason, it can also be concluded that due to the more effective and earlier error detection, the costs during the development process can be decreased [94], [108], [126].

Besides the various advantages that the introduction of several CAx systems in the entire product development yields, new challenges for engineers also arise. These challenges, e.g. an efficient integration of different CAx environments, effective data exchange processes, etc., will be considered in more detail in the following sections.

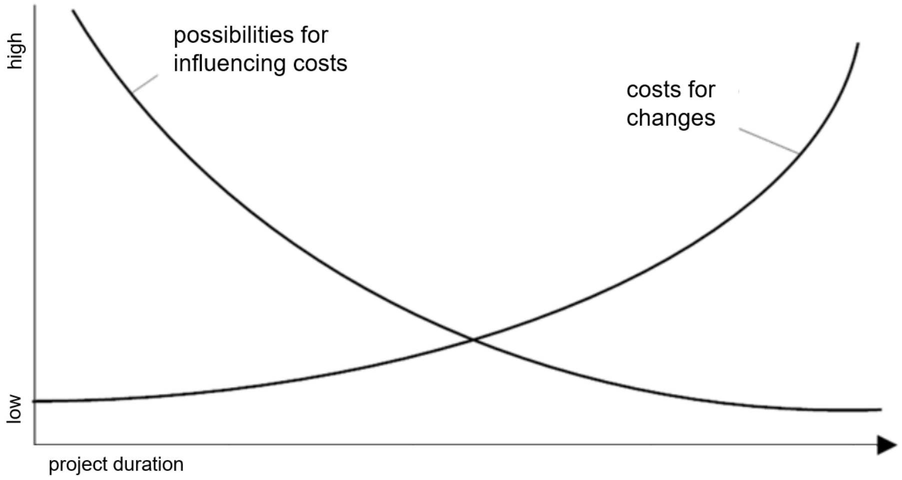


Fig. 9 - Possibilities for influencing costs during the project duration [94]

2.2. Interaction of Different CAx Systems

To enhance data exchange processes, it is of great importance to understand how the different CAx environments interact with each other. Therefore, this section provides an overview of relevant topics in this field, such as:

- the development environments, including used tools and systems
- the interfaces between the environments
- the used data exchange file formats

Fig. 10 shows a representation of the exchange process between three selected different CAx disciplines CAD, CAE and CAM. The discipline CAD supports the user in the field of computer-aided development, design and construction technology by provision of 2D- or 3D-models. With regard to BIW development, this means that a 3D-model of the body is created. This 3D-model contains information about geometric dimensions, material and location of the sheets, as well as joining technology-relevant information (e.g. type of joining technology elements, coordinates, normal vector...) and further meta-information (e.g. annotations, production-relevant information…).

The discipline of CAE covers all areas of calculations and simulations that are computationally performed. For the development of vehicle bodies, several sub-areas, e.g. FEM (Finite Element Method), CFD (Computational Fluid Dynamics), DMU (Digital Mock-Up), of CAE are used [55], [83]. The existing 3D-CAD model is converted according to the desired accuracy and sub-areas. Then the transfer into the CAE environment takes place. With the now available CAE model, different simulations, e.g. FEM simulations of stress and deformation, can be carried out and evaluated depending on the sub-area [55].

The term CAM describes computer-aided manufacturing and involves flexible manufacturing systems, industrial robots, etc. In CAM environments for car body development, a wide variety of systems and tools (e.g. Siemens Process Designer [113], Siemens Process Simulate [114]) are used to calculate and simulate production-relevant processes. Engineering-related information can be obtained, which exemplary contributes to the optimization of suitable joining sequences. In addition, space analysis (e.g. accessibility check for tools for creating joining technology elements) and the planning of optimized production lines (e.g. arrangement of robots, cycle time for creating of joining technology elements, etc.) are carried out [71].

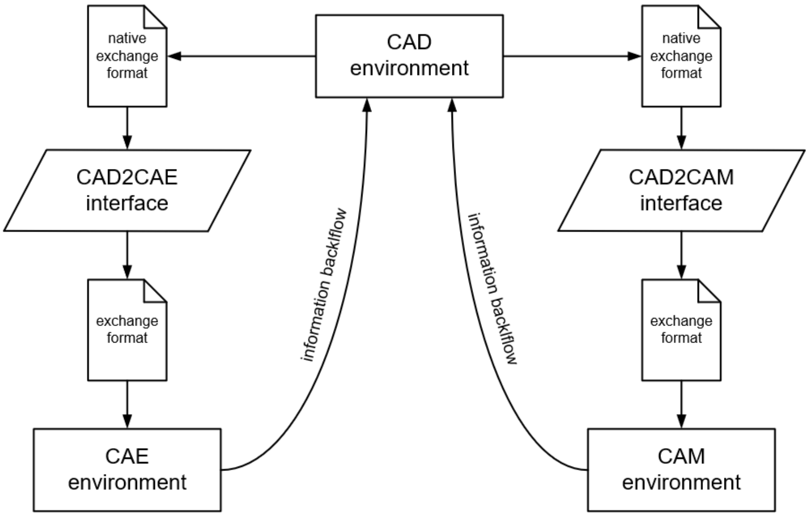


Fig. 10 - Exchange process between CAD-CAE and CAD-CAM environments

Environments of applied engineering tools:

Joining technology data as well as geometry data, including but not limited to parameters, design history, annotations, etc. are created in the CAD environment, which typically also serves as the master environment. In this way, the CAD master environment represents a CAx basic building block (3D-CAD model generation) of the development process. Any information delivered by simulation (CAE and CAM target environments) and leading to model-related changes, e.g. optimization of the joining technology elements, will be integrated into the master environment by adaptation of the 3D-CAD model. This data creation is based on 3D-CAD data models and provides native CAD data formats, e.g. CAT-part [24], NX-files [111], etc. When exchanging native data between different CAx environments (e.g. from CAD to CAE), the problem occurs that the target environments do not support the native data file formats. The reason for this is that each data format determines how the available data are to be interpreted during its processing. The structuring of the data is of crucial importance, as it explains how data are displayed and proceeded [61].

Furthermore, native data contain all the information (e.g. parameter, design history, annotations…) created, which, in turn, leads to larger amounts of data [1]. Most of the time, not all of the created information needs to be transferred. This is mainly due to the fact that certain information is not required in the target environments or cannot be integrated at all. Exemplary, both CAE and CAM environments do not require design history for simulation tasks. For these reasons, the introduction of interfaces between different CAx environments is necessary. These interfaces must ensure that the data to be exchanged can be integrated into the target environments in terms of appropriate data format and data structure and that unneeded information (e.g. design history) is not exchanged.

Interfaces between engineering environments:

Interfaces (c.f. Fig. 10) are necessary to convert data from one data format/structure into another one. One example represents the conversion of a native created CAD data format (e.g. CATIA-part [24]) into a neutral data format that is readable in the target environment (e.g.

XML (Extensible Markup Language) [91], Excel…). As mentioned above, interfaces must also ensure that only the required type and content of data arrive in the target environment. This means that data which are not needed in the target environments should not be exchanged. Thus, data interfaces generate a so-called "desired" data loss. Furthermore, interfaces must also ensure that there is no unwanted data loss, e.g. by deletion of information, which is required in the target CAx environment. For these reasons, interfaces must be designed so flexibly that changing input boundary conditions, e.g. different input data formats/structures, and output boundary conditions, e.g. further information required in the target environment, do not affect their functionality.

Exchange file formats:
The selection or development of suitable data exchange file formats is one of the main issues that must be solved for optimizing data exchange processes. On the one hand, suitable data formats must be selected in such a way that it is possible to transfer all the information required in the target environment. With regard to joining technology data, this means that the data structure must be designed in such a way that it can be easily extended (e.g. by adding new parameters). On the other hand, the data exchange file formats must be interchangeable with all CAx environments participating in the data exchange process. Regarding the present research, this issue is solved in chapter 4.

An example of an actual engineering data flow process is shown in Fig. 11. This illustration exemplary shows the interaction between a CAD and a CAE environment, exemplified by a crankshaft development. The creation of CAD data, the further processing of these data (CAE environment) and the data transfer between these two environments play a decisive role [55], [72].

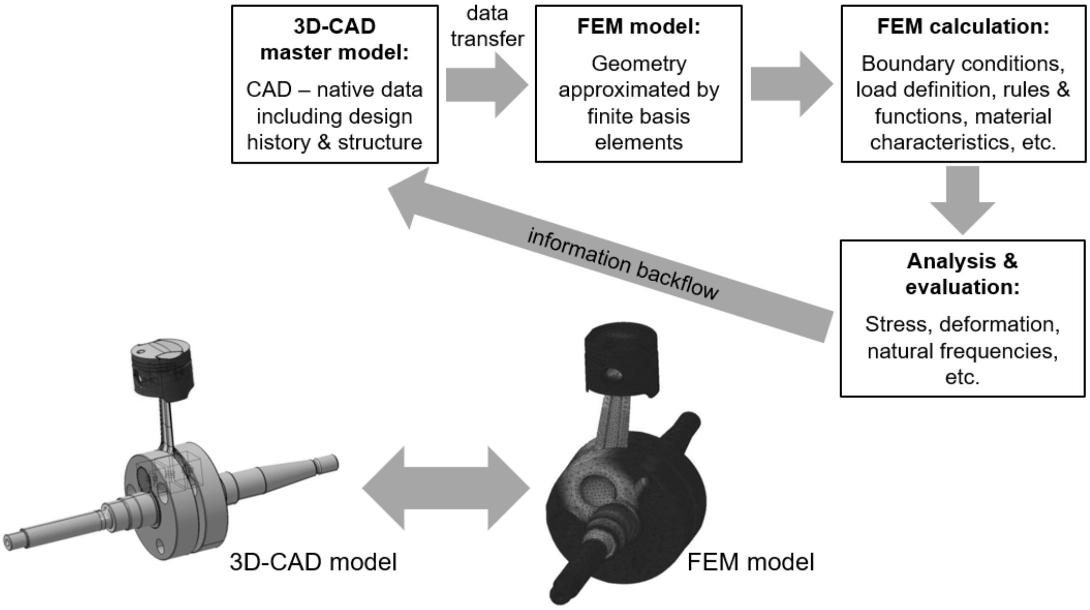


Fig. 11 - CAD to CAE data flow exemplary shown for crankshaft development [55], [72]

As visible in Fig. 11, the data exchange process between the disciplines CAD and CAE is a closed loop exchange process. Normally, it starts with the creation of data (CAD environment), which is, in this case, a 3D-CAD model of a crankshaft. Commonly, this CAD data creation takes place in the automotive industry widespread CAD programs, e.g. “CATIA” and “Siemens NX”. The next step of this data flow process is the FEM modeling, which is also called the pre-processing stage. The model preparation (pre-processing) serves to prepare the components for the simulation. The individual components are divided into small, simple, finite areas or volumes (so-called finite elements). This mostly labor-intensive process is called meshing (generation of a net). The FEM calculation processes are based on approximated geometries [54], [82].

After finishing the preparation tasks in the pre-processing stage, all simulation tasks in the CAE environment take place. Before the simulation steps can be started, information about loads (e.g. forces and moments), restraints (e.g. fixed parts), material properties (e.g. materials, characteristic curves), temperature behaviors (e.g. temperature characteristic curve) and other factors must be integrated into the FE program [55], [82].

After the mentioned three stages, the analysis and evaluation step, also called post-processing, takes place. In this step, the simulation results (e.g. information regarding stress, deformation…) are evaluated. These results contain information about stiffness and crash behavior, as well as some other safety-relevant information (e.g. durability simulation results). Now the information gained needs to be passed on to the CAD engineers. They incorporate the findings into the CAD model. After a certain processing time, the cycle starts again from the beginning until the vehicle is fully defined. Normally the development of a vehicle takes about four to six cycles if no data are available at the beginning.

2.3. Virtual Product Development

The term “Virtual Product Development” means that the product development process takes place entirely digitally. This connotes that all activities integrated in the product development process are supported by computational processes respectively the corresponding IT systems. Furthermore, the results are stored as digital data and are processed further in a digital form. Traditional information carriers (e.g. technical drawings on paper) or physical models, such as physical prototypes play only a sub-ordinated role in digital development processes. Most of the traditional information carriers are replaced by digital models and data formats [4], [43].

Since IT systems have become more powerful in the past years, VPD plays an increasingly important role in the entire development process of vehicles. This fact leads to an increase in the amount of data to be exchanged in all engineering areas. Two concepts, which bring this enormous amount of data under a single roof and support minimization of development time are simultaneous engineering (section 2.3.1) and frontloading (section 2.3.2).

However, it should be mentioned that both concepts are not limited to VPD. Hence, virtual prototypes (section 2.3.3) play an important role in virtual product development in the automotive sector. Virtual prototypes are always linked with a milestone or a gate in the development process. These milestones and gates determine the level of maturity (status) that a product or vehicle must meet at a certain time step in the process. This is primarily intended to harmonize all scheduled events of design, simulation and manufacturing [58].

Above all, VPD today supports all phases in the entire development process of a vehicle. This begins in the early phases, the quotation processing and the conception phase, but is also part of all design, simulation, manufacturing and assembly processes. In recent decades, it has become increasingly important to support engineers with digital data models in order to reduce costs and to accelerate development. The focus of VPD is on the digital optimization of the model and the provision of the generated information for the next development phases [32].

VPD includes the following stages (cf. Fig. 12):

- 3D-CAD model
- DMU (Digital Mock-Up)
- Functional DMU or virtual product (prototype)
- Virtual plant

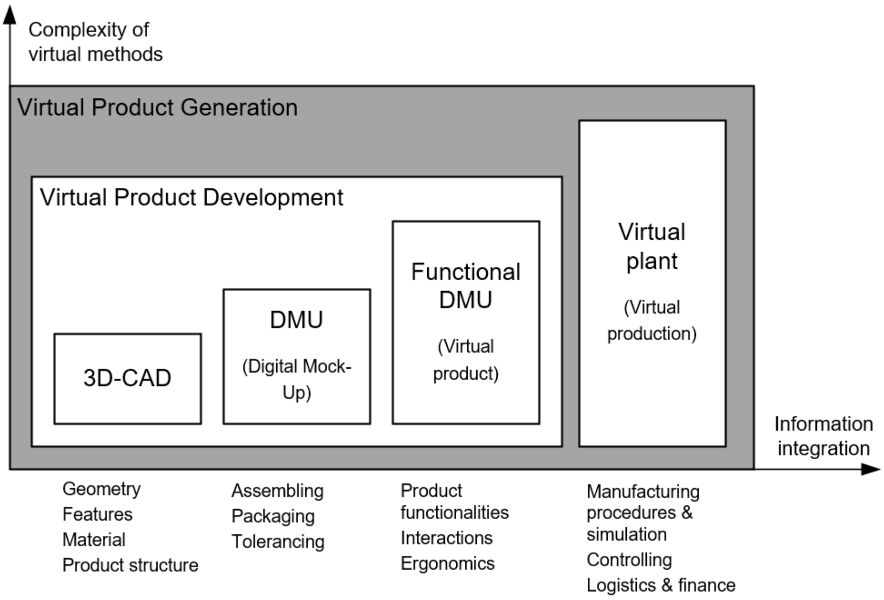


Fig. 12 - Different levels of virtual product development [44]

3D-CAD model

A 3D-CAD model serves as the basis for the 3D-description of geometry and structure (CAD-based data creation). This model can consist of individual components or one or more assemblies. Nowadays, the assembly structure (product structure) is realized by associative parametric modeling. In addition to the geometric information described in the 3D-CAD model, further metadata, such as material, manufacturing-relevant information, annotations, etc. are provided by the CAD model.

DMU

A DMU is primarily used to reflect the product structure and geometry of the components and assembled component groups. It is crucial to simulate all mounting and disassembling processes as well as collision checks. In addition, weight, COG (Center of Gravity) and moment of inertia are computed using both geometry and material information.

Virtual product

Besides 3D-geometry, parts and assemblies, material and product structure, the virtual product respectively the virtual prototype also contains physical and logical properties. By integrating these properties, these models are able to represent physical product behavior and logical conditions in different types of simulations, so that simulation in the virtual environment can be compared with simulation or testing results of different types of physical simulation.

Virtual plant

The virtual plant (virtual production) represents the virtual mapping of manufacturing and assembly processes, including their physical properties. The goal is to use virtual models instead of physical models to simulate production (manufacturing, assembly, testing) processes to reduce development time and costs [4], [44].

The terms of virtual product development and virtual product generation have the same essence, but VPD is a sub-set of the virtual product generation. Both have the essence to use and build up virtual models, products and processes to replace traditional, hardware-based information carriers. By means of digital representations, sequences of modeling, simulation and optimization have led to a continuous computer-aided product development process.

Since vehicles are developed partly or completely with the help of digital aids, such as CAx systems, VPD is also of particular importance for data exchange processes. Since the entire vehicle development process includes, but is not limited to creation, management, exchange and processing of joining technology data, these data are part of VPD. For this reason, VPD and the corresponding engineering approaches (see the following sections) are considered for the development of optimized data exchange processes in this thesis.

The following sections introduce state-of-the-art approaches to increasing efficiency in the application of VPD. “Simultaneous Engineering” (cf. section 2.3.1) and “Frontloading” (cf. section 2.3.2) are applied to increase effectiveness development processes. “Virtual Prototypes” (cf. section 2.3.3) replace physical by virtual models, leading to a cost reduction in the development processes.

2.3.1. Simultaneous Engineering

SE (Simultaneous Engineering) represents an approach to reduce the development time by integration of development tasks, which is often related to an intensive integration of methods of VPD. SE targets to a collaboration and simultaneous work of several departments and disciplines, which requires an effective project management to monitor activities. This leads to considerable time-saving potential in automotive development projects [30].

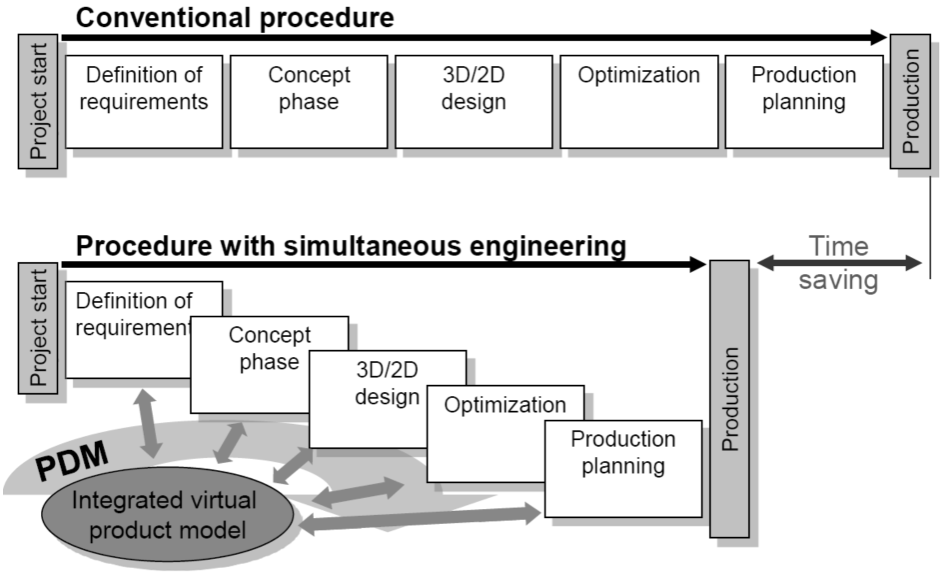


Fig. 13 - Project procedure with and without simultaneous engineering [54]

SE can be applied in the entire development process (cf. Fig. 13), including but not limited to design, simulation and manufacturing processes. The basic idea behind the approach of SE includes the configuration of simultaneous, respectively parallel workflows of different tasks instead of a successive execution of individual instructions [45]. Exemplary, the 3D-design phase can already start, while the concept phase is still not finished. Although, there is enormous potential to reduce the estimated development time, the total engineering manpower remains (nearly) the same [57], [106].

In summary, the goals of SE are to shorten the development process time and thus the time to market entry. Moreover, it serves as a way to reduce costs in line with overall total vehicle costs and to enhance the quality through an earlier information exchange between the various engineering participants, respectively departments [30], [54], [55], [105].

Due to a close cooperation of the individual disciplines, the amount of data to be exchanged increases. This in turn leads to an increase in data exchange volume, which leads to an increase in complexity in the area of data exchange optimization.

2.3.2. Frontloading

Frontloading offers another approach to support efficient product development by integration of VPD. Product specifications are defined in the early stages of the development process – in this context, the advantage of frontloading is that it aims at improved product quality or higher product maturity in the early phases to reduce the number of correction loops that occur in later phases [23], [54].

In addition to the time-saving potential, it is evident that the frontloading shifts resources towards the start of the project (c.f. Fig. 14). This means that more resources are needed in the early phases of the project. This increase in manpower demand can be counteracted in the later phases because of a higher maturity of the product development status. In this way, the total effort in the project should remain nearly the same, but with the potential benefit of an earlier market launch of the product.

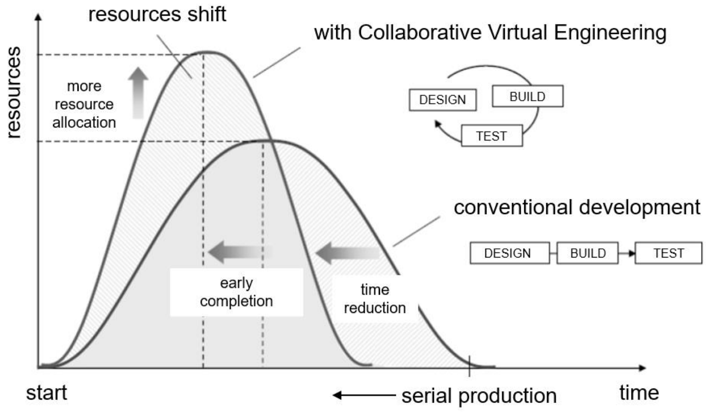


Fig. 14 - Development approach: Frontloading [23], [54]

Frontloading needs a strong interaction between different disciplines that are involved in the entire development process. Therefore, it is indispensable that an effective data management is available in the process (e.g. use of PDMS, c.f. sub-chapter 4.1) [23], [31]. This means that due to the increasing number of systems (e.g. CAD, CAE, CAM, PDM) the number of data exchange processes increases. This increase in complexity must be taken into account when optimizing the data exchange processes.

As mentioned in sub-chapter 2.1, it is of great importance to detect product and process-related errors as soon as possible. Therefore, it has become increasingly important to use both approaches – simultaneous engineering in combination with frontloading. An effective integration of these two approaches into the VPD processes opens a broad range of possibilities for improved product development – and thus supports the reduction of development time and enhancement of product quality [10].

2.3.3. Virtual Prototypes in the Automotive Industry

Virtual prototypes are primarily applied for design evaluation and verification based on digital models. Cost and time-savings can be realized compared to physical prototypes by faster and more variable modeling and simulation. In the automotive industry, virtual prototypes are realized through the use of CAD, CAE and CAM environments [22]. In the development process, virtual prototypes define a certain level of maturity at pre-determined development steps.

As visible in Fig. 15, a project is usually divided into several phases (in this example, it starts with PV – Product Vision and goes all the way to PS – Process Stability). At the end of each phase, the goal is to reach a certain virtual milestone or gate. Milestones and gates are fixed time points in projects and processes at which certain previously defined activities must be completed. Furthermore, milestones and gates describe different phases in the automotive product development process. In order for a project phase to be restarted, the agreed deliverables of the previous phase must be available [58].

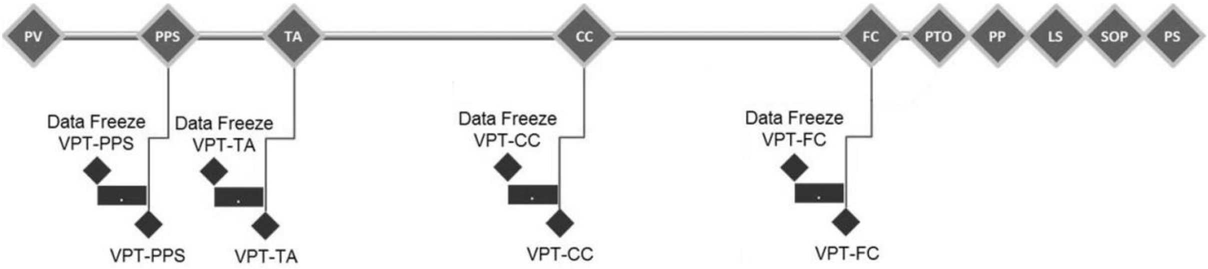


Fig. 15 - Virtual prototypes in the development process [58]

A number of virtual prototypes is defined in automotive development, depending on the scope of the project (typically at least four to six in a new car development project). A list and description of the used abbreviations of milestones in Fig. 15 can be found in Tab. 2. However, if it is only a matter of developing a partial scope (e.g. one module), then fewer virtual prototypes can also be defined [58], [71]. These prototypes are typically named after the linked milestones or gates, like VPT-TA, whereby VPT means Virtual ProtoType and TA means Target Agreement. Another possibility to name them is by using consecutive numbers (e.g. VPT-0, VPT-1, etc.). In general, each automotive company can name the virtual prototypes, milestones and gates according to their own defined terms.

Based on BIW development, Fig. 16 shows the three steps that must be fulfilled to reach a desired level of maturity at each virtual prototype stage. First, the input stop of all BIW parts (IS-BIW) takes place. This means that all relevant inputs concerning connections and interfaces of modules and functions (including inputs from production, development, after sales, etc.) up to the body structure are communicated to ensure their inclusion in the design process accordingly before the defined data freeze takes place [58], [71].

Abbreviation	*Description and goals*
PV	Product Vision – Description of the project is available
PPS	Preliminary Product Specification – Provision of feasible solutions for the project goals
TA	Target Agreement – Technical, economic and timing project goals have been assessed and are agreed
CC	Concept Confirmation – Confirmation of technical, economic and timing project goals
FC	Functional Confirmation – All simulation tasks have been finished and the production process is guaranteed
PTO	Production Try Out – The first PTO vehicles have been assembled and the production line has been put into service
PP	Pilot Production – The pre-series vehicle has been manufactured and fulfills the quality objectives
LS	Launch Sign Off – Completion of all tests for the used components and the specific cycle time for a certain production volume can be confirmed
SOP	Start of Production – First vehicles for the end customers have been produced, fulfill the quality objectives and are ready for distribution
PS	Process Stability – Final approval by the OEM

Tab. 2 - List of used abbreviations in Fig. 15

The next step includes the PF (Package Freeze). Hereby, a data deduction is made from the digital reference as a basis for the geometry checks. All COP (Carry-Over Parts), modified carry-over parts and individual parts are positioned correctly in the digital vehicle model at this stage. The last step to reach a VPT is DF (Data Freeze). The frozen design data of the specific digital prototype are entered into the agreed PLM (Product Lifecycle Management) system to perform a data backup. The frozen dataset is based on a defined design status, has been checked for 3D-design (package) and bears a date stamp. Parts scope and structure correspond to the parts list [58], [71].

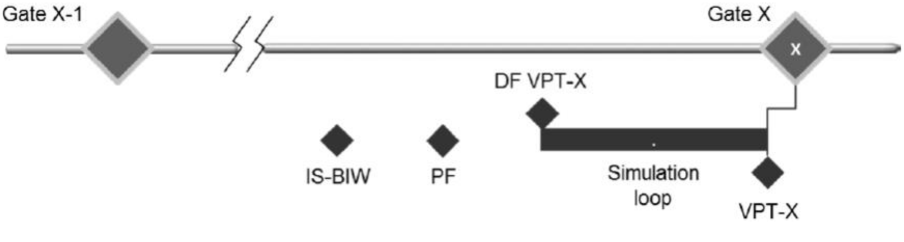


Fig. 16 - Approach to a virtual milestone [58]

In summary, the status of all simulations and risk-relevant tests for a virtual milestone, as agreed on in the project, is made available for the corresponding simulation loop. The simulation loop is based on data from the corresponding data freeze and has to consider the suggestions and measures derived from the results. The content varies with regard to required simulations as well as risk-related tests and the number of loops, depending on development scope and chosen development strategy, as well as the timeline. The process of achieving the required results for a virtual prototype is repeated for each loop [58]. Since simulation results should also be available for certain milestones, which are defined in the schedule of a vehicle development process, virtual prototypes contribute indirectly to the data exchange process. In order for simulations to be carried out, the existing data (e.g. prepared 3D-CAD model) are exchanged with the target environments before certain milestones can be reached.

3. Automotive Body Design

This section begins with a brief historical overview of automotive and body design, followed by an introduction to the product development process in the automotive industry. Subsequently, an overview of various types of modern car body design is given, including vehicle structures, materials and associated joining technologies.

3.1. Historical Background

The first ride of a road vehicle powered by a thermal engine took place on the 23rd of October 1769 (developer: Nicholas Cugnot [27]). It was a so-called steam tricycle with a total capacity of four persons. These steam-powered machines, as well as the subsequently introduced gas- and electric-powered vehicles, which were widespread at that time, could never assert themselves against vehicles driven by internal combustion engines. The first motor vehicles (father of the modern car) were launched in 1886 by Benz and Daimler [27]. Today, this event is considered in many literatures to be the origin of the modern car.

Considering another point of view, however, the type of powertrain is not the only decisive characteristic regarding the development of automobiles. However, the development of modern automobiles follows a long series of technical innovations that can be linked to carriage and body design [27]. The first automobiles, configured in a way that we know today as a car, did not appear until the end of the 1880s. Since then, there have been constant changes in all areas of the vehicle. The broad-spectrum of changes covers luxury-related (e.g. more comfort), technical (i.e. new technical possibilities), political (regulatory) and other (e.g. costs, safety-critical, eco-friendly…) changes [27].

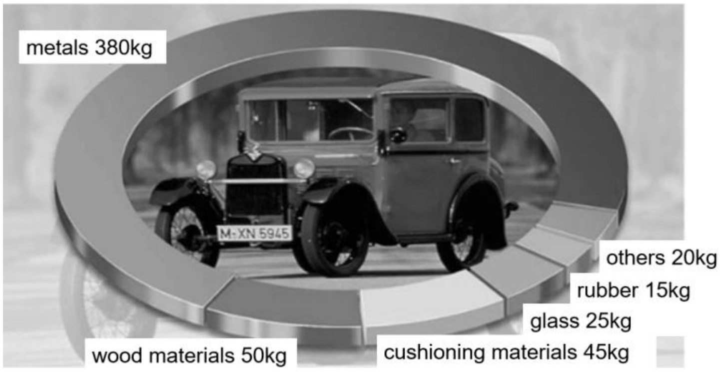


Fig. 17 - Material mix BMW DIXI (in 1920s) [17]

These changes, caused by various reasons, shaped the modern vehicle. Whereas in the early days of “modern” automobile design the total weight of a vehicle was approx. 500 kg (e.g. 535 kg BMW DIXI, cf. Fig. 17), today's cars have far exceeded this weight class. In addition to the changes in vehicle mass, the used materials and joining technologies have also developed further. These changes have an impact on the overall vehicle development, as well as on the development of single modules, like drivetrain, chassis, interior, etc. In this context, the changes in the area of mass reduction, the materials used, and the joining technologies have a great influence on the development process of car bodies (c.f. sub-chapter 3.3).

One example of the mentioned changes is that about 20 years ago, primarily steel materials were used in car body design. Nowadays, the situation is much more complex. In addition to bodies made of steel, which are still used in a broad range of applications, alternative materials (e.g. aluminum) and multi-material approaches are used [17], [118]. In addition to the introduction of new materials and joining technology types, the architecture of vehicle bodies also changed. In the first years of “modern” vehicle body design, the car bodies were mainly mounted on frames. This followed the structure of carriage design and is still used today in trucks and buses. However, the self-supporting body has established itself in the body development of passenger vehicles [17].

Before delving into the topic of modern body design, the product development process in the automotive industry should be brought closer. This product development process describes all workflows that are necessary to advance the new development of a new car model from the idea (product research) to product manufacture.

3.2. Product Development in Automotive Industry

Product development in the automotive industry can be divided into certain project sections (phases) by means of milestones. This division of the sections is summarized in the so-called product development process. In addition to the already mentioned milestones, this process also includes a complete description and chronological classification of all processes involved. Since these processes vary in the literature (e.g. [94], [119]) as well as company-specifically, different names and descriptions can be found for the individual project sections. Despite this diversity, strong similarities can be identified. A unified generic process is therefore introduced for the considerations carried out in this thesis (c.f. Fig. 18). This process reflects the individual process phases, associated milestones and development tasks. The development process presented here is divided into the following project sections, according to [55], [80], [124]:

- Definition phase
- Concept phase
- Pre-development phase
- Series development phase
- Pre-series & series production phase

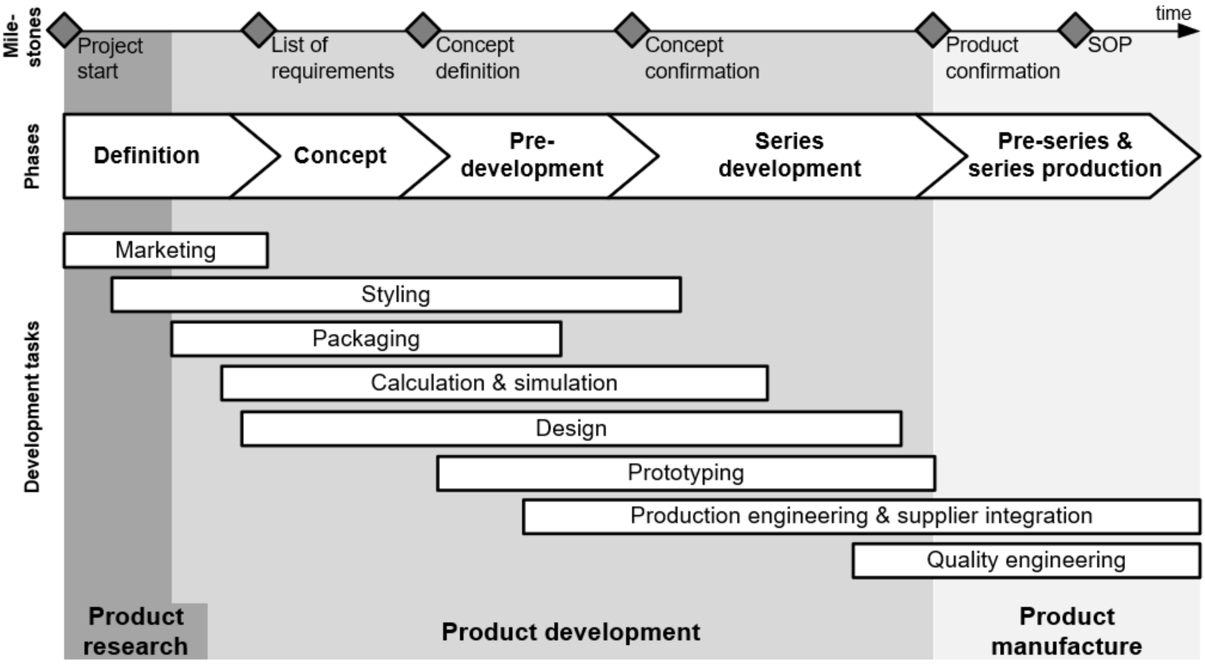


Fig. 18 - Exemplary product development process for vehicles, referring to [124]

In addition to subdividing the product development process into individual project sections, Fig. 18 shows a time division of the most important development tasks. Since it is not possible to start or end tasks abruptly in industrial projects, it is difficult to make a clear distinction. This, and the fact that the individual departments enter the process as early as possible, in turn, leads to parallel development tasks [51], [55].

Definition phase

The definition phase of the product development process can be divided into two further phases, the strategy phase and the initial phase [38], [51], [109]. In the strategy phase, all requirements placed on new vehicle developments are elaborated. The collection of these requirements is summarized in a target catalog focussing on economic success of the planned project. In addition to the creation of the target catalog, the first design studies of the future product are carried out in this phase. However, technical feasibility studies are carried out in the subsequent phase, the initial phase. Since a technical feasibility analysis is missing in the strategy phase, it is primarily attributed to product research. For this reason, the definition phase is part of both product research as well as product development (c.f. Fig. 18) [38], [51].

The initial phase, as mentioned in [132], deals with the generation of ideas and the draft of a complete vehicle concept [15]. The first installation space analysis, ergonomic studies as well as legal regulations are carried out here. In the initial phase, CAS tools are applied to develop first styling concepts, which are tailored to the technical requirements. Besides the draft of the complete vehicle concept and the first design drafts, a plausibility check of the requirements of the target catalog is conducted. This plausibility check is documented in a framework booklet (called list of requirements in Fig. 18), which contains the essential characteristics of the vehicle (e.g. type of drive, body architecture, dimensions of the vehicle...) [51], [55].

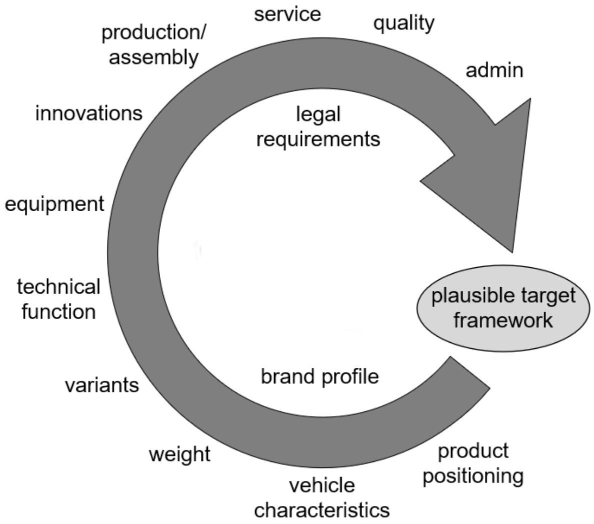


Fig. 19 - Target framework for new car models, referring to [132]

In summary, it can be stated that the definition phase describes economic and technical possibilities that can be derived from the requirements already mentioned in the catalog of objectives. Some of these requirements are shown in Fig. 19.

Concept phase

After finishing the technical and economic feasibility studies (definition phase), the next stage in the development process is the concept phase. The main focus in the concept phase is put on ensuring the feasibility of the new product to be developed. In this way, a detailing of the draft (by using CAS) of the complete vehicle, worked out in the definition phase, is performed.

Furthermore, with the help of simulation and calculation processes, proposals for engineering-related solutions are worked out in order to verify the design proposals [51], [55], [122]. Since many parameters are not available yet or are still under development in this phase, the simulation processes often must be carried out with simplified models. However, with each new simulation loop, the concepts are modified sequentially, which leads to progressively detailed models.

In addition to detailing the overall vehicle concept, the concept phase also includes detailing of the styling. Up to this point in the development process, the vehicle design is mainly formed under artistic aspects. This stage is now supplemented by the feasibility of the technical requirements. This comparison of design – artistic aspects and technical feasibility – is known in the automotive industry as so-called styling-technology-convergence. During the styling-technology-convergence process, extensive changes are usually made to the styling surfaces. This involves the use of flexible tools, the so-called parameter-associative CAD programs, and the application of specific parametric vehicle conception models [51], [55], [104].

Parametric-associative CAD systems are systems in which parametric-associative geometric elements are generated for each applied function. These new created geometric elements include information about mathematical description, creation function, default parameters and default geometry elements. Since this information is stored in the generated geometry elements, networked structures with associations between the elements are created so support the effective creation of variant constructions [104], [121].

The vehicle-DMU plays a decisive role in the further development of packaging-related aspects, which is an important task in the concept phase besides the styling development. In packaging development, the geometric integration and the creation of the vehicle concept geometry are driven forward. The DMU serves as a central data model that provides interfaces for the detailed design of individual components. The approach of DMU is based on virtual packaging, respectively assembling of the components, by use of geometrical descriptions. To deliver geometrical information of the components, CAS and CAD programs are used [55]. The focus of packaging is on covering the requirements for the placement of vehicle modules (e.g. suspension, powertrain, seats, air conditioning, etc.), ergonomics and space requirements [55], [124].

The concept phase is concluded with the milestone "Conception definition". At this point in the product development process, a detailed description of the vehicle concept is available. This includes an overview of the vehicle setup, which integrates styling, packaging and functional aspects [55], [122].

Pre-development phase

In the pre-development phase, the vehicle concept developed in the first two phases of the product development process is to be elaborated and detailed. In this way, the vehicle concept is created, secured and optimized by means of suitable measures. For this reason, the method of virtual prototypes, mentioned in section 2.3.3 is utilized in this phase. Another reason for the use of virtual prototypes is that a fewer number of physical prototypes must be developed in the course of this phase [51], [55].

In order to optimize the virtual prototypes, suitable simulation tools (e.g. CAE, CAM) are integrated into the product development process. The 3D-CAD model, which has a level of detail with which the properties of the vehicle can be examined, serves as the basis for this step. Exemplary, the simulation of the crash behavior of the vehicle body provides information on how the 3D-CAD model has to be adapted (e.g. necessary increase in sheet thickness in the area of the side panel) so that, the safety-related requirements can be met [51], [55].

A further important step in the pre-development phase includes the integration of CAM tools which leads to a further detailing of the initial 3D-CAD model. In addition to the detailing of the CAD model, simultaneous development of the manufacturing plant (e.g. production line) and the required tools (e.g. molding tools for car body components) takes place [51], [55].

Typically, selected suppliers and sub-suppliers are involved into the product development process in this phase (c.f. Fig. 18). The end of this phase is marked by the milestone “Concept confirmation”. This means that at the end of the pre-development phase, a verified and detailed vehicle concept is available that meets the requirement specification [51], [55].

Series development phase

The series development phase includes the complete and detailed development of the new car model as well as the required production facilities and manufacturing tools. This phase is concluded with the milestone “Product confirmation”. In order to achieve the aforementioned targets, physical prototype vehicles are used as test vehicles. First and foremost, the results of the tests with physical prototypes are used to verify the conducted development and to compare the results of the simulations that have already been determined using virtual prototypes. Furthermore, the results from physical prototype tests are used to adjust the simulation parameters for future simulations with virtual prototypes. [51], [55].

Since design (e.g. 3D-CAD model), manufacturing plants and manufacturing tools are already well advanced in this phase, the degree of freedom for changes is continuously decreasing. Even the smallest design changes in a sub-module can result in massive changes. For this cases, an extensive release and change process is required that also involves the supplier industry. At the end of the series development phase, near-series components and vehicle prototypes are produced in preparation of the finale stages, pre-series and series production phase [51], [55].

Pre-series and series production phase

The final phase of the product development process is the series production, which is often divided into pre-series and series production phase [55]. The results of the series development phase are used as a basis, which include manufacturing plant and manufacturing tools. This means that in the pre-series production phase the manufacturing of the vehicles starts by ramped the production volume up step by step. Once this ramp-up process is completed, the pre-series production phase is replaced by the series production phase [51], [55].

Another difference between pre-series and series production can be found in the vehicles themselves. While in pre-series production phase there can always be small errors on the vehicles, which have to be repaired by manual re-working, no re-work is allowed in the series production phase. In addition, every step, such as computational processes or employee training, is monitored in terms of quality management. Furthermore, during pre-series production, the product development process is gradually transferred to the product manufacture process. This point in time is marked with the milestone “SOP” [51], [55], [124].

Another important topic, which already starts in the series development phase, is quality engineering. The main focus here is put on series production support, to ensure the fulfillment of quality-related aspects. In addition, product enhancements are communicated to the customer or spare parts are delivered. In the course of vehicle facelifts, an extensive revision of the vehicle is conducted. During the facelift process, all phases of the product development process (c.f. Fig. 18) are passed through again. However, this is not a new development but usually a further development of the existing vehicle status [51], [55], [132].

3.3. Product Development in Automotive BIW Design

Before the structures, materials and associated joining technologies used in automotive body design are discussed in more detail, this sub-chapter presents body development on the basis of the general product development process in the automotive industry. The requirements for car bodies are derived from the requirements on the entire vehicle. The following product development process refers to the BIW respectively closed BIW, which is according to the definition in sub-chapter 1.1 “the vehicle body without external and internal components” (e.g. seats, instrument panel, safety belts, mirrors, bumpers…).

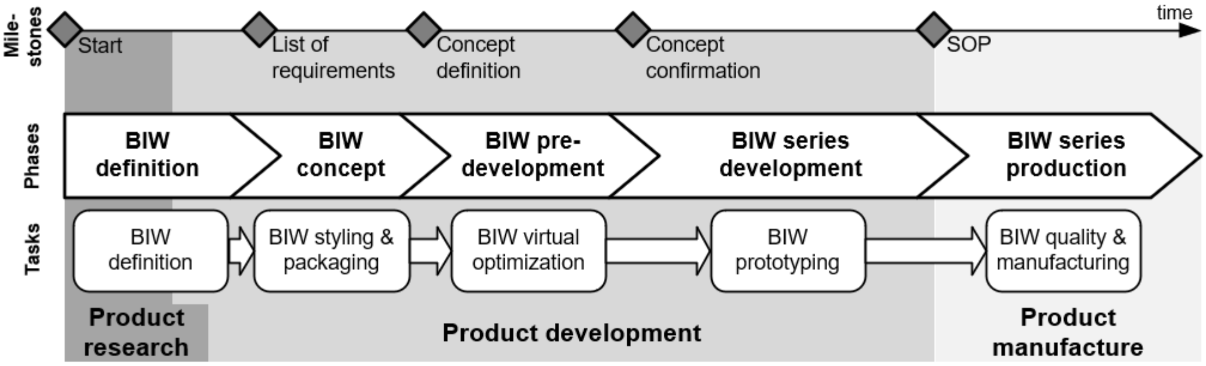


Fig. 20 - Product development process tailored to BIW development

In general, the BIW with an average weight of about 20% of the total car [76] contributes significantly to the vehicle characteristics. As the trend is towards lightweight design, the BIW development process is asking for a wide range of issues in order to achieve weight reduction [69]. The car body itself is influenced by the overall vehicle design, the vehicle type and different functional aspects and in turn influences fuel consumption (weight), value retention of the vehicle (body workmanship quality), aerodynamics (outer skin of the body), interior space layout (ergonomics) and other aspects, such as driving comfort and driving dynamics [69]. Based on the generic full-vehicle product development process introduced in sub-chapter 3.2 and Fig. 18, Fig. 20 shows a product development process that is specifically tailored to BIW development.

As with the general product development process, the BIW development phase is embedded between the BIW product research phase and the BIW manufacturing phase. In addition to this classification, the BIW product development process can be divided into five main phases (Definition phase, Concept phase, Pre-development, Series development, Pre-series & Series production). Each phase focuses on certain tasks (c.f. Fig. 20) and is completed by pre-defined milestones.

BIW definition phase

The BIW definition phase includes an initial elaboration of the BIW and exterior styling proposal [124] and is divided into the strategy phase and the initial phase In the strategy phase, all requirements for the BIW to be developed are worked out and recorded in a target catalog. For this purpose, a market analysis is carried out to determine the customer's desires and a feasibility study is carried out to proof technical and economic feasibility. In the initial phase, on the other hand, ideas are brought in that contribute to the styling and design of bodies, which also includes initial ergonomics studies and installation space analyses. Furthermore, legal regulations (e.g. crash requirements) are observed and the body structure is determined on the basis of the planned production volume (c.f. section 3.4.1). Since the milestones are the same as in the general product development process, the definition phase is concluded with the creation of a list of requirements for the subsequently performed BIW development process phases.

BIW concept phase

The BIW concept phase is mainly driven by styling and packaging-related aspects. The most important part here includes the description of the basic vehicle body concepts by use of CAD models. The above-mentioned (c.f. sub-chapter 3.2) styling-technology-convergence (c.f. Fig. 21) in terms of BIW development is made up on the basic body concepts and the geometry descriptions, which also includes initial simulation procedures, e.g. for stiffness and crash evaluations. The concept phase is concluded with the milestone “BIW concept definition”, at which a technical and styling-related target agreement is to be elaborated. At this point, a detailed description of the vehicle BIW concept is available [69], [124]

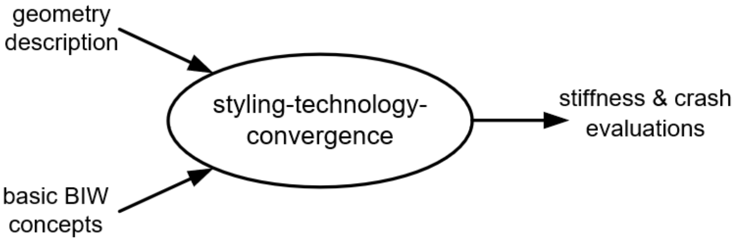


Fig. 21 - Styling-technology-convergence for BIW concepts [69]

BIW pre-development phase

In this phase, the BIW concepts created in the first two phases are elaborated. Therefore, the BIW concept is secured and optimized in such a way that it is suitable for the next process step, the BIW series development phase. In addition to an integration of styling-related data (CAS) into a 3D-CAD model, this phase also includes the initial development of CAD-based joining technology data. This is important because CAE (e.g. durability simulations) and CAM-specific simulations (e.g. space analyses, generation of a suitable joining sequence…) are already carried out in this phase in order to refine the 3D-CAD model accordingly. This requires that data exchange processes of CAD-based data (e.g. geometric dimensions of the sheets, joining technology, metadata) are introduced effectively. In this phase, the integration of suppliers and sub-suppliers plays an important role, which requires an effective exchange of corresponding design, simulation and joining technology data between OEM, engineering and manufacturing supplier.

BIW series development phase

The aim of this phase is to advance the development of BIW to such an extent that production of the vehicle bodies can begin in the next process step (BIW series production). In addition to BIW development, the manufacturing equipment and tools required for production must also be planned. As with the general product development process, physical prototypes of the body are used for tests (e.g. crash tests, durability tests…). The physical test results are compared with the simulation results from the BIW pre-development phase. This phase is concluded with the milestone “Product confirmation”, at which it near-series prototypes and components of the BIW are produced.

<u>BIW series production phase</u>

In the final phase of the BIW development process, the so-called BIW series production, the production is gradually ramped up. Both the production plants and the production tools are brought to the planned production volume output. Besides components manufacturing (e.g. metal sheets), the process steps of BIW joining and painting are included. At the end of this phase, the finished BIW are already joined and painted and prepared for the final assembling procedures in the car production process.

3.4. Modern Body Design

This sub-chapter gives an overview of the most common body structure types in the automotive industry. In addition, the applied materials are introduced and analyzed in view of design, production, economic and weight-related factors, and the associated joining technologies are explained.

3.4.1. Body Structures

As already mentioned in sub-chapter 3.1, body development follows a continuous change. In addition to the influencing factors of materials, body structure and joining technology, aspects such as weight, volume of production, costs, platform development and others play a crucial role. This sub-chapter summarizes these factors and provides an overview of the most commonly used body structures and materials in the automotive industry. The car bodywork represents itself as an essential component of the vehicle and an important factor influencing the customer's purchasing decisions. It influences the structure, materials and design of the vehicle massively. In general, vehicle bodies can be divided into vehicle bodies for passenger transport (especially cars and buses) and vehicle bodies for goods transport (especially trucks). This subdivision influences both the body structure and the associated materials and, subsequently, the applied joining technologies. The most important vehicle body structures in the automotive industry are explained below (c.f. Fig. 22) [92], [129].

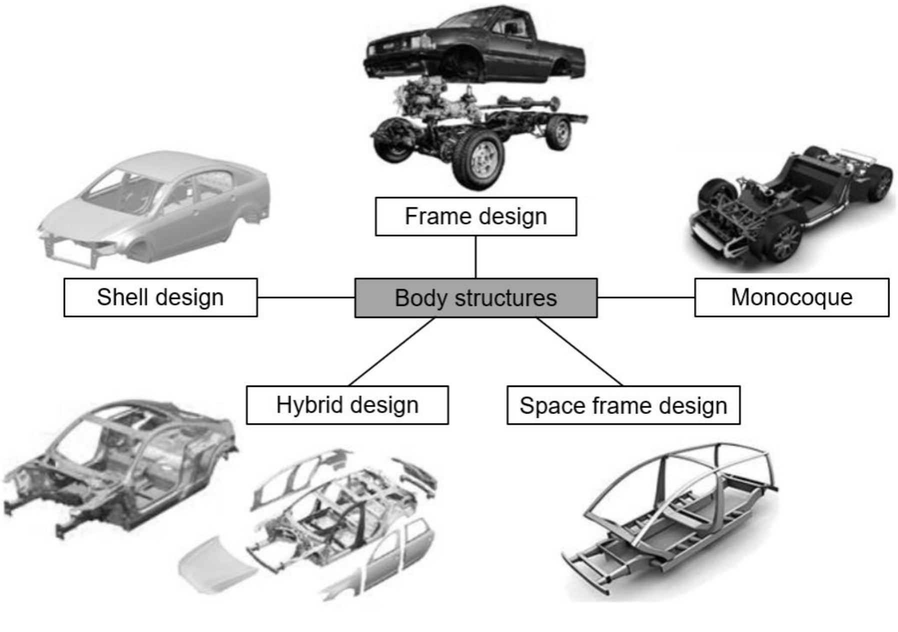


Fig. 22 - Overview of body structures applied in automotive industry [92], [129]

Frame design

Frame design represents itself as the most common structure for commercial vehicles (e.g. trucks and buses). It consists of an arrangement of steel tubes, respectively profiles, as carrying elements and an outer skin that is typically made of steel, plastic or aluminum. The frame also supports all chassis and drive components. Due to the high production effort, this type of structure plays only a subordinate role in passenger vehicles design (excepted off-road vehicles and some types of sports cars) [16], [92], [129].

Shell design

Shell design describes a self-supporting body structure, typically consisting of formed steel sheets and structural elements. The steel sheets and structural elements are closed with a suitable joining procedure so that a load-bearing and rigid structure is created with large cross-sections. This design method was used above all before the turn of the millennium, since the total vehicle weight could be reduced through the increasing application of high-strength and ultra-high-strength steels. Nevertheless, this body type is still the most frequently used structure for car bodies today [16], [92], [129].

Spaceframe design

Spaceframes became popular with aluminum car bodies (use of extruded profiles and aluminum castings). The first pure aluminum spaceframe design was introduced in the Audi A8 in 1998. The spaceframe is a structure that consists of a solid skeleton and non-structural body parts. By using aluminum, the total body weight can be reduced by about 40% in comparison to standard steel bodies [16], [92], [129].

Monocoque

Monocoque structures are sheet steel constructions that origin from racing cars. This type is a self-supporting, highly rigid and safe shell construction. Due to the high manufacturing costs compared to the other structure types, this construction method is mostly used for high-priced niche vehicles with a low number of production [16], [92], [129].

Hybrid design

Hybrid design combines different structure types in one body in form of an integrated shell and frame design. In addition, mixed material structures (so-called multi-material body design), is used [16], [92], [129]. The combination of different body structures and/or material combinations offers advantages, such as weight savings and cost reduction. The complex integration of different design strategies and materials increased the development effort, especially with regard to joining technology, corrosion protection and recycling technologies. Especially in the field of joining technology, the combination of different materials leads to an increase of complexity and variety in design, simulation and manufacturing processes [92], see sub-chapter 3.4.3.

3.4.2. Body Materials

As with the vehicle body structures, there is a variety of different materials used in vehicle bodies. This variety results from continuous development of the body structures (e.g. spaceframe – the introduction of aluminum) on the one hand and external factors such as environmental issues, weight and cost savings, etc. on the other hand. Commonly used materials for vehicle bodies in the automotive industry are:

- Steel
- Aluminum
- Carbon fiber
- Magnesium
- Synthetic materials

Steel

The material steel dominated body design for decades. Even today, steel is still the most used material in automotive bodies, mainly in the form of sheet metal and profiles. The steel sheets, which are sub-divided into hot-rolled and cold-rolled products, have a sheet thickness of 1.6 mm to 6 mm [98].

Body steel sheets are divided into deep-drawn sheets (carbon steels with a carbon content of less than 0.1%) and high-strength deep-drawn sheets. The latter, in turn, are divided into phosphorus-alloyed steels, silicon and manganese-alloyed steels, precipitation-hardened steels and two-phase steels. A disadvantage of steel sheets is its poor corrosion resistance, which requires corrosion protection measures, e.g. zinc, tin or aluminum coating. The corrosion protection coating reduces the weldability of steels, which has to be considered in the development of the joining processes [98].

Steel sheets show advantageous economic behavior in case of large series production (quantities larger than 100.000 pieces per year). In addition, steel has good structural and fatigue strength and is well recyclable. The properties relevant to joining technology and the joining technology itself have also been continuously developed over the last decades [74]. In the past years, increasingly high-strength steel alloys come to use, which enable a reduction of the wall thickness and, thus, a lower body weight [130].

For steel connections in car body design, spot welds, seam welds and adhesives are usually used as joining technology.

Aluminum

Until the 1990s, the material aluminum was used only for specific parts in BIW (e.g. engine hoods, doors, trunk lid...). However, this changed with the introduction of spaceframe body structures in larger production volume cars, which use extruded aluminum profiles and casting nodes [96].

In general, aluminum has a lower density compared to steel ($\rho_{steel} = 7.86 g/cm^3$ [78] and $\rho_{aluminum} = 2.71 g/cm^3$ [78]), which makes it useful for lightweight design in different branches. Besides the lower density and the associated weight advantages, the material offers benefits in manufacturing processing, e.g. casting, forging, rolling... [74], [92]. Furthermore, vehicle bodies made of aluminum components offer good corrosion resistance [74].

A major disadvantage of aluminum is its modulus of elasticity, which is about two-thirds lower than those of steel (E_{steel} = 200.000N/mm² [78] and $E_{aluminum}$ = 70.000N/mm² [78]). In order to take this disadvantage into account in the development process, the BIW design must be provided with larger cross-sectional areas and increased wall thickness [92], [96]. Furthermore, due to the high energy demand required for the production of primary aluminum, the material price of aluminum is about three times higher than those of sheet steel [74].

Compared to steel bodies, the selection of an appropriate joining technology is more complex for aluminum. In this context, a variety of technologies such as rivets, bolts, screws, clinches, clips, nails, spot welds, seam welds and adhesives is applied in car body design.

Magnesium

In addition to aluminum, the non-ferrous metal magnesium is occasionally used in the automotive industry for specific components of vehicle bodies. Magnesium offers an even lower density ($\rho_{magnesium}$ = 1.83 g/cm³ [78]) than aluminum, with similar physical properties [93]. It is, therefore, possible to produce components with a very low weight, but the costs of these components are about twice those of aluminum components [6], [74]. This is also one of the reasons why magnesium is still rarely used today – mainly in the higher-priced vehicle segments and racing cars.

For automotive joining processes of magnesium components, welding processes (e.g. MIG (Metal Inert-Gas), TIG (Tungsten Inert-Gas)) and adhesives are dominating. Besides these two types, certain kinds of rivets, bolts and clinches come to use [48].

Synthetic materials & carbon fiber reinforced components (CFRP)

In addition to the mentioned metals, non-metallic materials, such as plastics, can also be used in vehicle bodies. Synthetic materials are divided into reinforced and non-reinforced synthetic materials. Due to their low strength, non-reinforced plastics are mainly used for body outer shell parts. Fiber-reinforced plastics are of greater interest for body design because they can also be used for load-bearing structural components.

Especially CFRP are of central importance for lightweight design due to their low density (ρ_{CFRP} = 1.6 g/cm³ [78]) and high strength at the same time. CFRP are mainly used in niche vehicles today (e.g. luxury vehicles, vehicles with low production quantities, racing cars). Carbon fiber components are mostly used in combination with other fiber reinforced materials, e.g. GFRP (Glass Fiber Reinforced Plastic) or SMC [74]. Due to the low density, weight savings of up to 52% can be achieved compared to steel in BIW [39].

One disadvantage is the high raw material price of carbon fiber, which is approximately 40 times higher than those of standard steel materials [78]. The cost-related disadvantage is partially compared by low investment costs for tools and production machines. This means that for small series production, a car body made entirely or partly of carbon fiber reinforced plastics can appear to be quite economical [74].

In the automotive body design, welding processes cannot be used for carbon fiber-based joints in particular. To ensure that carbon (e.g. CFK) and plastic components can still be joined, adhesive procedures are used. In addition, mechanical joining processes (e.g. screws, rivets) are applied, as it is the case with magnesium joints.

Tab. 3 summarizes the most important materials for car bodies and gives an overview of main areas of application, material density, weight saving potentials compared to standard steel and material costs.

Material	*Body structure (main use)*	*Costs* [78] *[$/kg]*	*Density* [78] *[g/cm^3]*	*Weight saving potential* [39], [74]
Steel	Shell design	1	7.86	-
Aluminum	Spaceframe design	2.8	2.71	40%
Magnesium	Hybrid design & niche vehicles	4.8	1.83	49%
Carbon fiber (CFRP)	Monocoque & hybrid design	20-40	1.6	52%

Tab. 3 - Comparison of the most important materials for car bodies

A general statement as to which material and body structure is to be preferred cannot be made. One important aspect for the selection includes the cost factor. In this context, the unit costs (mainly material costs and production costs) are set into relation with the investment costs for tools and machines (c.f. Fig. 23).

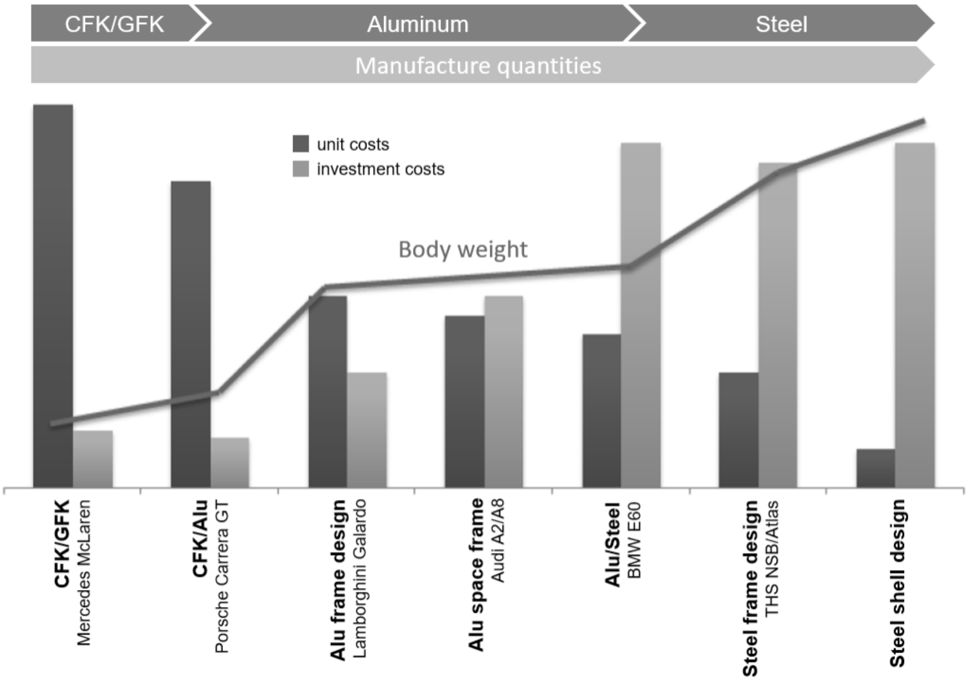


Fig. 23 - Conflict of body weight and cost factors according to [19], [92]

A differentiation of body structure and materials as function of the intended production volume is very difficult. It can be estimated that above about 100.000 units per year the high investment costs of tools and machines for steel-based body structures are amortized by the unit costs [56]. An example to verify this statement shows a comparison of the Mercedes Benz S-Class with the Audi A8. While the A8 body (approx. 60.000 units per year [79]) is based on an aluminum space frame technology, the S-Class with over 100.000 units per year relies on the self-supporting body (steel metal shell design).

Since it is difficult to make a general statement here, Fig. 24 reflects quantitative trend lines representing body costs as a function of the production volume by a comparison of the monocoque structure with aluminum space frame-based bodies, steel-based space frame and shell design [74]. In addition to the use of different body structures and materials, the continuing trend of the platform strategy plays a decisive role in the automotive industry. While in the 1960s mainly just three vehicle derivates “sedan”, “sports car” and “spyder” were offered, the situation changes over time with more than 15 vehicle derivates in 2000 [129]. For example, BMW already has 59 different derivates currently (2019) available on the market (including all X, Z, M, i and plug-in hybrid models, as well as all derivates of the BMW 1 to 8 series) [12]. In addition to the existing diversity of derivatives, the introduction of new types of propulsion technologies after the turn of the millennium also led to new vehicle – and thus body architectures.

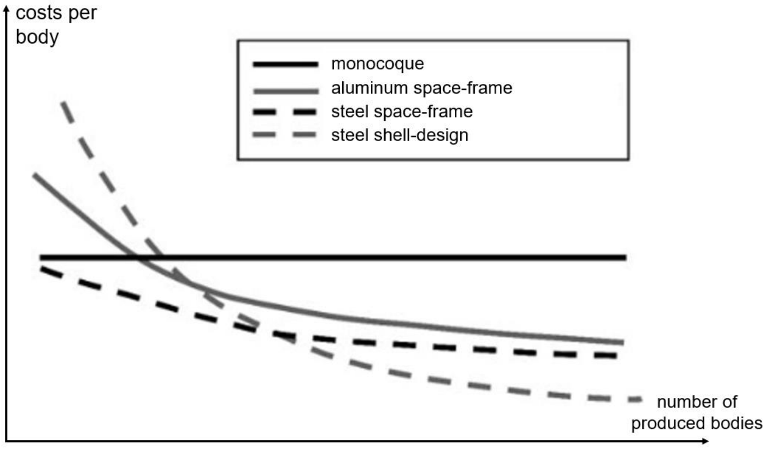


Fig. 24 - Correlation between costs and quantities of body structure types [18], [74]

In platform design, several derivatives of an OEM use the same basic modules (e.g. basic module, wheel base module). This has the advantage that for the individual derivatives (e.g. convertible, SUV, roadster vehicles) only individual modules (e.g. upper body module) have to be developed separately.

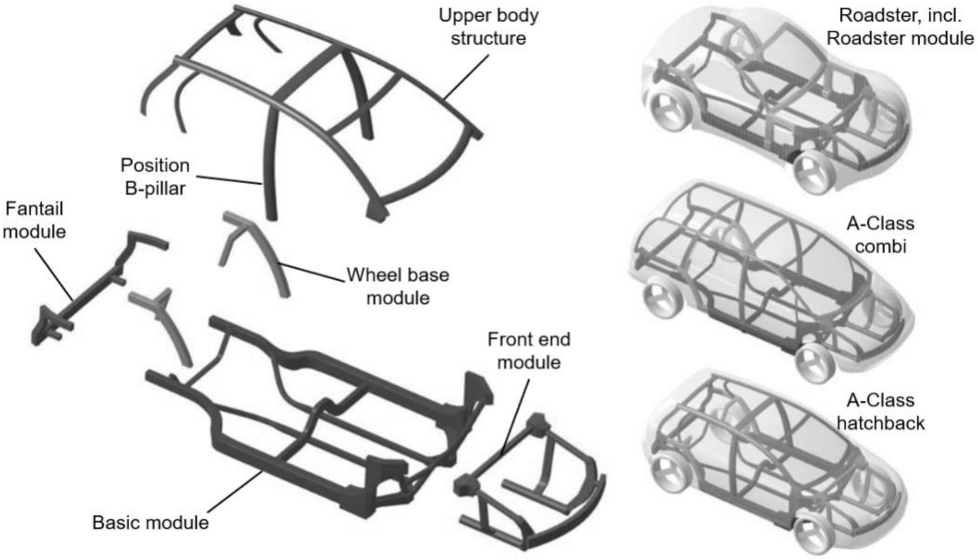


Fig. 25 - Distribution of individual modules and exemplary derivation of vehicle derivates, referring to [18]

The use of the same basic structure (basic module, wheelbase module and fantail module) minimizes development costs while simultaneously increases the number of units produced. The upper body module that shapes the individual appearance of the vehicle, on the other hand, must be developed separately for each derivative. This leads to a lower number of produced units per upper body derivate [18]. The individual modules used in Fig. 26 are illustrated in Fig. 25.

For this reason, the quantities of individual modules vary significantly. Fig. 26 shows a scenario of different materials exemplary used for various modules. It should be noted that in the shown example, the basic module with an assumed production volume of more than one million units per year is used in each individual derivative. For this reason, it is advisable to use the material steel for the basic module. For the modules “Convertible” and “Roadster” it is recommended to use aluminum due to the small number of pieces (i.e. <10.000 pieces per year) [18].

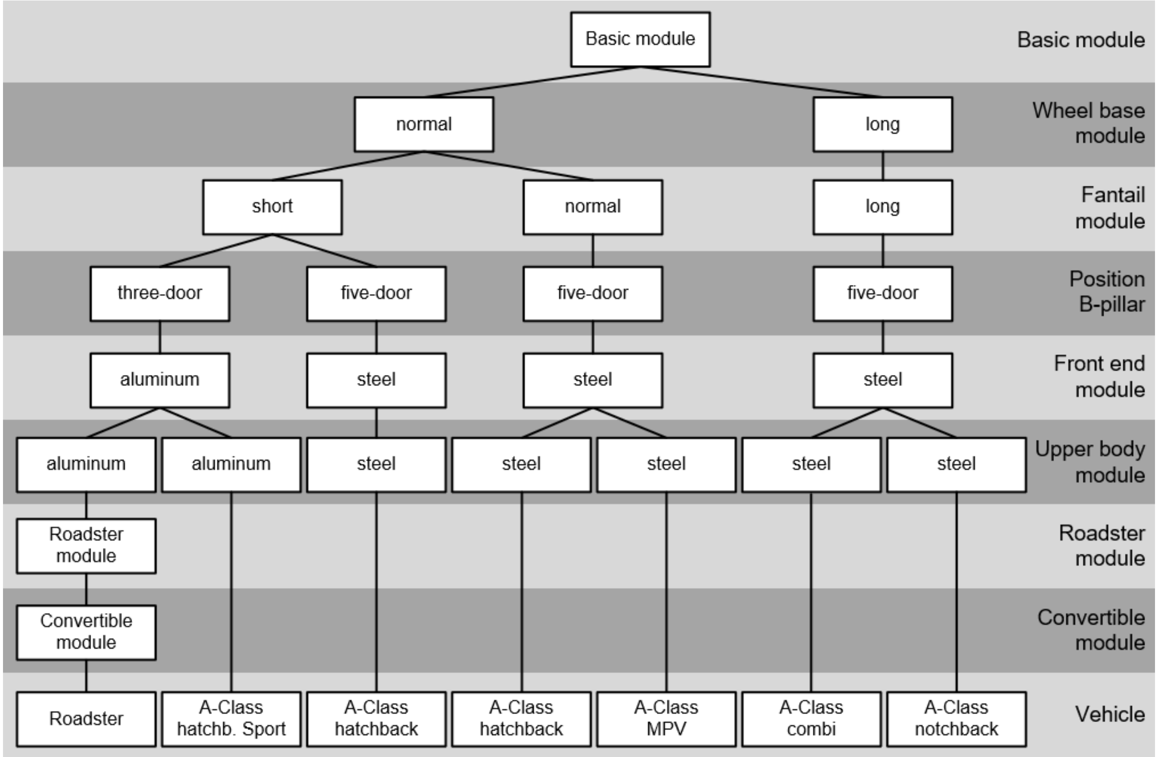


Fig. 26 - Possible combinations of modules resulting in different vehicle derivates, referring to [18]

Due to the high variety of variants of body structures, materials and material combinations, as well as the platform design of derivatives that is common in the automotive industry, the requirements on joining technologies increase. New body design and configuration solutions as well as different material pairings call for continuous further development of already used joining technologies and innovative joining technologies. Section 3.4.3 provides an overview of joining technologies in vehicle body development with a focus on the required metadata and parameters for CAx application in development processes.

3.4.3. Body Joining Technologies

According to DIN8580 classification, there exists a total of six different main groups of manufacturing procedures. Joining, which is of great importance in the automotive industry, is placed in the fourth group [40]. In the following section, an overview of joining technology in automotive body development (c.f. Fig. 27) is given. For all further considerations, especially in view of the data exchange process, these procedures are divided into punctiform (0D-joinings), line-shaped (1D-joinings) and surface-shaped (2D) joining technologies (cf. section 3.4.3.1 – 3.4.3.3). This distinction into three main groups is based on the xMCF (Extended Master Connection File) standard [29], which is of great significance for further considerations in this work.

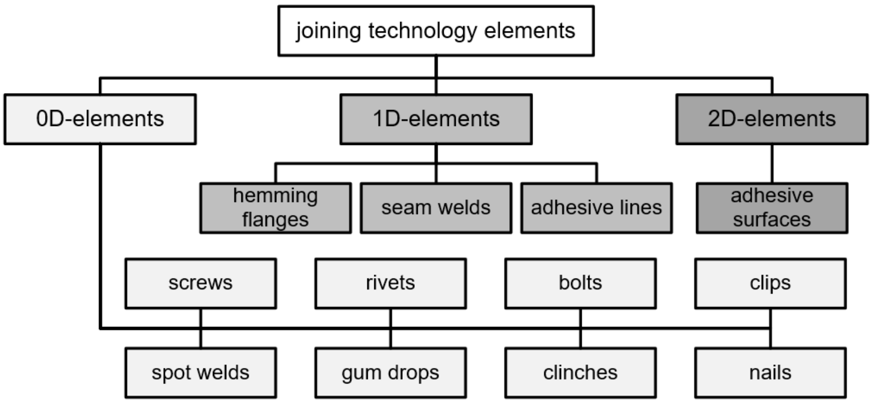


Fig. 27 - Overview of joining technology elements in automotive body development

First, a brief introduction is given to the topic of joining technology elements used in automotive bodywork. As shown in Tab. 4, the number of different joining types and the number of individual joining technologies has changed massively in recent decades. This increasing complexity in the field of joining technology of course has an impact on the data exchange process of the joining technology data, because of increasing number of parameters and meta-information, which are necessary to describe joining elements, different input sources, heterogeneous data exchange file formats, etc. The complete list of parameters, subdivided by types of joining technology, according to the xMCF standard, can be found in annex A.2.

Just a few years ago, spot welding was the predominant type of joining technology in BIW applications. Today, it has become a more complex topic because of increased number of various types of joining technologies, mainly due to the use of different materials. Furthermore, there has also been further development in joining procedures and manufacturing, which led to the introduction of new joining types in automotive BIW development processes [26], [40].

As shown in Tab. 4, the body of a popular car in Europe in the 1990, the Fiat Uno, was joined by using 2.700 spot welds. Since this vehicle had a self-supporting steel body (shell body structure made of steel only), spot welds were used as the only type of joining technology. Compared to the other newer car models in Tab. 4, which all have a multi-material body design, the complexity in the field of joining technology (spot welds only) can, therefore, be regarded as low at the Fiat. Especially in the field of multi-material car body design, the use of different types of joining technology is widespread (c.f. Tab. 4).

Another example can be given with the Audi A8 (D2) manufactured in 1994, which was the first mass-production car with a spaceframe body structure made of aluminum. The bodywork was joined with 1.100 self-pierce rivets, 70 meter of MIG welding lines, 500 spot welds and 178 clinches [41].

Type of joining technology	*Fiat Uno (1986)* [88]	*Skoda Kodiaq* [115]	*Aston Martin DB11* [99]	*Volvo V90* [86]	*Peugeot 3008* [101]
Spot welds	2.700 pcs	6.283 pcs		5.250 pcs	4.157 pcs
Arc welding				4.9m	143m
MIG welding		1.52m			0.16m
Laser welding		1.86m		4.4m	2.18m
MAG welding		3.12m			1.43m
Brazing		6.56m			3.52m
Clinches		30 pcs			14 pcs
Weld studs		248 pcs		247 pcs	83 pcs
Adhesive line (structure)		95.96m	113m		1.05m
Adhesive line (PU)			39m		
Adhesive line (hotmelt)				7.2m	
Adhesive line (rubber)				69.6m	
Adhesive (anti-flutter)				2.6m	14.9m
Adhesive line (sealing)					4.27m
Structural rivets			841 pcs		
SPR (Self-Piercing Rivet)			437 pcs		
Screws			52 pcs		
Hemming flanges		26.65 m			19.87 m

Tab. 4 - Comparison of joining types in five different vehicles, including the manufacturing year

Generally, it can be stated that the selection of an appropriate joining type primarily depends on the material pairing, e.g. for steel/steel pairing, spot welding is the predominate joining procedure. However, other factors such as costs, weight, detachable (e.g. screws) or non-detachable joining (e.g. spot welds, seam welds, rivets), required production time for one joining element, environmental-related aspects, etc. also play a significant role [40]. In view of the development processes applied, it is essential that all types of joining technologies have to be handled throughout the entire VPD processes, which includes CAD, CAE and CAM environment, as well as the corresponding data management and exchange.

Tab. 5 gives a cost overview of different joining types and Fig. 28 shows a typical joining sequence in the production of an automotive body. The economic comparison of selected joining processes is based on [63] and refers to two-sheet connections. Especially for steel/steel pairings, welding processes are still the most used technology in automotive applications, as they are characterized by the lowest costs (cost factor 1.0). Furthermore, there is no or only a slight increase in body weight if spot welds are used. For aluminum/aluminum pairings, welding processes are les advantageous (cost factor at least 2.9) and instead, rivets, bolts and clinches are used.

Joining technology	*Cost factor*	*Main field of application (materials)*
Spot welds (steel)	1.0	mainly steel/steel pairings
Adhesives (0D)	1.4-1.7	applicable for nearly all material & material combinations
Clinches	1.5-2.5	mainly for aluminum pairings
Bolts	2.5-3.0	mainly for aluminum pairings
Clips	2.5-3.0	mainly for aluminum and plastic
Rivets	2.6-3.5	mainly for aluminum pairing
Spot welds (aluminum)	2.9	mainly aluminum/aluminum pairings
Seam welds (steel)	2.9	mainly steel/steel pairings
Screw	3.6	mainly for aluminum pairing
Seam welds (aluminum)	4.3	mainly aluminum/aluminum pairings

Tab. 5 - Cost comparison of different joining technologies according to [34], [63] and fields of application (materials)

Fig. 28 shows a possible joining sequence of a self-supporting body structure. Firstly, the two components of the underbody (rear and front module) are connected to the front end. Then the inner and outer quarter panels as well as the roof frame structure are mounted to the existing basic module (underbody and front end). Now the BIW, without doors and flaps, is already finished. In the next step, the doors and flaps are added (e.g. tailgate, side doors, engine hood), which leads to the finished closed BIW structure. Again, this process is a way to determine the order in which the components/sheets of the body can be joined. If other body structures or materials are used, the sequence may differ.

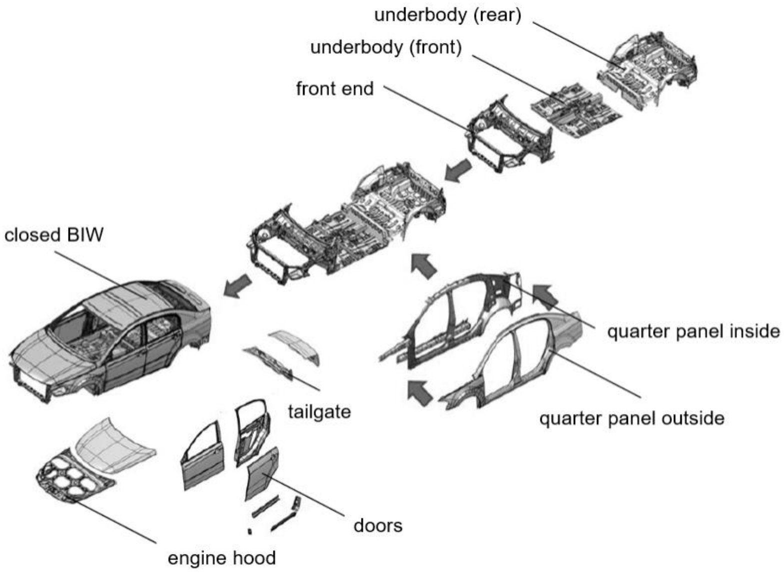


Fig. 28 - Exemplary joining sequence of a car body [92]

3.4.3.1. 0D-Joining Technologies

The first major group in the field of joining technologies includes the 0D-connections, also called punctiform joining technology elements. In general, different types of 0D-joints are used in automotive BIW development. It is crucial for the data exchange that 0D-connections are described by a coordinate vector (x-, y- and z-coordinates), a diameter, material and geometry parameter (e.g. material, thickness) of the adjacent sheets and possibly additional parameters (e.g. normal direction, length of a rivet) tailored to the type of joining element.

Spot welds

Welding, especially spot welding, is still one of the most important types of joining technologies used in the automotive body design today. Modern vehicles bodyworks can be joined by more than 5.000 spot welds, depending on the body material mix, the size of the vehicle and the available budget for manufacturing (c.f. Tab. 5). In spot welding, up to four overlapping sheets can be joined together using two electrodes. This is done by means of an electric current, which serves as a heat source and a force application. This leads to melting metals and thus to a connection in a punctiform manner (c.f. Fig. 29) [98]. Typically, spot welding is used to connect two or more parts made of steel (e.g. in steel bodies). In the automotive industry, modern production lines are planned in such a way that a degree of automation (use of robots) of 90% or even more can be achieved for spot welding. This leads to fast processing time, low failure probabilities during joining processes due to precise application, and cost-effective production.

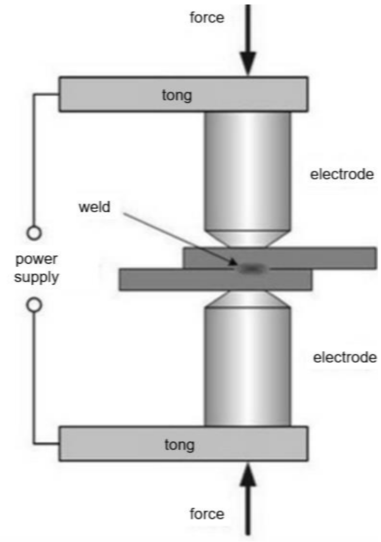


Fig. 29 - Process method of spot welding [50]

In general, welding results in a material bond between two or more components, which are held together by cohesion and adhesion forces. This means that an inseparable bond is produced, which can only be released by destroying the connection – and thus the parts. Besides the procedure of punctiform spot welds, linear types of welding are also used in automotive body development processes (c.f. section 3.4.3.2).

The costs per welding spot are relatively low in comparison with other joining technologies and the total weight of the vehicle body does not increase considerable with this technology. Although spot welding is still one of the most important joining processes in vehicle body design, it has its limits, e.g. not fully developed joining procedure for steel/aluminum and aluminum/aluminum pairings with high costs. Therefore, it will become increasingly important in the future to include other joining technologies [28].

Advantages:

- High strength of the joining point can be reached
- High degree of automation
- No post-processing of joints necessary

Disadvantages:

- No continuous seam is possible (e.g. no sealing function)
- Two-sided accessibility is required for the joining process
- Non-destructive disassembly possible

Glue points

As with welding, a classification of different types can also be made for gluing. Therefore, the classification according to [29] again includes 0D-, 1D- and 2D-processes. In principle, a wide variety of materials can be bonded by choosing the right adhesive material. Bonding is the joining of two or more components using a thin layer of adhesive. Hereby, as shown in Fig. 30, it is particularly important to consider the inherent strength (cohesion) and the deformation properties of the adhesive as well as the bonding forces between the adhesive layers and the surface of the component (adhesion) [40], [67].

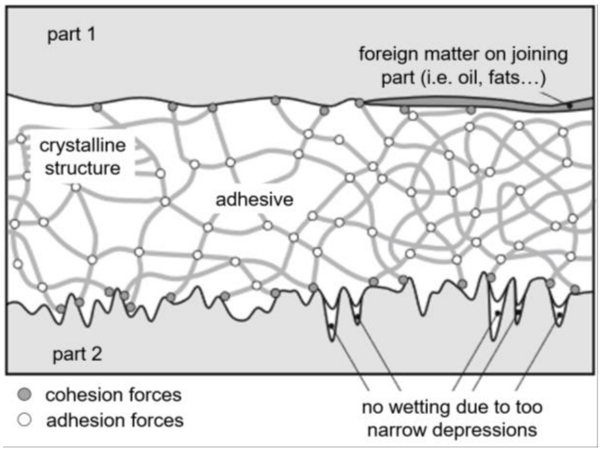


Fig. 30 - Cohesion and adhesion forces displayed in adhesive gap [40]

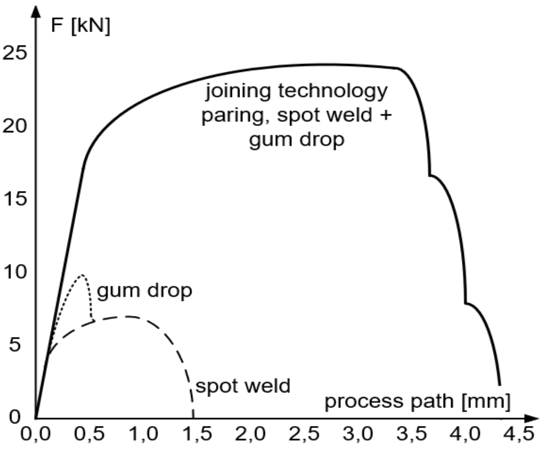


Fig. 31 - Change of joining properties, exemplary on tensile loading [28]

Gluing is used for connection of material mixes and in combination with another joining process. For example, in case of multi-material body design, gluing is used to prevent corrosion (e.g. for joining of steel and aluminum parts). With this joining process, it is possible to produce an electrical and galvanic separation, which in turn is necessary to avoid corrosion [28]. Another important fact is that adhesive joining processes, especially glue points (equals gum drops according to [29]), can be used in combination with other types of joining, like spot welds, screws, clinching, etc. This mixture of two different joining methods combines the advantages and partially compensates disadvantages of single joining technologies. Fig. 31 gives an example, how the combination of a spot weld and a gum drop can change the properties of the joining, exemplary on tensile loading. As shown, a much higher force can be applied in case of a combination of both technologies. The process path d, that represents the deformation behavior is much longer compared to an application of the technologies individually.

The principle of gluing:
Adhesion is only effective if the components are completely wetted with adhesive. This can best be achieved with clean surfaces (i.e. no contamination). The term cohesion summarizes all forces that are responsible for the interconnection of the adhesive. In the case of cohesion forces, chemical bonds within molecule and Van-der-Waals forces play a decisive role in the quality of the bond. It is important to note that the larger the wetted area, the better the bonding result [40], [46], [67].

Advantages of using adhesive joining in BIW design, according to [135]:

- Very good strength and stiffness properties of structurally bonded vehicle bodies
- High potential to reduce the number of used joining elements (e.g. rivets) in the vehicle body design
- Bonding enables the advancement of lightweight bodies and multi-material design
- Due to the good sealing function, the corrosion standard can be kept high
- Offers potential as the flexible standard joining technology in vehicle body design

Gluing in the automotive industry:
The procedure of gluing is becoming more and more important in modern body design. The aspect that almost all materials can be bonded is of primary importance. Since many BIW already consist of multi materials, bonding is predestined for joining components. However, as this is still a relatively new type of joining in the automotive industry, there are still some challenges, e.g. aging problems of the adhesives, required pre-treatment of the surfaces and the increased space requirement for the adhesive seam [67], [107].

Advantages:

- Joining of different materials possible
- Good for use with thin parts/sheets
- Hybrid joining technology possible

Disadvantages:

- Aging problems of adhesive materials
- Pre-treatment of surfaces necessary
- Low load-bearing capacity of the joint

Rivets

Rivets are mostly used in automotive body design where welding processes reach their technical limits, e.g. in case of steel/aluminum pairings. A classification of the most important types of rivets used in automotive bodies is shown in Fig. 32.

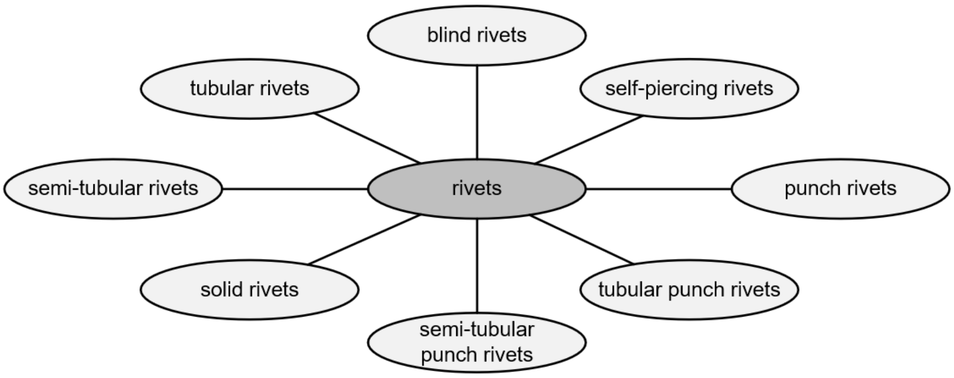


Fig. 32 - Classification of rivets, used in the automotive industry

Note: The literature often does not distinguish between rivets and clinches. In this thesis, the different types of joining technologies are sub-divided according to the xMCF standard. Therefore, clinches are treated separately in the next section.

Riveting is a mechanical joining process that could partially replace spot welding in the future. Rivets are mainly used for materials that are very difficult or impossible to weld (e.g. steel/aluminum connection, carbon fiber…). A further advantage is that, unlike welds, rivets have no notch effect and are, therefore, more suitable for dynamic load cases [49]. However, the following facts can be regarded as disadvantages [28], [59]:

- Low static strength
- High space requirement of the joining tools
- High joining forces necessary

Fig. 33 shows the process principle of punch riveting. Briefly explained, the rivet is pressed into the material with a punch. The material is punched out of the part to be joined and the ends of the rivet are bent over. The shape of the bending, respectively the shape of the rivet after the riveting process, is determined by means of a die. This method of punch riveting eliminates the need to drill a pilot hole, which is a significant advantage over most other riveting methods. With this variant, up to four parts can be joined together. This is completely sufficient for automotive applications, since joints of four sheet metal parts are very rare in automotive body structures. In addition, a combination of gluing and riveting can also be used if required, e.g. in terms of corrosion protection [2], [3], [13], [28].

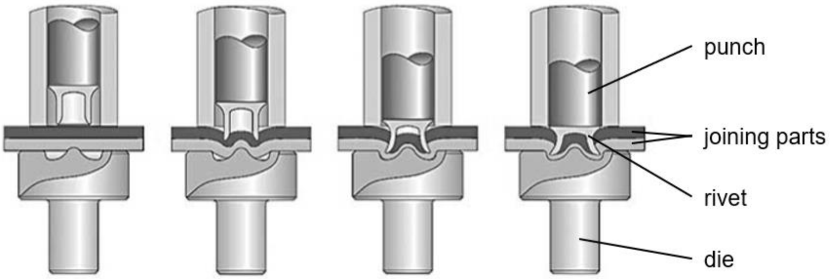


Fig. 33 - Principle of punch riveting, referring to [7]

Advantages:

- Low costs realizable
- High degree of automation
- Joining of different materials possible

Disadvantages:

- No continuous seam possible (i.e. no sealing function)
- Two-sided accessibility is required for the joining process
- Only applicable to materials with sufficient ductility

Clinches

Clinching has almost the same advantages and disadvantages as riveting, but the costs of punch riveting are higher compared to clinching, which shows about the same costs as spot welding. In this way, clinching is gaining importance in automotive body design [2], [28], [87]. The process principle is quite similar to riveting, as visible in Fig. 34.

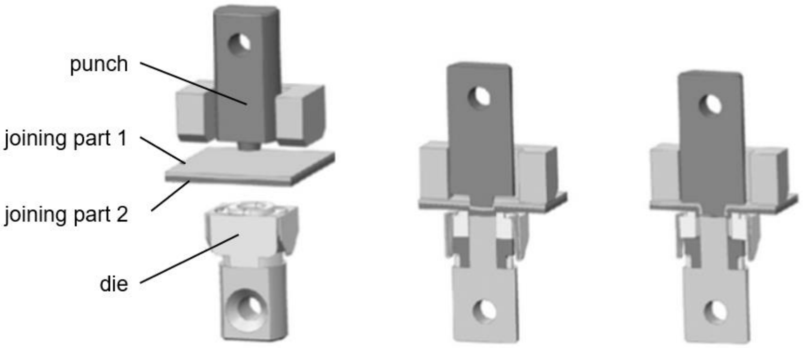


Fig. 34 - Process principle of clinching, referring to [25]

Advantages:

- Low costs realizable
- High degree of automation
- Suitable for thin sheets

Disadvantages:

- No continuous seam is possible (i.e. no sealing function)
- Two-sided accessibility is required for the joining process

Bolts and Screws

Screw and bolt connections of all kinds are increasingly used for joining of vehicle bodies. Fig. 35 shows an assembly process of a self-tapping screw [36], [92] In view of data management, the large amount of parameter (cf. annex A.2) that is necessary to describe bolts and screws within VPD represents a considerable challenge.

In automotive bodies, bolts and screws are mainly used for safety-relevant applications. One example of this represents the body of the Audi A3, which contains several thousand welding spots as well as 250 screws to ensure a safe structure in view of the crash behavior [100]. In car body design, applications can be marked as safety-relevant where there is an indirect or direct danger to life and limb. Examples of this are the use of safety-relevant bolted connections in the area of chassis, wheel or brake system screwing.

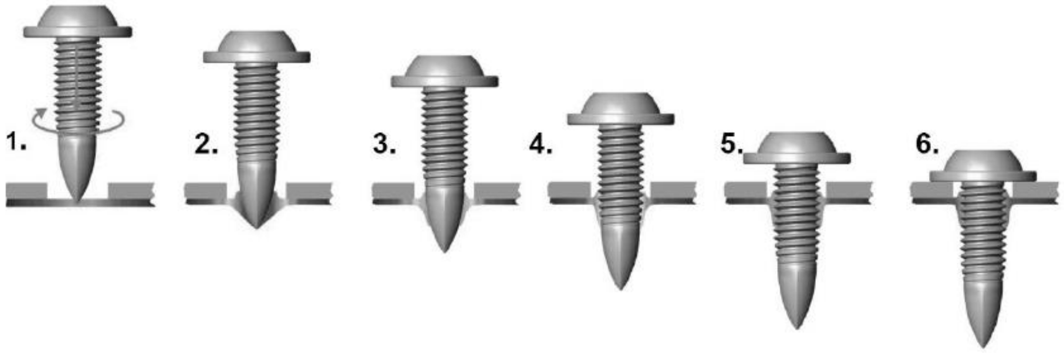


Fig. 35 - Assembly process of a self-tapping screw [36], [92]

Furthermore, screws represent a detachable connection type without causing damage to the joined components and can be used almost independently of the material. Another main field of application for bolts and screws is in combination with adhesives to guarantee a certain sealing effect, and to reduce the probability of self-opening or loosening due to continuous dynamic loads (vibration slope).

Advantages:

- Detachable joining element
- Suitable for thin sheets
- Applicable for various materials and material combinations
- Useable for safety-relevant applications

Disadvantages:

- No continuous seam is possible (i.e. no sealing function)
- Two-sided accessibility is required for some variants
- Lower degree of automation compared to spot welds or clinches

<u>Clips</u>

Generally, clips are fasteners with elastic components attached to a fixed counterpart. The elastic component is hooked in and can possibly be removed non-destructively (depending on the clip type). The number of clip connections in car bodies has increased constantly during the past few years.

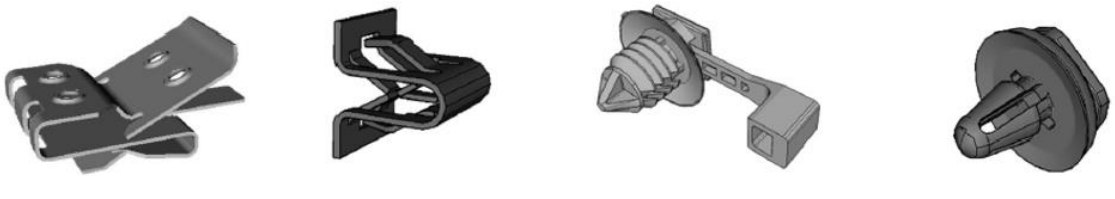


Fig. 36 - Depiction of different clip types [29]

Fig. 36 shows different types of clips, which are in use in the automotive sector. The two clips on the left are “clips sliding onto a flat surface”, while the two clips on the right side are “clips pushed into a hole” [29]. Clip connections can be used for almost all materials (e.g. heat plate connections at exhaust pipes, connection of plastic components with steel/aluminum sheets). This flexibility is, in addition to the possibility of non-destructive disassembling, a decisive reason for the increased application of clips.

Advantages:

- One-sided accessibility required only
- Applicable for various materials and material combinations
- Easy assembly process

Disadvantages:

- No continuous seam is possible (i.e. no sealing function)
- Low static strength

Nails

Nails are a rather emerging type of joining in the field of automotive bodies. Especially for vehicle bodies that use non-steel materials, it can be an interesting alternative because it supports cost reductions in manufacturing processes. One disadvantage of using nails is the high noise level that is generated during the joining process [29].

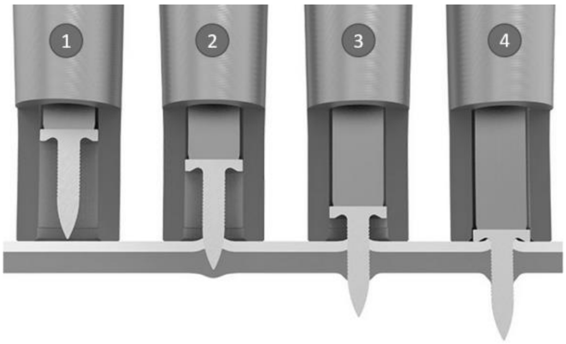


Fig. 37 - Nailing process of two sheets [14]

High operation speeds for hammering are used in industrial nailing processes. This also means that the joining process is associated with a high noise level (>110dB). Normally, the sheets to be joint, need a pre-drilled hole to attach the nail (Fig. 37, no. 1). After the nail has been placed, the entering (Fig. 37, no. 2), respectively penetration (Fig. 37, no. 3), of the nail into the sheets is conducted. Finally, the bracing takes place (Fig. 37, no. 4) which guarantees a fixed joining [14], [29].

Advantages:

- One-sided accessibility required only
- Applicable for various materials and material combinations
- Fast joining process

Disadvantages:

- High noise level while joining
- Pre-drilled hole necessary
- New joining procedure with low level of experience in automotive manufacturing
- No continuous seam is possible (i.e. no sealing function)

3.4.3.2. 1D-Joining Technologies

The second main group, according to xMCF classification (c.f. [29]), comprises all linear types of joining technology elements: seam welds and adhesive lines. These are regarded as continuous line-shaped elements with a certain height and width. Further parameters, e.g. type of welding, type of adhesive, are to be considered for the data exchange process (c.f. section

3.4.3.4). In contrast to the types of punctiform joining technologies, where a defined coordinate vector can be assigned to each individual point, linear joining elements are usually described by approximations of lines and curves, e.g. by geometrical discretization.

Seam welds

The joining procedure of linear welding can be divided into different subtypes, e.g. MIG, WIG, brazing, laser welding. Especially for the connection of steel bodies, this technology offers a cost-effective variant for joining of two or more components. In automotive BIW design, seam welds are applied when the use of spot welds is no longer sufficient for reasons of fatigue strength, crash behavior or production processes. However, welding can also be used when two aluminum sheets are to be joined together, but it is not suitable for joining of carbon fiber components, plastic parts or components of different materials.

Advantages:

- High strength
- Continuous seam (i.e. sealing effect)
- High degree of automation
- Suitable for thin sheets
- Cost-effective solution

Disadvantages:

- Non-destructive disassembly impossible
- Influence of the joining process on the material characteristics
- Partially two-sided accessibility is required for certain welding process
- Problems with joining of different materials (restricted use in multi-material vehicle bodies)

Adhesive lines

As with seam welds, adhesive lines are declared as a linear type of joining technology. Adhesive lines are mainly used for two or more components made of different materials, but they can also be used for pairings of the same material. Primarily, gluing processes are applied in vehicle bodies in higher-priced segments such as luxury or sports cars, but todays they are increasingly used in vehicles lower price segments, too to achieve weight savings. A further field of application are sealing elements. Since gluing usually enables imperviousness against water and dirt penetration, the fastening of sealing elements (mostly steel or aluminum with plastic connection) is another field of application.

Advantages:

- Continuous line (decisive for robot-controlled application)
- High degree of automation possible
- Suitable for thin sheets
- Well suitable for multi-material bodies
- Sealing effect against water and dirt penetration

Disadvantages:

- Aging problems of the adhesives
- Pre-treatment of the surfaces required
- Increased space requirement due to large contact surfaces
- Higher costs than seam welds

3.4.3.3. 2D-Joining Technologies

The third main group according to the xMCF standard is the group of 2D-joinings. Only one type of joining technology – adhesive faces – is treated here. The main difference between 1D- and 2D-adhesives is that 1D-adhesive joinings are generally lines with a certain thickness and height. 2D-adhesives, on the other hand, are surface bonds. These 2D-adhesives can be geometrically described by a (bent) rectangle of a certain length, width and height (c.f. Fig. 38). This distinction is also a question of definition, especially in different literature.

In view of data management, the adhesive faces are described by using approximations of surfaces, similar to the linear-shaped joining technology elements. In the case of the xMCF standard, the 2D-joining technology types are described by so-called “connection faces”, which are based on tessellations. For example, a triangle or rectangle consisting of three or four corner points can be assigned to each tessellation (c.f. Fig. 39).

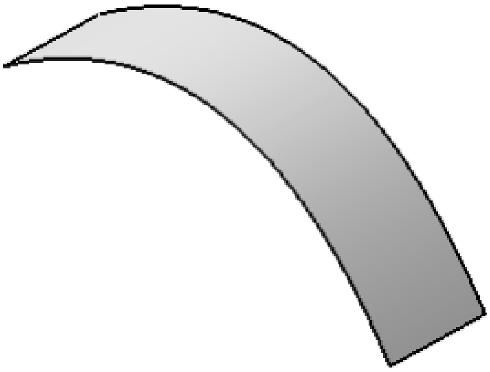


Fig. 38 - Adhesive surface created in CAD

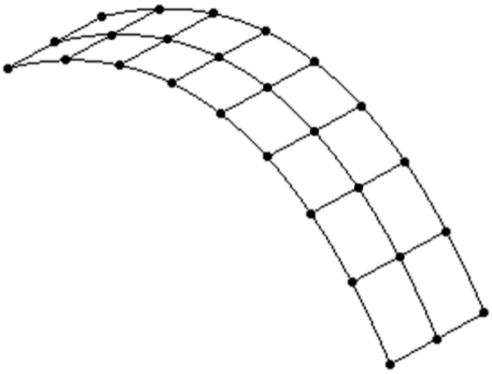


Fig. 39 - Tessellation of the adhesive surface using rectangles and corner points

Advantages:

- Continuous, meandering line, which can be applied by robots (when the joining parts are pressed together, an adhesive surface is created)
- High degree of automation possible
- Suitable for thin sheets
- Well suitable for multi-material bodies
- Sealing effect against water and dirt penetration

Disadvantages:

- Aging problems of the adhesives
- Pre-treatment of the surfaces required
- Increased space requirement due to large contact surfaces

3.4.3.4. Management of Joining Technology Data

The ongoing changes in BIW design, driven by different factors influencing the automotive industry, also affect the joining technology. This means that the changing boundary conditions influence the entire vehicle development processes and consequently the data exchange of joining technology data. The three main factors that play a decisive role here are the increasing number of joining elements in vehicles, the introduction of new types of joining technology in automotive body design and the rapidly evolving project landscape due to increased number of vehicle variants and new entry car manufacturer and supplier.

Increasing number of joining technology elements

The increasing number of joining technology elements in vehicles is primarily due to the introduction of new materials and material combinations. For example, to ensure that a body made of aluminum has a similar body stiffness as a body made of steel, additional components, like stiffening plates, that have to be joined together, might be added. In addition, car bodies have become larger in recent years because of new vehicle segments, e.g. SUVs, and the increasing development of long versions e.g. for the Asian market. With increased automation in the production lines, joining technology elements can be produced faster and with lower costs.

In view of data management and data exchange processes, the increasing number of joining technology quantities and variants means that a higher amount of joining technology data, including metadata, has to be handled. Exemplary, in the 1980s, approx. 2.700 spot welds have been applied in an averaged car (c.f. Tab. 4). Nowadays, this number has at least doubled and the applied joining technology in vehicle bodies became more heterogeneous. Finally, the development of modern cars involves a significantly higher share of computational development (VPD), which requires significantly higher effort for data transfer.

Introduction of new types of joining technology in the automotive industry

One of the main reasons for the introduction of new types of joining technology elements is the variety of used materials in BIW design. Exemplary, the increased use of aluminum in vehicle BIW design required the development of new joining technologies since aluminum and steel sheet cannot be welded in conventional way.

This increasing number of different types of joining technology has an influence on the data exchange process, because the number and kind of parameters and metadata required to describe the elements has also increased. This applies in particular to the representation of joining technology elements in CAD environments. While a spot weld can be represented as a circle and thus clearly described with the coordinates of the center point and the spot weld diameter, the situation is much more complex for other elements. Exemplary, a screw requires further metadata – such as length, head diameter, shaft diameter, thread length, thread pitch, etc. – for a complete definition. Other environments (e.g. CAE, CAM) also require an enhanced set of parameters and metadata to fulfill their simulation tasks.

Evolving project landscape

Besides an increasing number of joining technology elements and the introduction of new types of joining technology, the diversity in the project landscape increases. For supplier industry in BIW development and production, especially new-entry OEMs play a crucial role in view of joining technology data exchange processes. Since new OEM often do not provide uniform standards for the creation and exchange of joining technology data, this must be taken into account in the elaboration of data exchange in collaborative development projects.

This requires a detailed analysis of the data exchange strategies of the OEM (c.f. section 4.4.3 and the development of corresponding conversion stages for data exchange processes. These converter stages primarily serve to ensure the integration capability of the differently created joining technology information in external and internal CAx environments. The exchange of joining technology data is becoming increasingly important in automotive bodywork development processes. Fig. 40 gives an overview of the phases that the joining technology data typically goes through, from the creation in CAD environments to the import in other CAx target environments and back to re-import the modified joining technology data into the original CAD environment.

Fig. 40 - Phases of management of joining technology data

Creation of joining technology data
Since the integration of joining technology data into the product development process of car bodies is initially started with the help of CAD tools, the consideration of the management of joining technology data begins with their creation within the CAD environment. First, the geometry data of the 3D-CAD model are created in the respective CAD environment. In general, this geometric data creation of the respective virtual prototypes (c.f. section 2.3.3) is completed with the milestone “IS-BIW”. Afterwards, the creation and incorporation of joining technology data into the 3D-CAD model starts. In a typical BIW development process, this process usually takes about two weeks and is completed with the so-called “Data Freeze”. At this point, all geometry and joining technology data required for the certain VPT status are available and the simulation loop can be started (c.f. Fig. 16).

As already mentioned, the integration of joining technology data into the product development process starts in CAD environments. Especially automotive suppliers and OEMs who integrate different sub-supplier and engineering companies into their processes are faced with the challenge of creating and managing joining technology data in common CAD tools. Standard CAD tools offer only limited possibilities to generate the required wide range of joining technology data. For this reason, an optimized data exchange process has been developed in the course of the present Ph.D. project, that is able to support the creation and management of joining technology data.

Independent of the CAD environment selected, the different types of joining technology are always created according to a similar scheme. The geometric data, which contain all information regarding sheets and other parts of the bodywork must be available under consideration of pre-defined quality criteria. Independent from the joining technology type applied, the corresponding geometry data (e.g. sheet surfaces, sheet edges) serve as important input data that define the boundary conditions for the creation of the joining elements. An exact positioning of the joining elements is then carried out in the CAD system via coordinate vectors or, for linear and surface elements, via a number of position vectors. Thus, the joining technology elements are primarily determined by the position and the parts to be joined. In the next step, the joining technology element is supplemented with all required metadata (e.g. diameter, length, width) to deliver the required information for the next development phase.

Store & manage of joining technology data
After the creation process has been finished, the issue of storing and managing joining technology data arises. While for geometry data the administration process runs almost in standardized procedures, PDMS (Product Data Management Systems) offer only limited possibilities for managing joining technology data. For this reason, the applied CAD environment is usually used as the master environment for handling of joining technology data. Because of this, an optimized data storage, tracking and exchange process must be provided

to support both the creation and the management of the joining technology effectively, see chapter 4.

Export of joining technology data

Since CAD environments usually serve as master environments for creation and administration of joining technology data, the data export procedures are linked with this master environment. It is important that joining technology data, which are available in form of different types of native CAD files, can be merged into a uniform data format. This uniform data format represents the basis for a standardized data exchange process. In addition to the already mentioned native CAD-based formats in which the joining technology data are available, it is also possible that neutral data formats come to use, e.g. in case that two or more companies share their work in the development process. In this case it is of central importance that related data are exported in the same formats. Consequently, a uniform export data format has to be structured in such a way that it can transfer all required information in one procedure and thus reduce data processing time in the target environment.

Exchange of joining technology data

The exchange process of joining technology data between different CAx environments is of central importance for the present research. In this context, a tailor-made process is created, which considers all boundary conditions (c.f. chapter 5). Since at least two different CAx environments (e.g. CAD and CAE environment) are involved in a data exchange process, the mentioned uniform exchange format must be designed in a way that the corresponding data conversion processes are also supported in the target environment (e.g. for the import of data).

Import of joining technology data (in target environment)

The phase of exchanging joining technology data ends with the data import phase. The exported and already exchanged data format, which contains all relevant information for the subsequently performed computation processes, is read into the target environment (import of joining technology data). Besides an effective transfer of data, it is important to keep post-processing effort in the target environment as small as possible.

Since export, exchange and import of metadata-based joining technology data takes place in parallel to the geometry data exchange process, an unambiguous correlation must be established between the two types of data. Normally, the geometry data set is transferred first. Then, the metadata-based data set is transferred and assigned to the corresponding components and geometry data. Metadata include the identification feature (e.g. element name or number), material parameter, manufacturing-related information.

After the joining technology elements have been positioned correctly in the target environment, including geometry data and metadata, the intended simulation tasks of the target environment can be started. This exemplary includes crash and durability simulations in CAE environment and the creation of a suitable joining sequence or accessibility checks in the CAM environment. The entire data transfer is performed automatically, without manual intervention and includes geometry and metadata transfer as well as the correct positioning of the joining elements in the corresponding simulation model.

Re-import of joining technology data (in master environment)

After the simulation tasks have been performed in the target environment, the results and findings are evaluated and fed back into the CAD environment. For this reason, the simulation results of the respective target environment are re-imported into the master environment to be incorporated into the 3D-CAD model by the responsible CAD engineer. Subsequently, the CAD model is updated with the corresponding modifications and the phases of creation and management of joining technology data starts again.

4. Investigations of Data Management

The following chapter deals with data management processes in automotive development. Therefore, Product Data Management (PDM) processes, possibilities to exchange data between several CAx environments and file formats, which are widely used in the automotive industry to exchange geometry and joining technology data, are introduced and discussed here. Since data management is a very complex topic, sub-chapter 4.1 gives an introduction to the topic of PDMS and the main functionalities of PDM with a focus on BIW development.

4.1. Product Data Management in Automotive Development

Today it is state-of-the-art to include various CAx environments in the development processes of vehicles. These different types of CAx environments, interact with other environments such as Product Data Management (PDM) or Product Lifecycle Management (PLM) systems. While PLM systems manage all information that is created and collected during the entire life cycle of products (e.g. development, production and sales & marketing-relevant information), PDM represents a sub-area of PLM that is focused on product data for development-related processes.

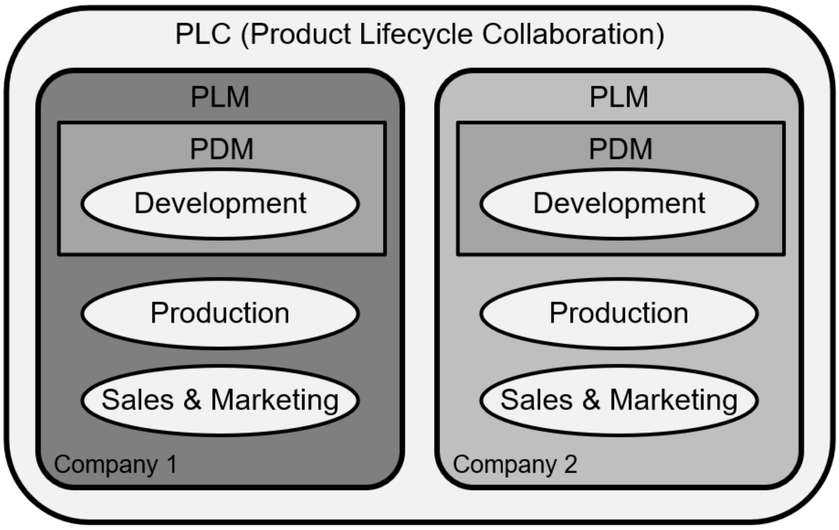


Fig. 41 - PDM/PLM collaboration in the product lifecycle, referring to [54]

PDM includes storing and managing of product data, e.g. CAD documents, simulation data, BoM (Bill of Material) and product data information [109], [110]. Besides, the close integration into the different procedures of car development also supports the product development process themselves [21], [95]. For this reason, PDM plays a decisive role in product development. PLM is intended to serve a broader view on the product and also covers production, recycling, sales and marketing processes (c.f. Fig. 41). This sub-chapter is intended to provide an introduction to the structure and functionalities of PDMS and the integration of PDMS into data exchange processes between various CAx environments.

Since product data are classified in several categories, the management of product data involves different types of file formats. The following list gives an overview of these categories:

- Geometry-based data – any kind of data comprising CAD models or styling data, including parts, assemblies, joining technology elements, etc.
- Metadata – include product-related information, e.g. diameter of spot welds, thickness of components, etc.

- Product configuration data – include information varieties of variants and different kinds of setups of components, parts and assemblies
- Development process-related data – include all information regarding the development process, e.g. workflow data
- Product defining data – include all kind of data which specify the product, e.g. car weight, fuel consumption, driving performance, etc.
- Product describing data – all information that can be found in list format, like BoM, joining technology data, etc.

Note: In addition to the examples above, product data can be further classified according to the age and maturity level of data or data quality. In addition, the data format and the use and validity of the data are another classification criterion [33], [55]. Anyway, because these further classifications are not relevant to the present work, they will not be treated in more detail.

Before starting with data exchange processes related to PDMS, an introduction is given about the tasks and basic structure of PDMS. PDMS are mainly used to connect several application systems or application environments (e.g. CAD, CAE, CAM environment…) and DB (Data Bases) via one common system to supply these environments with the actual valid product data (c.f. Fig. 42) [21], [133].

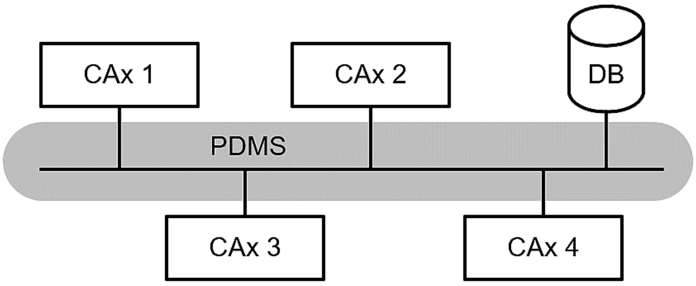


Fig. 42 - PDMS as central system for connecting several CAx environments, referring to [133]

As previously mentioned, PDM deals with the storage and management of product data and supports the product development process. The focus is on the provision and administration of product data (e.g. geometry data) including metadata, the administration of necessary product configurations as well as the geometry data supply of processes [104], [110]. The basic idea is that all electronically available data are processed with the help of PDMS, no matter of the data formats used and the type of source programs (e.g. CAx environments) in which the data have been created. An exemplary basic structure of PDMS (basic components used in PDMS) is shown in Fig. 43 [133].

The main component of PDMS represents a data storage system, i.e. a database, which is also called "vault" in many literatures (c.f. [33], [133]). In this system, all documents and files are safely tracked, stored, maintained and provided for further utilization. All changes made to the stored documents are documented via a DBMS (Database Management System). This prevents unnoticed intentional or unintentional manipulation of the data [133]. Furthermore, PDMS offer a GUI (Graphical User Interface), for user-friendly operability, as well as interfaces for the connection of several application environments, such as CAx environments and systems. In addition to a large number of basic functions (classification according to [42], [133]), which are listed below, most conventional PDMS also offer additional tools, called “customization tools” (c.f. Fig. 43). With the help of these “customization tools” the PDMS can be adapted to company-specific requirements (e.g. adaptation of the GUI, extension of interfaces for the integration of special tools) [33], [54], [133].

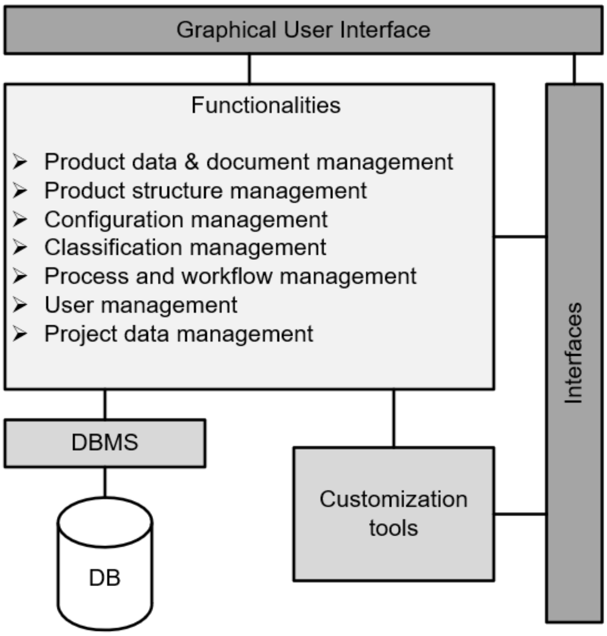


Fig. 43 - Basic structure of PDMS, referring to [133]

Product data & document management

The main functionalities of product data & document management include version control, i.e. storage, retrieval and common use of product data and documents, as well as data safe operations, which offer administration of access rights to information, versioning support and revision ability of documents [21], [95].

Product structure management (PSM)

In order to explain PSM, the term product structure must first be introduced. A product structure represents the hierarchical division and order of individual components (e.g. parts), typically using a tree-structure for this purpose. The content of the structure can vary depending on the purpose, e.g. breakdown according to production-relevant aspects. An example of a product structure in commercial PDMS is the BoM-structure including metadata. The term PSM was described in 1998 in CIMdata [21]. In summary, the definition contains the following points, according to [120]:

- Simplify the creation and management of product configurations
- Tracking of several versions and design variations
- Product definition data can be linked to structures
- Availability of different technical views of product data and structures

Configuration management:

One of the main objectives of PDM is to configure products or product data. Configuration management provides clearly defined, unambiguous product information according to a certain time (e.g. development milestone), in the development process. In practice, configuration management changes between different datasets, distinguishing the new dataset and tracked older versions [33], [104]. This distinction of datasets is also called revision. In Fig. 44, three datasets/revisions (named “past”, “present” and “future”) are shown. A new revision of product data is available as soon as changes occur in product data. A possible use case for data exchange processes is that only when a new revision occurs, the data will be exported/exchanged. If there is no new revision since the last export/exchange, data are not explicitly exported/exchanged, thus minimizing the size of the data to be exchanged.

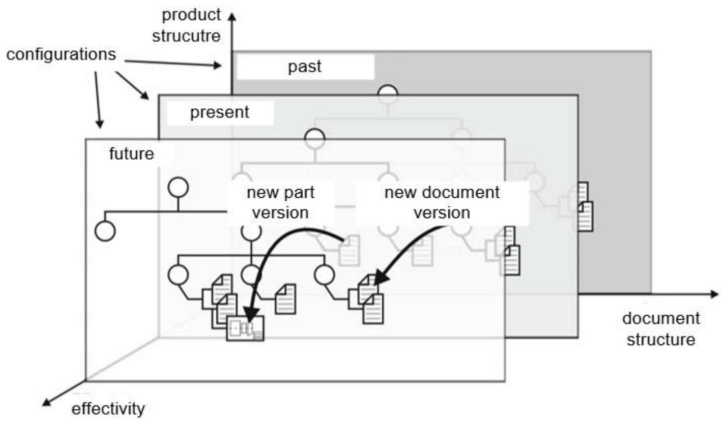


Fig. 44 - Configuration management in PDM [33]

Classification management

The classification of product data represents an important task of PDMS to manage the growing number of documents in automotive development projects (typically more than 100.000). Through the classification, the users (e.g. CAD engineers, data managers) can assign characteristics or objects to documents to support maintenance, release or data tracking operations [21], [42], [127], [133].

Process and workflow management

Process management in PDM means that defined processes and workflows are carried out and monitored by means of pre-defined mechanisms [21], [95]. This includes the control of workflow events, e.g. control of changes of product data and access authorization for certain persons [21]. Workflow management deals with product definition-related processes, e.g. design status approving including rules for approving and involvement of the corresponding engineers. It is important that correct information is available at a certain project sequence in time, e.g. so meet the requirements of a virtual prototype definition procedure (c.f. sub-chapter 2.3) [95].

User Management

The user management allows the administrators to divide users into certain user classes (also called user roles), e.g. for the definition of “read and write access” for responsibilities and project data. Further responsibilities of administrators include the definition of new users and user roles, password management as well as maintenance and service activities [21], [127], [133].

Project data management

Due to the large amount of product data available in PDMS and the deep integration of the data structures into the applied development processes, many PDMS provide functionalities of project management. These functionalities comprise scheduling elements, task planning and task controlling. Project management functionalities in PDMS offer the advantage of a simple traceability of change processes on the respective product data. In addition, this provides an overview of the progress in terms of planning, implementation and tracking of projects [42], [133].

Summarized, it can be stated that PDM, respectively PDMS support the management of product data and product development processes in a comprehensive way. Furthermore, PDMS control all activities related to product data, e.g. product information, status levels, approval processes, authorizations [95]. For these reasons, PDMS play a crucial role in automotive development processes, and thus also in data exchange processes during BIW and joining technology development.

4.2. Product Data Management in BIW Design

PDMS are implemented in the automotive industry for a series of product data management processes. This includes the development process of vehicle bodies (c.f. sub-chapter 3.3) and the associated joining technology. The following sub-chapter deals with the management of joining technology data in PDMS and the corresponding requirements for tailored data exchange processes between various CAx environments. Joining technology data are provided in different types and file formats (c.f. Fig. 45). A more detailed consideration of the applied file formats is given in section 4.4.3.

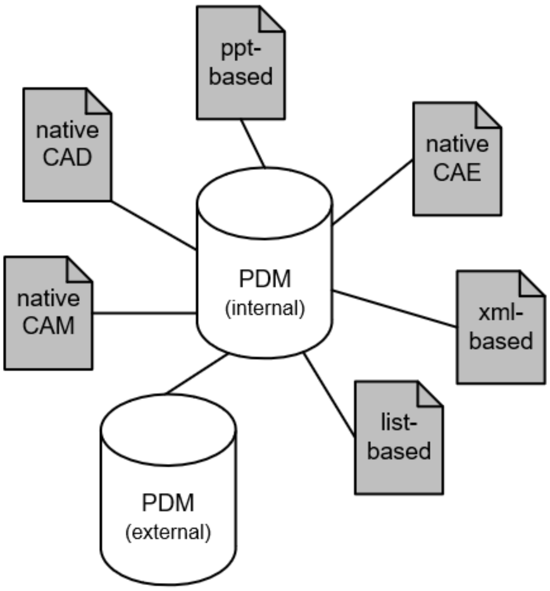


Fig. 45 - Typical data and file formats of joining technology in PDMS

As already mentioned in sub-chapter 4.1, PDMS are capable of managing a broad variety of product development-related data. This also applies to joining technology data, which are available in a variety of data formats, originating from different source systems.

In development processes, PDMS manage a large number of different data formats and make them available for the involved participants in the corresponding target environments. Basic functions are provided by commercial PDM software by handling standardized geometry data formats (e.g. native CAD CATIA data, neutral JT data). The data provision for other CAx environments, e.g. CAE or CAM, is accomplished by means of converters for neutral geometry exchange formats. Due to a lack of standards for creation and exchange of joining technology data, different data formats including different input sources and file formats have to be handled. This multitude of data formats can be managed in standard PDMS in general, but the conversion into a uniform data format can only be realized with large effort. Standard converters (such as JT converters for geometry data), which are integrated into PDMS, do not cover this bandwidth of different input variables, respectively input sources. However, since it is desirable, especially with regard to an optimized data exchange process, to supply all CAx environments involved with the same data format, a specific interface for joining technology data exchange must be created and implemented into the development processes.

4.3. Possibilities of Data Exchange Process

This chapter shows four possibilities how data can be exchanged between different CAx environments in general. The content and type of data is not relevant for the introduced methods, but the data are subdivided into native and neutral (distinction c.f. sub-chapter 4.4) data formats. Native data formats are created initially in the corresponding CAx programs (e.g. CAD, CAE, CAM). In the ideal case, these native data formats can be transferred, read-in and processed directly in the target environment. However, this is only possible with a data exchange process between two or more CAx systems, if both the source and the target environment(s) support the native data format. Since this scenario is rarely to be applied (usually it is only used in the same CAx environments), neutral data formats provide an alternative way to exchange data between different CAx environments. Here, the native data formats are transformed into standardized neutral data formats by specific data converter and then read-in and processed in the target environments [125].

Possibility 1 – Exchange of native created data

One possibility to exchange data between two different CAx environments includes the exchange of native data formats (c.f. Fig. 46). The simplicity of the exchange process is a great advantage here. This type of exchange is mainly used for projects with a small amount of engineering workload (e.g. development of one module in a vehicle). One disadvantage of exchanging data using this method includes that all the created information is exchanged, e.g. including the design history that is not necessary in simulation processes [125]. This is often undesirable, as it can lead to increased pre-processing effort in the target environment. Another disadvantage is that both environments involved (CAx 1 and CAx 2 environment) must be able to handle the native data. On the other hand, the exchange of data using native data formats is very effective, if the same environments are involved, e.g. a transfer from CATIA to CATIA [72], [73], [125].

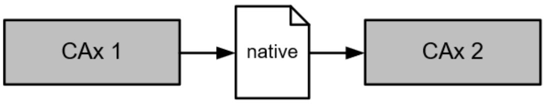


Fig. 46 - Data exchange using native data formats

Possibility 2 – Data exchange using neutral data formats

The second possibility to exchange data between several CAx environments involves neutral data formats (c.f. Fig. 47). Here, the natively created data must be converted or exported to a neutral data format. The data size to be exchanged can be reduced by reducing the content of information. This can lead to undesired side effects, e.g. loss of data that is required in the target environment, but can also be used to not transfer information, which is not needed in the target environment. By pre-definition of the data that is to be exchanged, preparation time in the target environment can be reduced [72], [73], [125].

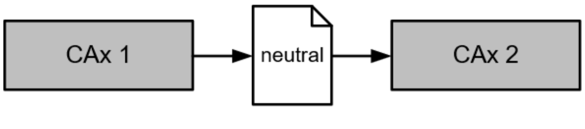


Fig. 47 - Data exchange using neutral data formats

Possibility 3 – Data exchange using native data controlled by PDM
In this variant (c.f. Fig. 48), the PDMS serves as a central unit, which not only stores data but also manages transfer processes. Since native exchange represents a homogeneous exchange process, it must be ensured that all CAx environments involved can operate with the corresponding native data. A main field of application of this possibility is the data exchange between two identical CAx environments within large industrial PDM landscape, e.g. data exchange between two CAD environments in two different companies, e.g. the transfer of CATIA data from an OEM environment to a CATIA environment at an engineering supplier company [72], [73], [125].

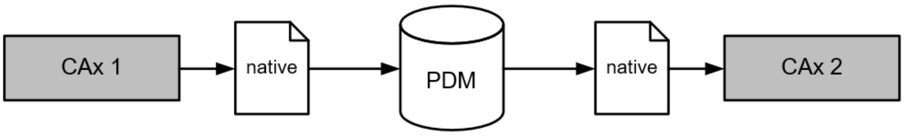


Fig. 48 - Data exchange using native data controlled by PDM

Possibility 4 – Heterogenous data exchange controlled by PDM
Heterogeneous data exchange processes (mix of native and neutral file formats, c.f. Fig. 49) within PDMS are frequently used in the automotive industry, e.g. for data exchange between different CAx environments (e.g. between CAD and CAE environments) [72], [73], [125]. The newly introduced optimized data exchange process developed in the present work is also based on this approach (c.f. chapter 5). In this way, native files are forwarded, stored and managed in a PDMS. The PDMS include one or more converters for export of data to convert native data into neutral data formats. This method of data exchange is very effective in projects with a high engineering workload (e.g. full vehicle development). Another advantage is that the PDMS also provide data exchange with external environments (e.g. OEM-specific PDM environments) [133].

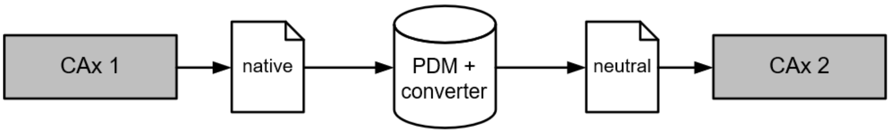


Fig. 49 - Heterogenous data exchange controlled by PDM

4.4. Frequently Used Data Exchange Formats

This sub-chapter provides an overview of frequently used data exchange formats in automotive BIW development. Therefore, a distinction is made between geometry and joining technology data. Geometry data contain all information, which is necessary to create and describe sheets and parts of the automotive body in CAD environments. Examples for geometry data-related information include information about geometrical shape and all dimensions (e.g. length, height, thickness) of the sheets as well as metadata, such as the material and COG of the sheets. Joining technology data contain all information, which is necessary for the creation of joining technology elements in CAD environments. In addition to the geometric representation, each joining technology element is assigned to a number of parameters. While the geometric representation shows the joining technology element in a more or less accurate visualization, the associated parameters contain required general information (e.g. coordinates, ID of adjacent sheets, type of joining technology, diameter, length of joining elements). In the present work, a separation into data formats for geometry data exchange and joining data exchange is considered. In the following, general challenges of data exchange, related to different source systems, are discussed.

4.4.1. Challenges of Information Exchange in Automotive Product Development

If data are exchanged between different environments (e.g. between two CAD environments or between a CAD and a CAE environment), this exchange process can take place in native-based or neutral-based data exchange formats.

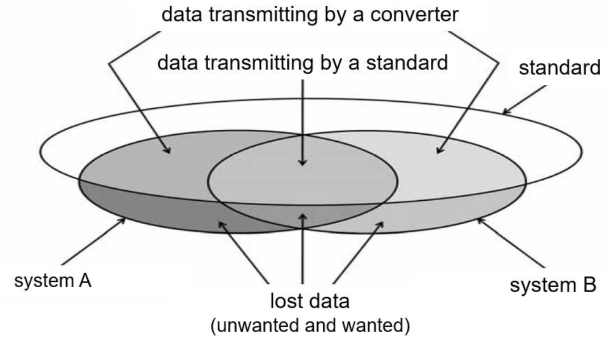


Fig. 50 - Possible data losses during data exchange between different systems [125]

If the exchange process takes place by use of native formats, all created data can be transferred. If the data exchange takes place using neutral data formats (neutral standards), the amount and type of information transported is determined by the specific neutral data format and the definition of accuracy and parameter sets (c.f. Fig. 50). Thus, a complete exchange of information via neutral standards based on appropriate data formats is only possible in the rarest cases, if at all [104], [125].

Due to limited computational resources, certain simplifications and reductions of data volume, data conversion process may lead to a reduction of information, respectively data losses. Depending on the application, the conversion processes desire a certain reduction of information content in the data to be generated to achieve reduced file sizes or to protect specific know-how [104], [125]. Since both native and neutral data transmission are important for the exchange of geometry and joining technology data, native and neutral data exchange formats come to use in automotive body development.

4.4.2. Geometry Data Exchange File Formats

The exchange formats for geometry data shown in Fig. 51 are examined in more detail in this section to provide a fundamental basis for the subsequently performed selection of a suitable exchange format (c.f. chapter 5). In order to describe the various file formats in more detail, they are sub-divided into native and neutral data formats.

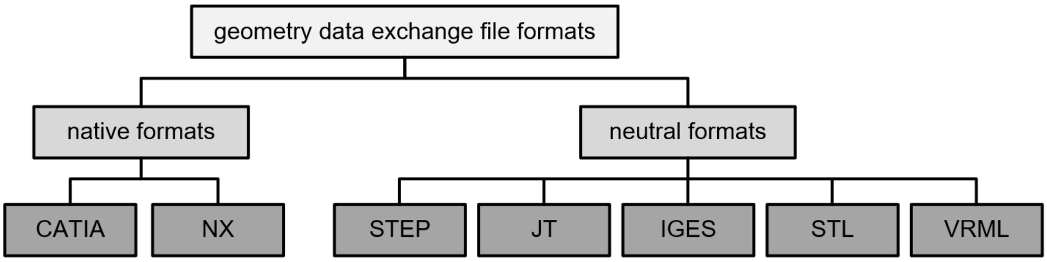


Fig. 51 - Analyzed geometry formats for the exchange process

However, before starting to describe the individual data formats, important terms that are prerequisite for this section are introduced. First, geometry representation in CAD systems is explained. Exact geometry information in CAD environments is provided by native geometry formats. However, this is not a matter of mathematically exact geometry definition, but of geometries data, which are very close to a possible mathematically exact definition by use of different approximation methods. Exemplary, modern CAD systems work with 64 bits architecture for the representation of geometries, which leads to the fact that with an object size of 1.000 meter it is still possible to achieve an accuracy of one thousandth of a millimeter [103]. State-of-the-art CAD systems use so-called exact geometry model structures, e.g. BREP (Boundary REPresentation) and CSG (Constructive Solid Geometry), and different approaches for description of 2D- and 3D-elements, which include rational curves (e.g. Bézier curves, B-Spline curves, NURBS (Non-Uniform Rational B-Splines)). In addition, simplified geometry is represented by tessellated 2D- and 3D-elements, e.g. by CGR-format (CATIA Graphical Representation) or STL-format (Surface Tessellation Language).

CSG

CSG is a modeling technique that uses Boolean operators for creation of geometries consisting of several elements [55], [125]. Fig. 52 shows an example of two bodies that are be combined to form one body using Boolean operators. Two cases occur – case 1: Body I is subtracted from body II and case 2: Body I is added to body II.

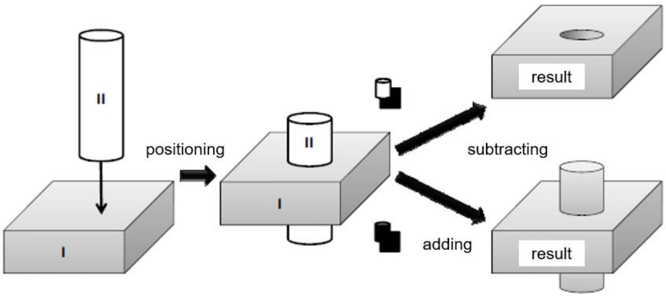


Fig. 52 - Merging two bodies using CSG [125]

BREP

In the application BREP method, each boundary element of a surface or volume model is described exactly and assembled to a complete model. This is useful for complex components, which consist of a number of single surface elements. Here, the models are divided into individual surfaces (F_i…surface, E_i…corners) as shown in Fig. 53 [55], [104]. BREPs are used in the automotive industry especially for simulation and calculation processes in CAE and CAM environments [90].

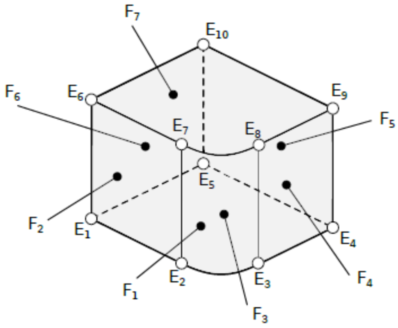


Fig. 53 - Division of a model in several surfaces [104]

Rational curves

Based on Bézier curves, CAD systems use different approaches of so-called free-form spline techniques. The aim is to define a control polygon as boundary condition to define a spline (c.f. Fig. 54). The deviation between polygon and spline is determined by the so-called weighting of the parameters (degree) and the approach used, e.g. Bézier curves, B-Spline curves, NURBS. Besides curves, also surface elements are described in CAD systems by the same approach [53], [55], [75], [97], [131].

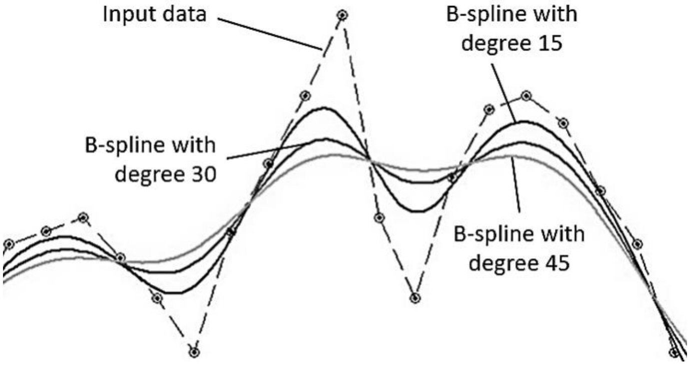


Fig. 54 - Example of a B-spline curve with various degrees compared with a control polygon [131]

Tessellated surfaces

The method of tessellation enables an approximation of the exact geometry in CAD systems. Simpler geometry (e.g. triangles) is used to divide complex curves and surfaces into a number of simplified elements. This allows an accelerated calculation time and can minimize the data size. So that the fineness of the tessellation can be determined, some data formats offer so-called LODs (Level Of Details). With these, a dynamic adaptation of the tessellation (determination of the number of triangles) is possible [55], [104], [124]. Fig. 55 shows the difference in the representation of a body, once with exact geometry and once with tessellated geometry [104].

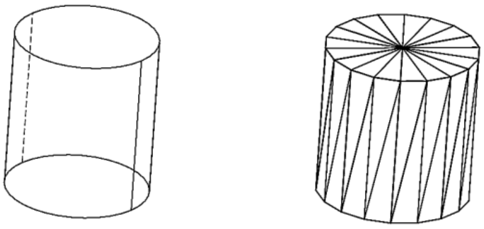


Fig. 55 - Comparison of exact (left) and tessellated (right) geometry in CAD [104]

4.4.2.1. Native file formats

In the present work, the use of native file formats in the automotive industry is focused on CATIA V5 and Siemens NX, because that two programs are the most widely used CAD tools in automotive body development. Native geometry data are created in the CAD environment by use of exact geometry description. In this formats, the entire design history (i.e. design sequence) of parts as well as the structure of assemblies is stored. In addition, other information, such as metadata, annotations, material, etc. can also be saved and transferred. Due to the high information content of native data formats, these are very powerful in data exchange processes, especially if performed within the same CAx environment. However, the file size increases with rising information content, which has to be considered when selecting a suitable geometry data exchange format.

4.4.2.2. Neutral file formats

Compared to native data exchange file formats, neutral ones offer the advantage of cross-environment data exchange. Often – but not in all cases – neutral formats result in a reduction of file size in comparison to native formats, which in turn leads to less storage space required and faster transfer processes. The level of reduction of information in neutral data formats depends on the type and the applied settings and involves geometrical information (e.g. geometrical simplification), design history-related information and metadata. In data exchange processes, the degree of data reduction is defined according to the intended use of data, e.g. in case of joining technology. Neutral data exchange formats are well suited for the information exchange between different CAx environments. This is mainly due to the fact that the required information content of the data varies in the different CAx environments. Compared to the native exchange formats, neutral file formats are compatible with multiple environments. This leads to a broader field of application and fewer necessary conversion stages in pre- and post-processing (c.f. Fig. 56 and Fig. 57).

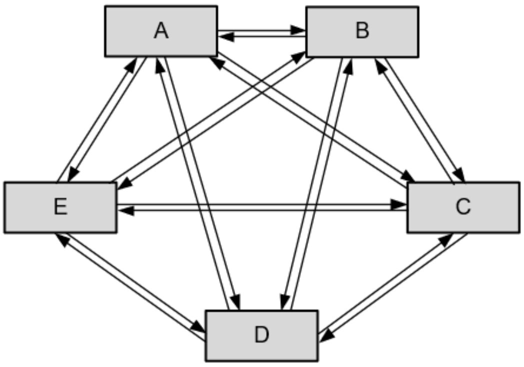


Fig. 56 - Data exchange behavior within different CAx environments without a unique exchange format [125]

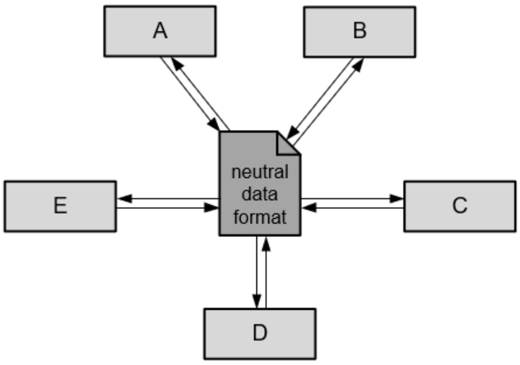


Fig. 57 - Data exchange behavior within different CAx environments, using a unique (neutral) exchange format [125]

In Fig. 56, the number of necessary converters (displayed by arrows) is much higher than in the procedure shown in Fig. 57. The reason is, that the exemplary shown neutral file format represents a universal format used for the data exchange between the five different CAx environments (A to E). Fig. 56 shows the same heterogeneous system environments, but instead of the use of one neutral exchange format, several native formats are used. This means that each of the five environments must be able to communicate with the corresponding target environment. Since most environments are not able to process each native file format, the number of converters those are necessary to enable a full exchange process is increasing. Each conversion causes additional computation effort and unwanted data losses may occur. Thus, it can be useful to include neutral data formats for data exchange between different CAx environments.

Certain data formats have become established for data exchange processes in the automotive industry. Data formats that can map geometry data, structural information and metadata are relevant for body development. For this reason, the following standardized neutral data formats are examined in more detail:

- JT (Jupiter Tessellation)
- STEP (Standard for the Exchange of Product Model Data)
- IGES (Initial Graphics Exchange Specification)
- STL (Surface Tessellation Language)
- VRML (Virtual Reality Modeling Language)

JT (Jupiter Tessellation)

The file format JT is a neutral file format that is widely used in the automotive industry for exchanging geometry data. It offers a broad range of different settings to change the conversion process from a native input file to the neutral JT file. JT offers the possibility either to transfer exact forms of geometry (BREP) or tessellated geometry in different LODs, or both. Due to these and other setting options, e.g. PMI (Product Manufacturing Information), the file size can be reduced significantly in comparison with a native file format, which has a direct impact on the viewing performance, transfer behavior and simulation speed.

The smaller file size that can be achieved with JT makes this format useful in a large number of automotive development applications. Furthermore, JT is supported by many commercial CAD programs [104]. The neutral file format JT plays an important role for the further considerations in the thesis, so detailed information regarding the structure of the format can be found in the annex A.4.

STEP (Standard for the Exchange of Product Data)

The file format STEP [5] can be used to exchange geometry data between different CAD environments, as well as between several CAx environments. The aim of STEP is to enable a clear, computer interpretable representation of all product data. STEP is standardized in the ISO 10303 [60].

The ISO 10303 standard describes the methods with which the neutral data are modeled [62]. In this way, STEP must not be regarded as a finished data format in which the exact data definitions for all types of products are stored in an application-oriented manner. There are several STEP standards those differ from each other by APs (Application Protocols). These APs refer to the different application areas. To go into each of these protocols would be beyond the scope of this work, but some are listed here:

- AP203 – Configuration controlled design
- AP214 – Core data for automotive mechanical design processes
- AP218 – Ship structure
- AP233 – Systems engineering data representation

The most import AP in the automotive industry, especially for cross-environment data exchange is STEP AP214. STEP also provides both geometrically exact geometry required for simulation and calculation tasks as well as approximations of the exact geometry. Other information such as design history tree-structure, PMIs and attributes can also be transferred via the STEP AP214 standard, but this expands the file structure and thus the file size is increasing too [104], [125].

IGES (Initial Graphics Specification)

The IGES data format is primarily used for the exchange of exact geometry information. In the early phases of this standard, only wireframe and surface information could be exchanged. Following further development, NURBS surfaces can be transferred and solid models displayed, making the format suitable for comprehensive exchange of CAD data. NURBS are, according to the definition of [97], mathematically defined curves or surfaces that are used to model forms in the field of computer graphics. However, since no tessellated geometries can be saved in IGES, the format is not suitable for visualization topics in particular. In automotive engineering, IGES is mainly used in car body styling and design development in the course of surfaces data exchange [104], [125].

STL (Surface Tessellation Language)

The STL file format originated from rapid prototyping and was developed at the end of the 1980s. STL can only store tessellated information in the form of triangular surfaces (c.f. Fig. 58).

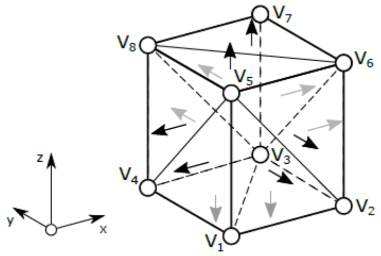


Fig. 58 - STL procedure – cubic element split into triangles [104]

The STL approach splits the surfaces into a certain number of triangles. Exemplary, two triangles are created in the case of a cuboid surface. For each triangle point the coordinates (coordinate vector x, y and z) and the corresponding normal direction vector are displayed. STL is used above all for data input of production machines or rapid prototyping, e.g. 3D-printing [104], [125].

VRML (Virtual Reality Modelling Language)

VRML is a node-based data format for displaying 3D-scenes. A VRML file denotes a 3D-scene that can be composed of geometry, environment, lighting and textures and also allows the use of various LODs. With regard to geometry data transfer, VRML is able to represent (simplified) polygonal elements as well as exact geometry.

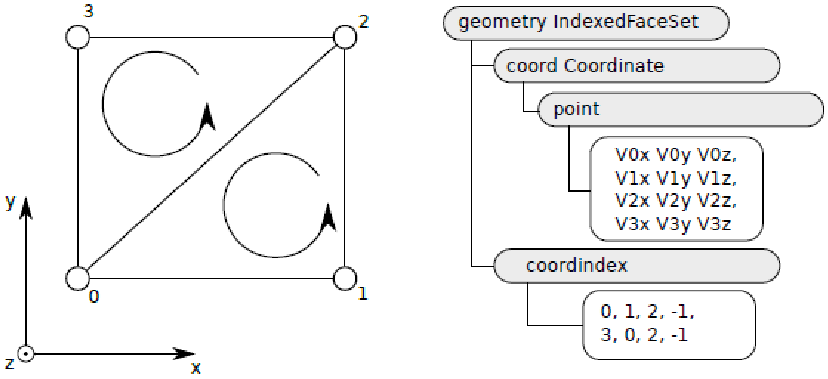


Fig. 59 - Description of a rectangle in VRML [104]

A surface can be represented by a so-called "geometry IndexedFaceSet". This set contains information about the definition of the coordinates (points) as well as the order of the points (coordindex) [104], [125].

4.4.3. Joining Technology Data Exchange File Formats

Similar to geometry data exchange file formats, there is a variety of different joining technology data exchange file formats available in the automotive sector. The different types of joining technologies and the corresponding data to be handled by use of data exchange formats are introduced in section 3.4.3. Because there exists no standardized format, the automotive manufacturer and supplier have introduced a number of tailored solutions. Fig. 60 gives an overview of the general possibilities to exchange the information of joining technologies.

Similar as with the geometry data, a distinction between native and neutral data formats is made.

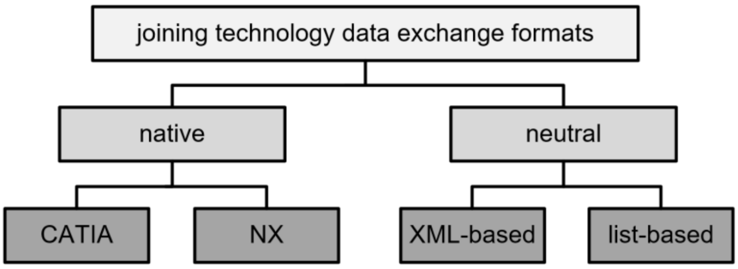


Fig. 60 - Analyzed joining technology data formats for exchange processes

4.4.3.1. Native file formats

Native joining technology data are created in the CAD environment (e.g. CATIA V5 or Siemens NX) and contain all information, parameters and metadata required for the 3D-CAD model and other CAx environments. Particularly, when exchanging data between the same CAx environments (e.g. CAD to CAD), it can make sense to transfer these data in native formats. With native data transfer, geometry and metadata are transferred directly without data conversion.

However, if data are to be used in CAx systems that are not of the same type (e.g. data exchange between different CAD and CAE systems), it may happen that target environments do not support the native data of the source environment. In this case, data conversion of native formats and/or data exchange with neutral data is applied.

4.4.3.2. Neutral file formats

While the geometric representation of sheet metal parts is in the main focus when exchanging geometric data, this is not necessary for joining technology data. For this reason, both list-based and XML-based neutral data formats have been established for joining technology data. The following section introduces the xMCF standard (XML-based) and list-based file formats (e.g. MS Excel-based).

xMCF (Extended Master Connection File):

The xMCF file format, referring to [29], is a standard for describing joining technologies in the automotive industry and bases on the neutral file format XML [91]. It was developed more than ten years ago by the Research Association of German Automotive Industry (FAT/VDA) in a cooperation with several industrial companies. There were two reasons for developing this standard. The first reason was the introduction of a uniform data format for the exchange of joining technology between different CAx environments. Due to the unification, there is no need of additional conversions to transfer data between different CAx systems. The second reason for this format includes cost optimization due to reduction of the number of data conversion processes [29]. The main benefit of this file format is an easy readability and adaptability for engineers. It delivers a variety of attributes and properties to describe all necessary types of joining technologies that are used in the automotive industry. With this file format the data exchange in the field of joining technology can take place between the disciplines CAD, CAE and CAM. One important issue, especially for CAM, is that the xMCF file format does not provide information about product structure or assembly sequences [29].

The xMCF standard divides the types of joining technology elements in three main groups, the group of 0D-, 1D- and 2D-joinings. 0D-joinings are described by at least a coordinate vector (x, y and z) and the diameter of the object, e.g. a spot weld. In addition, additional attributes such as the normal direction (e.g. necessary for rivets and screws) or the type of adhesive are used to define the elements. 1D-joinings are described by a curve (discretized by points) and additional parameters, which support the definition of the curve shapes (e.g. height, width). The type of adhesive or welding as well as some other parameters, like the manufacturer of the welding device, can also be communicated in this standard. Information of 2D-joinings contains the adhesive faces described by geometrical information, e.g. tessellations and faces. Again, additional attributes, like the height of the adhesive surface or the type of adhesive, can be specified. Furthermore, the parts, which should be connected, are listed in the xMCF file for each joining element. A full list of the different attributes can be found in annex A.2 [29], [72], [73]. Tab. 6 gives an overview of the types of joining technologies, which are included in the xMCF standard.

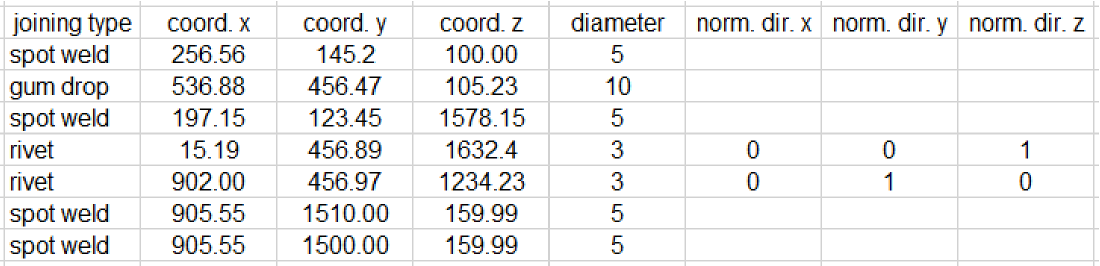
Group of joining	*Type of joining*
0D-joinings	Spot welds, rivets, bolts, screws, gum drops, clinches, heat stakes, thermal stakes, clips and nails
1D-joinings	Seam welds, adhesive lines and hemming flanges
2D-joinings	Adhesive faces

Tab. 6 - Overview of types of joining technologies in xMCF standard [29]

To make this file format easier to understand, a few examples with regards to the xMCF data exchange format are given in annex A.3. Besides, the structure of xMCF is stated in A.1 and the different parameters that can be used for each joining element are shown in annex A.2.

List-based file format:

Joining technology data can also be transmitted by using list-based file formats (e.g. MS Excel lists). In this case, the necessary information, including metadata, is available in list form. The information of each joining technology element is displayed in column and row form. This provides flexibility for the configuration of the data exchange lists, which has the advantage of an easy creation of company-specific solutions, but hinders the introduction of standardized formats (cf. Fig. 61).



joining type	coord. x	coord. y	coord. z	diameter	norm. dir. x	norm. dir. y	norm. dir. z
spot weld	256.56	145.2	100.00	5			
gum drop	536.88	456.47	105.23	10			
spot weld	197.15	123.45	1578.15	5			
rivet	15.19	456.89	1632.4	3	0	0	1
rivet	902.00	456.97	1234.23	3	0	1	0
spot weld	905.55	1510.00	159.99	5			
spot weld	905.55	1500.00	159.99	5			

Fig. 61 - Extract of an exemplary joining technology data list

In case of joining technology data transfer via list format, the lists can either be filled out manually by the CAD engineers or the lists are generated automatically during export processes (e.g. by converter) from the CAD environment. Research has shown that these list formats must be included in optimized data exchange processes because of their simplicity, and because they are easy to read and edit. Furthermore, the exchange of joining technology data by means of list-based formats provides high flexibility and thus a wide range of applicability in automotive development processes.

It makes sense to introduce a combined approach for joining data exchange, which is able to transfer both geometry data and metadata. Geometry data can be operated in neutral formats and metadata in list-based formats. When using list-based data formats, the native CAD data must be converted either manually or automatically correspondingly. This conversion process must also have a certain variability, since the structure of each list (e.g. rows and columns arrangement) may be different. The exact file format plays no crucial role here; any file format that is processable in Excel (.xlsx, .csv, etc.), as well as completely different list formats that can be opened with alternative programs, e.g. text editors, can be used for the transfer of joining technology data.

5. Boundary Conditions for the Development of a Tailored Data Exchange Process

The previous chapters introduce opportunities to exchange data between different CAx environments. In this chapter, the existing technologies are combined under consideration of specific boundary conditions. Standard methods are enhanced with customized solutions and a comprehensive process for effective data exchange of joining technology is developed.

In this context, the involved CAx environments play a decisive role for the definition of data exchange file formats and the data exchange strategy. As a result, different opportunities for exchanging data between varying CAx environments are integrated to create a unified data exchange process that can be used in a broad area of automotive development projects.

In the first step, the boundary conditions required for the data exchange process of joining technology data are recorded. This is done on the basis of an analysis of several industrial projects and taking into account the requirements of the individual CAx environments. In addition, a selection is conducted to determine, which data formats are best suited for the exchange of geometry data and for the exchange of joining technology data, e.g. joining metadata. Once the data formats as well as requirements for the data exchange process are defined, the gained knowledge is incorporated (sub-chapter 5.3) to optimize the data exchange process, to provide an instrument for engineers in their daily work.

To ensure that the optimized data exchange process can be applied in industrial projects, it must be supported by suitable software tools and systems. The determination and description of the tools especially developed for this purpose are included in sub-chapter 5.5. These specific tools are indispensable both for the engineers and for the correct functioning of the optimized data exchange process.

5.1. Requirements on a Tailored Data Exchange Process

In order to optimize the data exchange process for the needs in the automotive industry, specific requirements are derived. Based on these requirements, appropriate data file formats are selected (c.f. sub-chapter 5.2) and the data exchange process is then be optimized (c.f. sub-chapter 5.3). Finally, specific tools are developed to support the tailor-made data exchange process.

The following requirements are derived from chapters 2 to 4 of this thesis, with the target to close the existing gap in data exchange of joining technology.

- Suitable data exchange file formats (c.f. sub-chapter 5.2):
  Due to a lack of standards for exchange of joining technology data, diverse data exchange formats are used. Therefore, it must be ensured that all these data formats can be integrated into the tailor-made data exchange process. In the present consideration, this applies to the exchange of joining technology metadata, but also the exchange of joining technology-related geometry data.

- Optimized data exchange process (c.f. sub-chapter 5.3):
  Different boundary conditions in industrial projects require flexible data exchange processes that are able to involve the specific exchange strategies of OEM and supplier. In addition, an optimized exchange process must enable uniform data exchange process for all types of projects.

- Tools to support the optimized data exchange process (c.f. sub-chapter 5.5):
  Tailor-made tools are required to support the specific tasks of the optimized data exchange process. These tasks are versatile, such as integrating data, converting data, or integrating the different data exchange strategies in the process. For the individual conversion and integration steps to be processed correctly, the tools should support the creation, management and export of data as well as the necessary data conversions throughout the entire data exchange process.

5.2. Selection of Suitable Data Formats for the Exchange Process

Suitable data exchange formats that support tailor-made data exchange of joining technology and the corresponding geometry data have to be defined. For this reason, a selection of the most suitable data exchange format is made both for geometry data (c.f. section 5.2.1) and for joining technology data (c.f. section 5.2.2).

5.2.1. Selection of a Suitable Geometry Data Exchange Format

The processes in the target CAx environments (e.g. CAE, CAM) do not need all information, which is created in the CAD environment. One requirement for the geometry data exchange is that the exchanged data must be available in geometric exact form (c.f. section 4.4.2) in the target environment. This means that native data formats, as well as all data formats that transmit the exact definition of geometries (e.g. BREPs, NURBS), can be used for the optimized data exchange process. All other data formats that use approximated geometric representations, such as tessellated surfaces, are not considered further in the selection procedure. For this reason, native data formats are compared with the two neutral data formats JT and STEP. The IGES data format could also be used, but since it leads to a large file size because of the text-based file structure, this format is not included in the consideration procedure [65]. The appropriate geometry data exchange format is selected based on the decision criteria shown in Tab. 7.

Decision criterion	*Native formats*	*JT format*	*STEP format*
Geometry in exact form available	yes	yes	yes
Created CAE/CAM data model size	very high	low	low
Includes not required information (e.g. design history)	yes	no	no
Data size	100%	<50%	<50%
Additional conversion of data necessary	no	yes	yes

Tab. 7 - Evaluation of selected geometry data exchange formats

Native file formats have the advantage of direct transferability without additional effort if they can be integrated into the target environment. However, since native CAD data provide a lot of information (c.f. section 4.4.2.1), which is not required in the target environment, the file sizes become large (cf. Fig. 62). Due to the larger file sizes, the models in CAE and CAM environments also become more complex, which is undesirable as it would slow down the entire system and have a negative impact on the computation time of the exchange process.

The second disadvantage of transmitting not required information is that the CAE and CAM engineers need more time for pre-processing, respectively the preparation of the CAE/CAM simulation model. This can be avoided by specific measures (e.g. omitting non-required information) when converting to a neutral data format. Furthermore, most CAx systems offer interfaces to import a variety of neutral data formats.

While native data transfer is usually only possible between specific source systems, neutral data formats have the advantage that they can be processed by several CAx source and target systems. Furthermore, with the help of suitable converters, the data content can be reduced so that only the actually required data are transferred. This leads to a reduction of data preparation effort in the target environment and thus to faster processing times. For this reason, neutral file formats are preferred for the exchange of geometry CAD data between different CAx environments [125].

However, native data formats are very desirable in terms of data exchange between the same CAD environments (e.g. OEM CAD environment and the supplier CAD environment), especially in cases that existing models of components (e.g. COP) are transferred.

For these reasons, it was decided to use neutral file formats for company-internal data exchange between the CAD source and the CAx target environments. In addition, the optimized data exchange process must also be able to integrate native geometry data from external sources (e.g. OEM environments). This means that data from external sources are first integrated into the data exchange process as native data. Based on the externally delivered native data, the corresponding 3D-CAD models can then be completed in CAD environments. After completion of these models, the conversion into a neutral data format takes place, so that the data exchange between CAD and target environment, which is processed in the internal environment, can take place.

For the exchange of geometry data between the internal CAD and target CAx environments, the neutral file format JT has been selected. The reasons for this selection (and thus against STEP) are that the file format JT is widely used in the automotive industry to exchange geometry data in the field of body design. Furthermore, JT is supported by different commercial CAD programs used in the automotive industry [104]. The wide range of settings (c.f. section 4.4.2.2) for the conversion process, which is offered, makes it an effective and more flexible format regarding different use-cases. The structure of JT supports exact geometry, so-called BREP, as well as tessellated (triangulated) geometry (LOD).

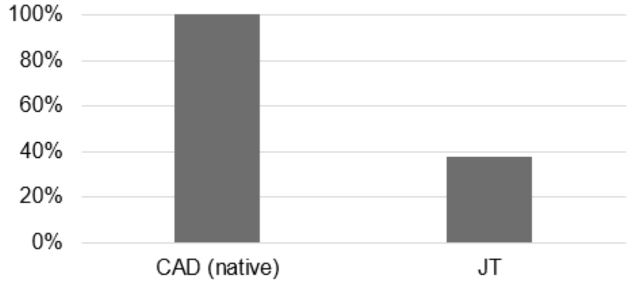


Fig. 62 - Data size comparison – CAD native vs. JT [20], [64], [125]

Fig. 62 shows a comparison of the quantitative average data size of several parts of an automotive body, displayed by means of two columns. The first column shows the average data size of different native created sheets (initial size 100%). The second column shows the data size of the same CAD sheets, but the sheets have already been converted to the neutral JT file format (including BREP and three LODs). The averaged data size of the converted sheets is only 38.5%.

A further selection criterion is that the file format JT is also used in other areas of the product life-cycle of car bodies, such as for visualization operations, VR (Virtual Reality) and AR (Augmented Reality). The uniform use of JT in different areas of application in industrial development processes combines the advantages of a reduced number of conversion steps and the existence of the necessary software (e.g. converters).

5.2.2. Selection of a Suitable Joining Technology Data Exchange Format

After the selection of a suitable geometry data exchange file format for the optimized exchange of geometry models between different CAx environments, a suitable data format for data exchange of joining technology metadata is chosen. The data exchange formats described in section 4.4.3 (XML-based formats (e.g. xMCF), list-based formats (e.g. Excel file) and native CAD data formats (CATIA V5 and NX)) are taken into account for this consideration.

As a basis for selecting an appropriate exchange format for joining technology data, Tab. 8 lists different boundary conditions and requirements from the considered CAx environments. However, for joining technology metadata to be exchanged, the optimized exchange process must be able to process all native and all neutral data formats that are created by the different sources.

Decision criterion	*Native formats*	*List-based formats*	*xMCF format*
Adaptability of joining technology data	CAD only	little effort in list file, additional effort in CAD	little effort in xMCF file, additional effort in CAD
Created data model size in target environment	high	low	low
Additional conversion necessary	no	yes	yes
Necessary metadata transferable	yes	yes	yes
Data size	100%	<10%	<10%
Including undesired information for target environment	yes	no	no

Tab. 8 - Evaluation of selected joining technology data exchange formats

As with geometry data exchange, native data formats deliver information, which has been generated during the creation process in the CAD environment. This leads to the fact that the data size of the native joining technology data is large. As can be seen in Tab. 8, this is at least ten times the amount of data compared to neutral list-based and XML-based (xMCF) formats. The values for the file size are determined on the basis of studies carried out in the present Ph.D. project. For this purpose, several automotive development projects were analyzed and a conversion of the native data into the two neutral data formats (list-based and XML-based) was carried out. As a result of the study, neutral exchange formats are selected for the joining technology metadata exchange between company-internal CAx environments. From this point on, only the two neutral joining technology exchange formats, list-based data format and the XML-based xMCF data format, are considered. In general, these two opportunities are very similar, as it is shown in Tab. 8.

Reading list formats into pre-processor systems can lead to problems (different structuring of the lists) or does not work at all. Another big advantage of using xMCF files is that the structure of joining technology data is defined by a standard (cf. [29]) and it shows a good adaptability, and readability. In this way, the XML-based xMCF format has been selected for exchanging joining technology metadata between company-internal CAx environments.

In summary, it can be stated that the requirements of involved CAx environments can be met with the selected neutral file formats, JT and xMCF. The most decisive factor for the selection of these two is the small amount of data that has to be transferred without losing important information. However, this also leads to the fact that conversions are necessary and, therefore, special tools must be created. These tools, the optimized data exchange process, as well as the implementation of these tools in the data exchange process are described in more detail in the following sections.

5.3. Process View of Data Exchange

This sub-chapter clarifies, which data must be available in which form and at what development step so that the data exchange process can be performed successfully. For this purpose, a list of different project configurations (called project types in the following) is introduced, which refer to the data exchange between different CAx environments. This subdivision into different project types also serves as the basis for the application-based discussion of the approach in chapter 6.

In general, it can be mentioned that requirements and boundary conditions of each project differ from the others. Focusing on joining technology, the projects differ in the creation and administration of CAD-based data and in the different data exchange possibilities (e.g. exchange processes, software included, exchange strategies of the companies & departments involved) between several CAx environments. However, there may be other differences as well (e.g. appropriate file exchange formats, data structure). In the following, this variety of project requirements and evolving boundary conditions is divided into three project types.

Note: The terms “external” and “internal”, which are frequently used in this thesis, describe the constellation of CAx environments involved in the data exchange process. If it is an internal data exchange process, it means that only CAx environments of one company are involved. Using the term “external” with regard to data exchange processes, this means that at least two CAx environments in two or more different companies are involved in the process. An example of external data exchange is that the data created in the CAD environment of an OEM (from the viewpoint of a supplier it is equivalent to the customer) is transferred to the internal target CAx environment of an automotive supplier company.

- Type I projects:
  The main engineering workload takes place in external CAD environments, like customer-specific CAD environments. In this type of project, the customer does not allow full access to its specific environment, thus access is provided through the use of

remote machines. Remote machines can provide remote access to any other computer regardless of location. This remote access (e.g. from another company) can be used to access application programs of computers and thus advances the creation of the 3D-CAD model. In addition, all processes, tools and methods to create and administrate CAD-based data are provided by the customer. This means that the entire process of creating CAD-based data, both geometry data and joining technology data, takes place in the customer's CAD environment. For data exchange, this means that the 3D-CAD model is exchanged between external and internal environments for each simulation loop. While geometry data are usually exchanged using native data formats, there are a number of different possibilities (due to missing unique standards in the field of joining technology data exchange) for exchanging joining technology data. For this reason, the internal environment must be able to handle and integrate these data, more precisely, the data structure and file formats. With regard to joining technology, this means that an optimized data exchange process must be supported by suitable tools, which can process the externally created joining technology data in different data structures and formats.

- Type II projects:
  The main effort of engineering is performed in an internal environment, e.g. for design and simulation of the BIW, but specific subsets of parts are provided by an external environment (COP). If this is the case, the existing CAD-based data must be imported from the external CAD environment into the internal one. Based on these data, the 3D-CAD model is then completed. This case often occurs in development projects that base on modular systems. Exemplary, the under body of an already existing car is used as a basis for the design of a new derivative, it is used as COM (Carry Over Module). The completion of all other components in the 3D-CAD model can then take place in the internal environment at an engineering supplier. In this way, the workload for creating the 3D-CAD model of the new vehicle derivate is divided into two main processes. External data are imported into the internal CAD environment; the 3D-CAD model is then completed in the internal CAD environment on the basis of the imported data. All further simulations tasks, which are carried out in the corresponding target CAx environments are performed internally. For this type of project to be implemented, a specific data exchange strategy must be set-up between the two parties, which defines the responsibilities for each component of the 3D-CAD model. In regard to joining technology, it means that tools and processes must be made available to create and manage these data in the internal CAD environment based on the delivered information from external sources. Furthermore, support of the data exchange processes between different internal CAx environments, e.g. for simulation processes, has to be provided.

- Type III projects:
  The entire creation of the 3D-CAD models as well as simulation processes take place in internal environments. Since the entire workload is performed internally, the degrees of freedom with regard to the creation and exchange of data allow a specific tailoring for according to the company-internal processes throughout the entire project. A typical field of application for this type of projects are co-operative projects with OEM start-up companies, which do not have their own systems, tools and methods for the development of BIW. In this way, the entire development process is performed in the internal environment of the involved engineering supplier. For the data exchange process of joining technology data this means that from the creation in the CAD

environment over the data exchange up to the evaluation of simulation results in different CAx environments (e.g. CAE, CAM), all tasks take place in the internal environment.

Since the three project types differ primarily in the creation of the 3D-CAD model, a process view of how the data exchange is given in Fig. 63.

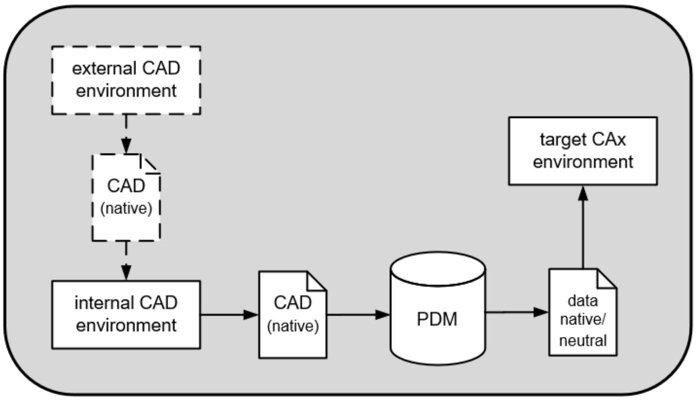


Fig. 63 - Process view of a CAD-based data exchange process between CAx environments

In the automotive industry, a pre-defined milestone (c.f. section 2.3.3) is used to start the data exchange between different CAx environments. First, the data are completed in the internal CAD environment on the basis of the three project types. The process of merging the existing external and internal CAD data is described in more detail in section 5.4.3. For this purpose, the scope of services agreed for the milestone is first created for CAD-based geometry data. Based on the geometry data, the joining technology metadata are then defined in the 3D-CAD model. The creation of CAD-based joining technology data is supported by suitable tools presented in sub-chapter 5.5. These tools are embedded into the internal CAD environment and are summarized in sub-chapter 5.4 under the term “Joining World”. Once the complete 3D-CAD model has been created, a data freeze is performed. This means that data for the specific milestone can no longer be changed and serve as the basis for the data exchange of CAD-based data. Depending on an appropriate data exchange format (c.f. section 5.4.2), the required information is then exchanged with the target CAx environment(s).

5.4. Optimized Data Exchange Process

The following section introduces an optimized procedure of the data exchange process, which is tailor-made to be applied in joining technology development processes in the automotive industry. The corresponding joining technology data can originate both from internal and from external sources. In this way the new approach of an optimized data exchange process considered both data sources (c.f. section 5.4.2). Section 5.4.1 gives an overview of the involved environments and section 5.4.3 explains the integration of externally generated data into the exchange processes.

5.4.1. Environments Involved in the Process

An overview of the individual disciplines involved in the data exchange process and their tasks considers both internal and external CAx environments:

- Source environment/CAD environment (internal)
- Data management environment (internal)
- Target environments (CAE and CAM, both internal)
- External environment (e.g. CAD environment of an OEM)

Source/CAD environment:
Computer-aided geometry modeling is a central component in virtual product development and thus delivers important data for the data exchange process. In the source environment, a 3D-CAD model of the vehicle body is created, which provides all information regarding the sheets metal parts, the assembly structure and the joining technology. In the considered development process, all information for the target environments are derived from the data created in CAD. Furthermore, it serves as the basis for installation space analyses and supports investigations regarding the producibility [52]. Therefore, the CAD environment is supported by tools, that make it possible to create, administrate and convert data. In this work, the CAD data model can be divided into two different types of data, parts/sheets of the vehicle (geometry data) and joining technology data.

In addition to ordinary data, such as dimensions (geometry data) or type of joining technology (joining technology data), metadata such as material, coordinates of the parts (geometry) or diameter, coordinates of the joining (joining technology data) are also managed in the CAD environment. In addition to the CAD tools used (e.g. CATIA, NX), a specific “Joining World” environment is included in the CAD environment for the creation, administration and export of joining technology data. “Joining World” environment supports the data exchange process with useful features, tools and methods. A more detailed description of this environment is given in sub-chapter 5.5.

Data management environment:
In the data exchange process between various CAx environments, the main focus of the data management environment is on the management and distribution of geometry and joining technology data. This data distribution as well as the exchange with several CAx environments is mainly done by the use of PDMS (c.f. sub-chapter 4.1). In addition to all tasks occurring internally in the PDMS, the administration of data also includes the import and export of data, for example COP or COM, from and into the customer environment.

External environment:
With regards to the data exchange processes treated in the present work, the external environment primarily focuses on PDMS-based data management issues and the provision of 3D-CAD models, created in a CAD environment (see Type I and Type II projects, introduced in section 5.3). In case of involvement of external data, the applied data management environment provides an interface to the corresponding customer environment. This interface that connects customer and internal environment, makes use of standardized functionalities of the PDMS at both parties involved.

Target environment:
In BIW and integrated joining technology development, different types of computational simulations are carried out to support the development processes in view of verification and evaluation of the design proposals and manufacturing-related investigations. Typically, these simulation processes are performed in the target environments of CAE and CAM. Exemplary, crash and NVH behavior as well as the durability of the car bodies are treated in the target environment CAE. In terms of joining technology, simulation procedures deliver statements about suitable application of joining elements type, technology amount and positions with regard to BIW crash behavior and durability. In the field of CAM, simulations of joining technology deliver statements about manufacturing processes (e.g. accessibility of weld robots, planning of the production line, cycle times), operational tests of joining tools (e.g. installation space analysis) and the optimization of the joining sequence.

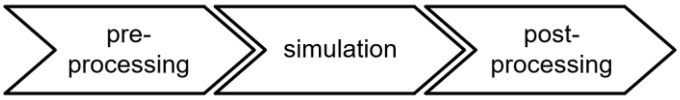


Fig. 64 - Typical process steps in target CAx environments

In the target CAx environments, three typical process steps are performed, which are represented as pre-processing, simulation and post-processing (c.f. Fig. 64). While the data imported into the target environment is processed in pre-processing, the steps of simulation include different types of computational calculation processes. In post-processing, the simulation results are prepared for illustration and evaluation. These results are then transferred back into the design process, which leads to an enhancement of the corresponding 3D-CAD models.

5.4.2. Approach of the Optimized Data Exchange Process

As one main output of this work, an optimized data exchange process is introduced that enables effective exchange of joining technology data in automotive BIW development. This approach integrates standardized data formats (geometry format JT and metadata format xMCF), specifically developed tools and a comprehensive data exchange process. Fig. 65 gives an overview of the optimized data exchange process between CAx environments as it can be applied for both internal and external data exchange. In addition, the process included the involvement of internal target CAx environments. For a better visualization of the process sequences, the different areas are highlighted with dissimilar greyscales. This approach is applicable to a variety of projects in the automotive industry under consideration of the boundary conditions introduces in sub-chapter 5.1. Above all, the different opportunities of exchanging data (e.g. data exchange file formats, data structure) and the different data exchange strategies of the parties in the automotive industry are of central importance here.

To ensure that the optimized data exchange process can be used in a variety of automotive projects, the entire process is supported by auxiliary tools. The tools have been developed specifically in the course of the present research works and are summarized in Fig. 65 under the term "Joining World” environment. A detailed description of the single modules of the “Joining World” environment and the individual tools follows in sub-chapter 5.5, while the application is described in chapter 6.

As mentioned above, the creation of data, respectively of 3D-CAD models, takes place in the CAD environment. It does not matter if the creation is performed internally or externally or which type of CAD software is used. External data creation can be conducted in the OEM or customer-specific environment or by using a remote access to the customer environment by the corresponding engineering supplier. In all cases, the externally created data are available in the customer environment. In a subsequently performed step, the data are imported into the internal target environment, which is typically integrated in the PDMS of the engineering company or department vial data transfer between the two involved PDMS (from the external PDMS to the internal PDMS.

In case that data are available in external sources, these data must be integrated into the optimized data exchange process first (c.f. section 5.4.3). As soon as all required data from external sources are available in the internal CAD environment, the completion of the 3D-CAD model can start. Once the data have reached the maturity level (c.f. section 2.3.3) required for data exchange, the data are always exchanged in the same way between several CAx environments using a project exchange platform. The existing geometry data – as JT files – and the existing joining technology data – as xMCF files – are then integrated into the target CAx environment. After the import of all geometry and joining technology data files, the simulation tasks can be processed in the target CAx environment, starting with the pre-processing step.

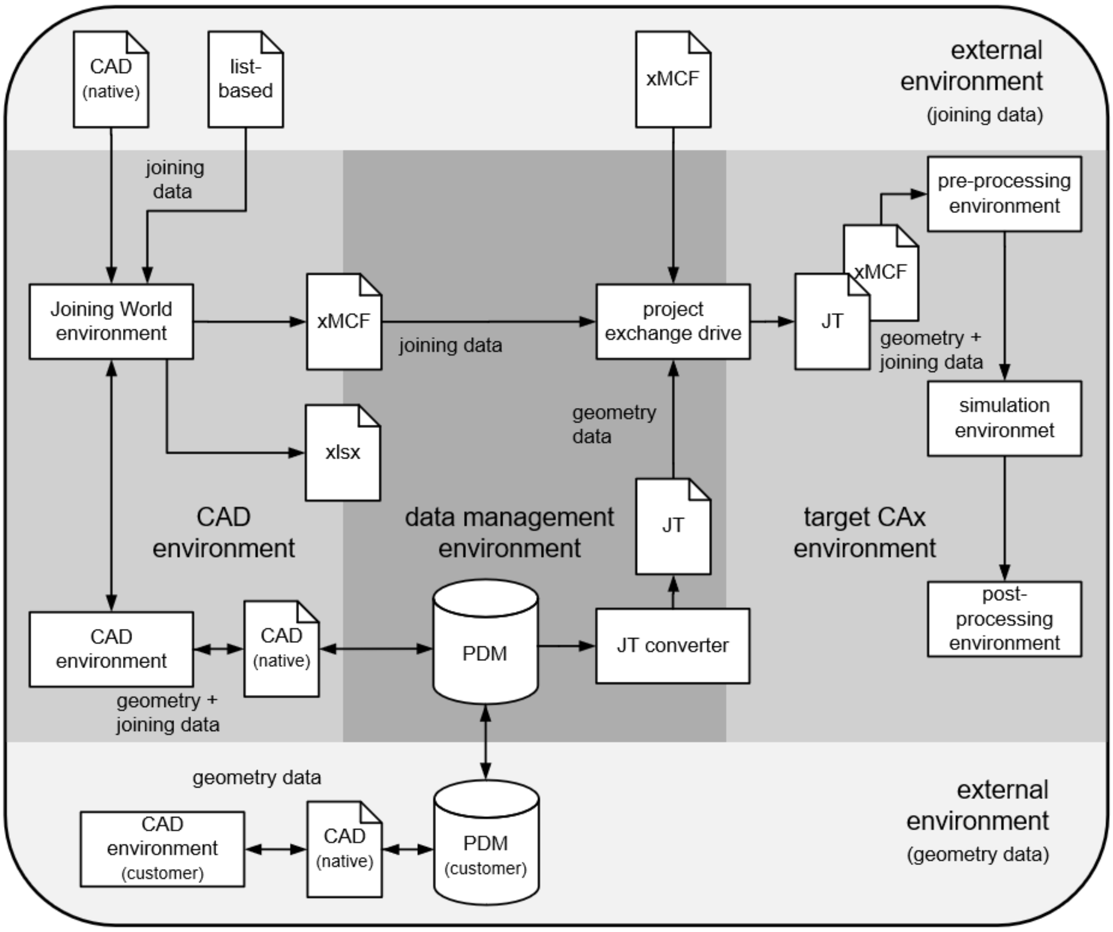


Fig. 65 - Approach of the optimized data exchange process

In this step, suitable simulation models (e.g. CAE/CAM models) are created by merging geometry data with joining technology data. The geometry files are first integrated into the pre-processor system and automatically positioned based on the transferred metadata that describe the positions of joining elements. Subsequently, an integration of joining technology data takes place using metadata provided in the xMCF file. The positioning of the individual joining technology elements is performed based on the position information provided by the metadata. In addition, the joining technology elements are automatically assigned to the components/parts to be joined, since this information is also transferred in xMCF file as so-called connectors.

Typically, the merged CAE model data are used for generation of meshes for subsequently performed simulation (e.g. FEM simulation), whereby the CAM model provides information for kinematics investigations, e.g. for Multi-Body Simulation (MBS) of manufacturing processes. After the simulation steps have been completed in the simulation environment, the so-called post-processing procedure is performed. Evaluation of simulation results, as well as the derivation of suggestions for improvement of the 3D-CAD model, takes place in this stage.

5.4.3. Data Flow from External Sources

The data exchange between CAD environments and target CAx environments at a certain process step (e.g. milestone) requires completely available data structures. In case that the 3D-CAD model is created entirely in the internal environment, the corresponding (internal) department is responsible for data volume and correctness. If the 3D-CAD model is created externally, either in whole or in part, these data are integrated into the internal environment. Therefore, the first step includes a check of data completeness. After that, the complete data structure is processed by use of the pre-defined internal data exchange formats JT and xMCF. The conversion process is performed in the tools “Joining World” environment and “JT converter”, whereby JT is applied for geometry data exchange and xMCF for joining technology metadata exchange.

In case that the data are only partially available, it must be determined whether the geometry data have been completely transferred. If not, the native CAD files are imported into the internal CAD environment to complete the 3D-CAD model in the internal CAD environment. As soon as the geometry data are completed, the tool “JT converter” is used to create the necessary JT files for further internal data exchange.

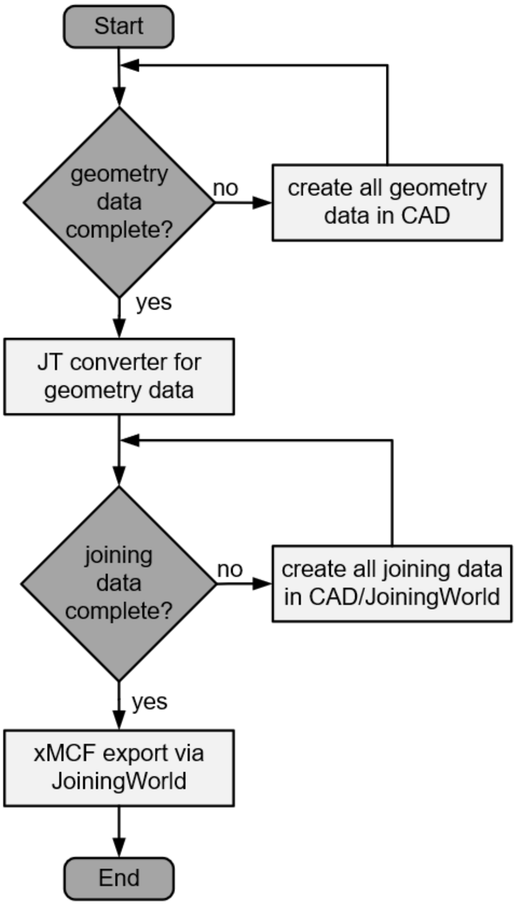


Fig. 66 - General selection process for integration of externally created data

After this step, a control process is performed, which checks the completeness of the joining technology data. This process is run through in tools of the “Joining World” environment until all joining technology data are complete. Subsequently, the export of the joining technology data is started using the xMCF format. If the complete joining technology data are available in a list format, the data export is started by use of the xMCF format, supported by the "Joining World" environment tool.

Another case is, that in addition to the (entire) geometry data, parts of joining technology data are already available in the external CAD environment. According to Fig. 66, the joining technology data would then be imported into the internal CAD environment. In this environment, the data would then have to be completed on the basis of the externally created joining technology data.

5.5. Joining World – Tools Supporting the Optimized Data Exchange Process

The optimized data exchange process between CAx environments is supported by certain tools, which maintenance the creation, processing and export of joining technology data. The next section provides an overview of these tools and their functionalities. The tools have been developed specifically in the course of the present research project in context with the project targets and are not available on the market. All the mentioned tools, which are used in the optimized data exchange process to support the creation, administration and export of joining technology data are created by using the software "Visual Studio (VB.NET)" [84]. A major reason for the introduction and development of new tools used in the "Joining World" environment is that there are currently no commercially available tools on the market that are able to meet the requirements of the optimized data exchange process.

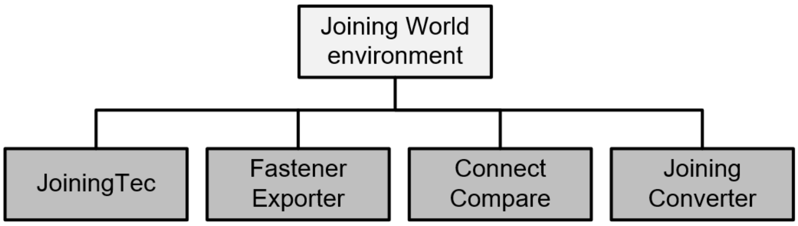


Fig. 67 - Overview of Joining World tools

Fig. 67 give an overview of the tools in the "Joining World" environment:

- "JoiningTec" – Used for the creation, administration and export of joining technology data
- "Fastener Exporter" – Used for exporting standard parts
- "Joining Converter" – Export of joining technology data from external sources
- "Connect Compare" – Comparison of joining technology data in case that two different data sources are available

Fig. 68 gives an overview of the integration of the tools into the approach of the optimized data exchange process (c.f. Fig. 65). All tools introduced here are embedded in the internal CAD environment and support the optimized data exchange process in creation, managing and exchanging of joining technology data. Access to the respective CAD programs is provided via an implemented API (Application Programming Interface). In general, APIs provide methods and functions of the (CAD) program package by use of programming languages (c.f. Fig. 69). The tools are structured in GUIs to offer users a graphical interface between code (main part of the tools) and APIs/CAD programs. A detailed description of the functionalities of the tools is given in the next sections.

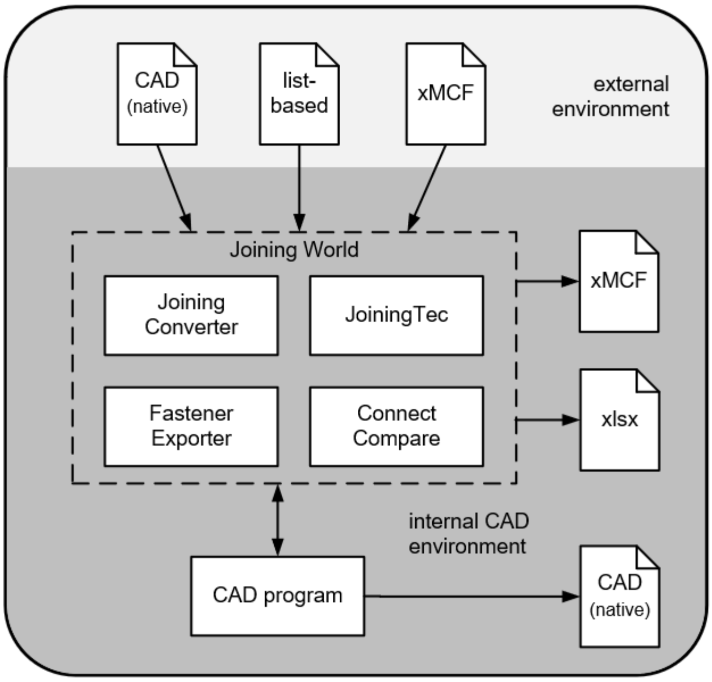


Fig. 68 - Integration of Joining World tools in the optimized data exchange process

On the left side of Fig. 69 the initial position, including a CAD model and list-based data (input parameter), is shown. In order for the list-based data to be integrated into the CAD model, the data must be converted. For this purpose, as shown in Fig. 69 (on the right-hand side), the "Joining World" tool accesses and processes the list-based data using the API. The converted data are then automatically (the API of the "Joining World" tool accesses the CAD system) imported into the CAD model.

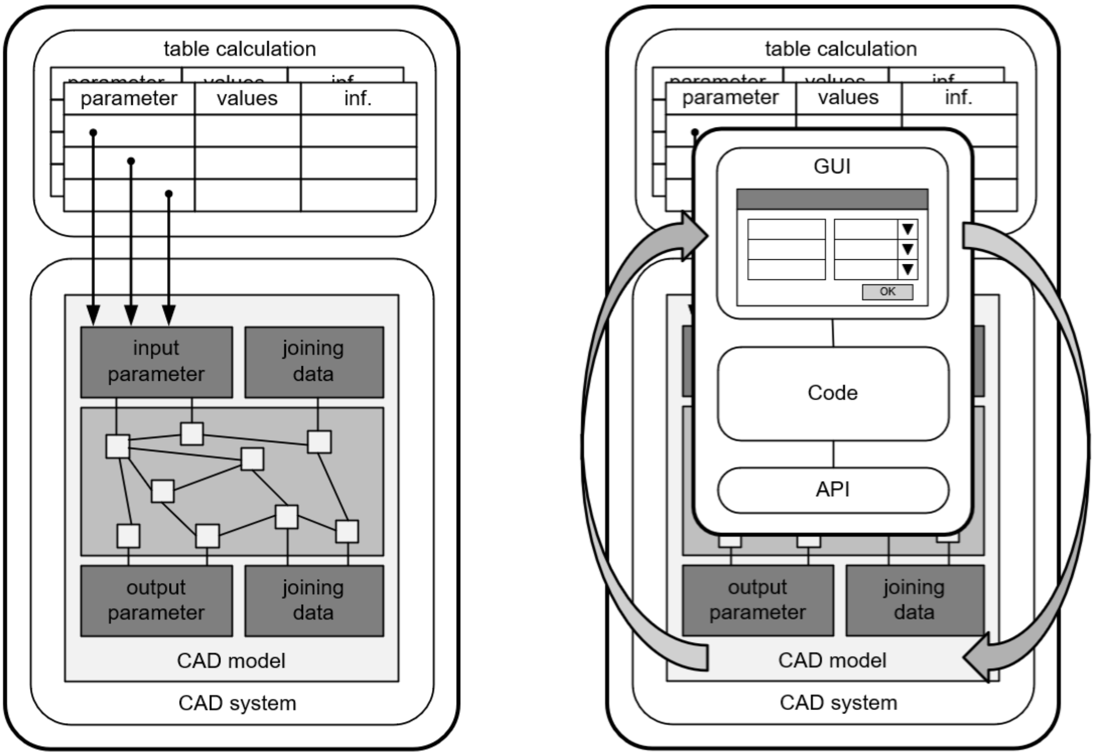


Fig. 69 - Embedding of Joining World tools in CAD environments with exemplary selected input and GUI parameter, referring to [104]

5.5.1. Joining World – JoiningTec

The tool “JoiningTec” is primarily used for the creation, administration and export of joining technology data. It comes to use if the creation of joining technology data takes place either completely or partially in the internal CAD environment. Typical scenarios for the use of “JoiningTec” are projects in which only internal tools and processes are used (c.f. sub-chapter 5.3, Type III projects); exemplary, the customer does not provide any own tools, methods and processes. In addition, projects in which missing joining elements are to be created, represent a field of application for “JoiningTec”. This scenario occurs if the customer provides partially generated data of joining technology, e.g. for single modules or COP. In this case, joining technology data already created in the customer environment are imported into the internal CAD environment and the missing types of joining technologies are then created internally by use of “JoiningTec”.

The main reason for the development and integration of the tool “JoiningTec” is that commercial CAD software packages offer only limited possibilities for creating, managing and exporting of joining technology data. Especially in the case that an engineering company has to handle a number of different projects with different customers, the standard CAD software packages do not provide the required functionalities for effective development processes. In addition, “JoiningTec” provides specifically developed export formats. The generated joining technology data are transferred in an appropriate format (e.g. xMCF) to be further processed in the target CAx environments. In addition, the exported joining technology data can be converted into list formats (e.g. xlsx) in a tailor-made way, which makes it easier to perform double-checks of the created joining technology data. Furthermore, the exchange of information with joining technology suppliers (e.g. for purchasing of standard parts like rivets, bolts) is easier with list formats.

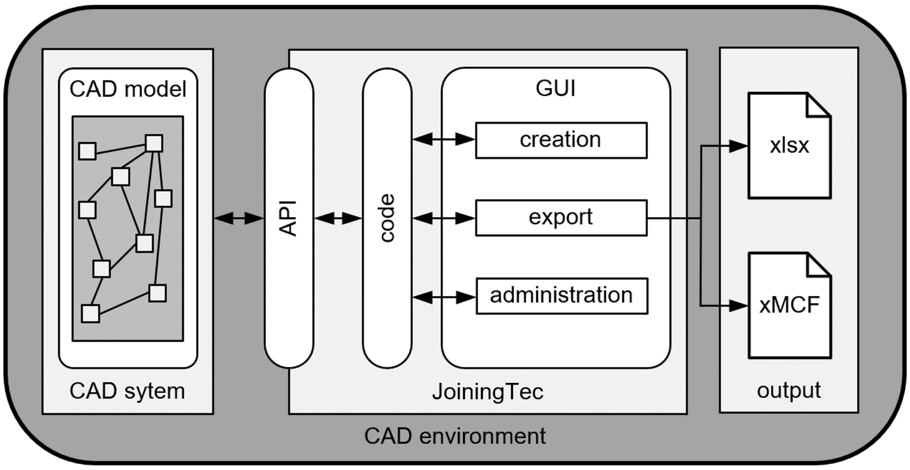
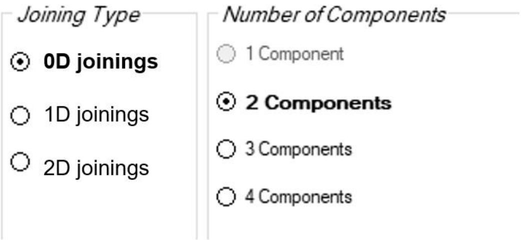


Fig. 70 - Embedding of the tool “JoiningTec”

“JoiningTec” can therefore be regarded as a sub-tool embedded in CAD software packages. The corresponding CAD programs are accessed via the available API (c.f. Fig. 70). When creating new types of joining technologies or editing existing joining technology data, the corresponding changes of the 3D-CAD models are transferred to the CAD environment. Therefore, special set up macros have been developed and implemented to provide and save the joining technology information in the associated CAD environment. To export these data, the tool “JoiningTec” accesses the data stored in the CAD environment and creates an xMCF file.

Creation of joining technology data

The GUI provides various setting options for the creation of joining technology data. In the first step, the classification of joining technology is selected according to the xMCF levels, cf. [29] and the number of components, which are to be connected is defined (cf. Fig. 71).


Joining Type
● **0D joinings**
○ 1D joinings
○ 2D joinings

Number of Components
○ 1 Component
● **2 Components**
○ 3 Components
○ 4 Components

Fig. 71 - First step to create a joining element in "JoiningTec"

Subsequently, the types of joining technology (e.g. spot weld, rivet, bolt, etc.) are selected. In the tool, various parameters for each type of joining technology are defined. Exemplary, for the creation of a spot weld, the sheets to be connected are selected first. After this step, the required parameters, such as the diameter, coordinates, etc. (cf. Fig. 73 – depiction in the CAD structure tree) are entered. A list of all parameters for the individual joining technique types can be found in annex A.2.

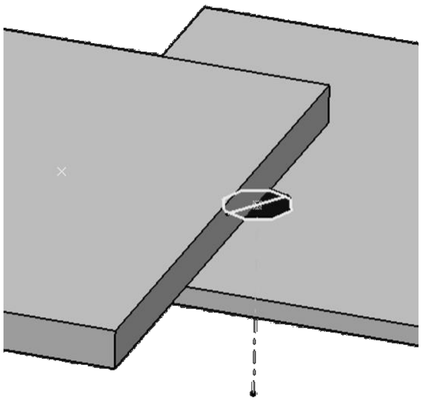


Fig. 72 - Depiction of two spot welds created by the tool "JoiningTec"

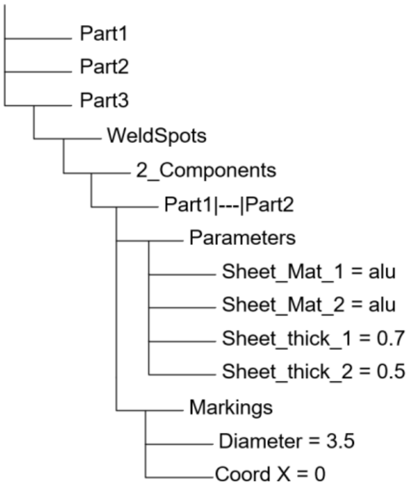

Part1
Part2
Part3
WeldSpots
2_Components
Part1|---|Part2
Parameters
Sheet_Mat_1 = alu
Sheet_Mat_2 = alu
Sheet_thick_1 = 0.7
Sheet_thick_2 = 0.5
Markings
Diameter = 3.5
Coord X = 0

Fig. 73 - Excerpt of selected parameters of the created spot weld element

After the selection of suitable joining technology, the sheet components to be connected and the required parameters are defined. Fig. 72 shows an exemplary spot weld displayed by a 2D-circle and a straight dot-dashed line, which symbolizes the normal direction of each element. Fig. 73 shows an excerpt of the parameter structure of the spot weld connection including the two connected parts (Part1 and Part2).

Administration of joining technology data

The tool reduces the effort to change already created joining technology data. In the introduced change process, the elements to be changed do not have to be deleted and recreated. Only the parameters to be changed (e.g. coordinates, type of joining technology, diameter) have to be changed. After changing the parameters, an automatic update takes place in the CAD environment.

Export of joining technology data

For the export process, the tool “JoiningTec” automatically creates a list of all available joining technology elements. The user can select whether the joining technology data are to be exported as an Excel-based list or an xMCF file (XML-based). Therefore, the tool “JoiningTec” accesses the corresponding CAD software package and thus, the CAD model by using the API. This access is then used to export the selected joining technology data in the selected export file format.

5.5.2. Joining World – Fastener Exporter

The tool “Fastener Exporter” is used to export standard parts (e.g. screws, bolts, rivets). In some cases, suppliers of these standard parts provide 3D-CAD models. In this case, the 3D-CAD model is available as a CAD native file and can be added directly to the components to be connected. If 3D-models are available for the standard parts, it is easier to add these parts directly than to create them individually or to use the tool “JoiningTec” for creating and managing joining technology data. Another benefit is that the supplier delivers a high information level of the components.

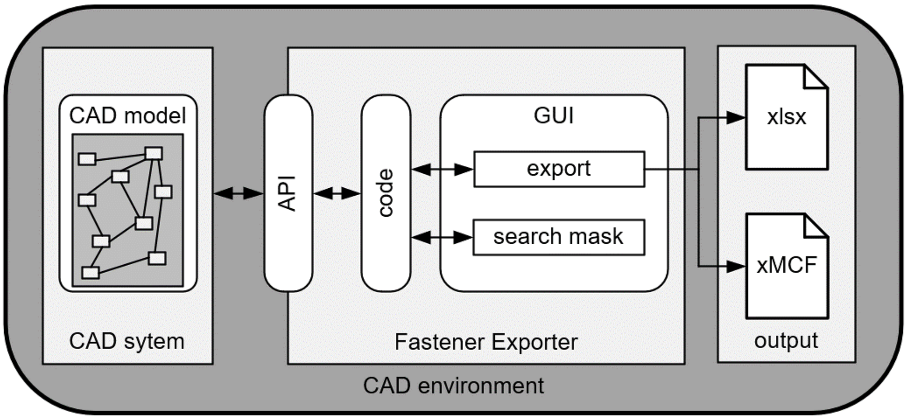
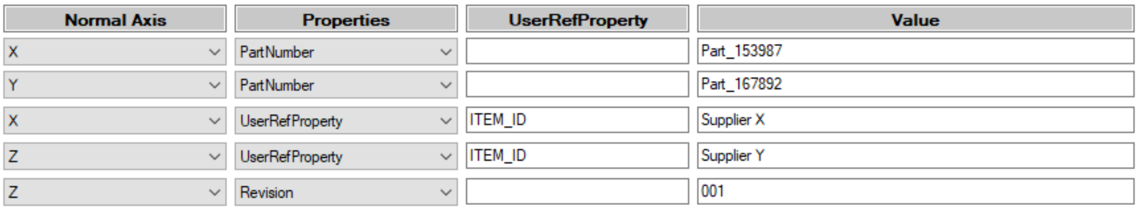


Fig. 74 - Embedding of the tool “Fastener Exporter”

“Fastener Exporter” (Fig. 74 shows the embedding of the tool in the CAD environment) enables an efficient export of joining technology standard parts. It can be set for searching elements by use of the GUI to distinguish standard parts from other components. The search mask, which is shown in Fig. 75, provides settings, which make it possible to apply a filter function for the data export. This procedure enables a specific selection of parts of a certain supplier, or all parts with a certain part or revision number to be exported. Another input parameter is the normal direction of the standard parts. This normal direction plays a decisive role in the programming of the robots in CAM environments but is also important for simulation tasks in CAE environment, e.g. for the definition of the normal direction vector of the riveting process.



Normal Axis	Properties	UserRefProperty	Value
X	PartNumber		Part_153987
Y	PartNumber		Part_167892
X	UserRefProperty	ITEM_ID	Supplier X
Z	UserRefProperty	ITEM_ID	Supplier Y
Z	Revision		001

Fig. 75 - Search mask for definition of export data

Once the entire structure tree is examined in the CAD environment (according to the search criteria) and the selected standard parts are found (cf. Fig. 76 and their parameter in Fig. 77), the corresponding data are exported. To make this possible, the data entered in the GUI are compared with the properties of the CAD model using the API. The “Fastener Exporter” provides the possibility to export different output files (e.g. xMCF file or a list format – xlsx file). The export as xMCF file format has the advantage that it can be further processed in the target CAx environments. The export in list format provides a good overview of all standard parts, e.g. as a basis for communication with suppliers. In addition, the output in list format shows which and how many standard parts are used in a certain project.

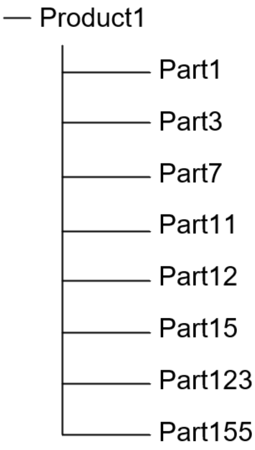
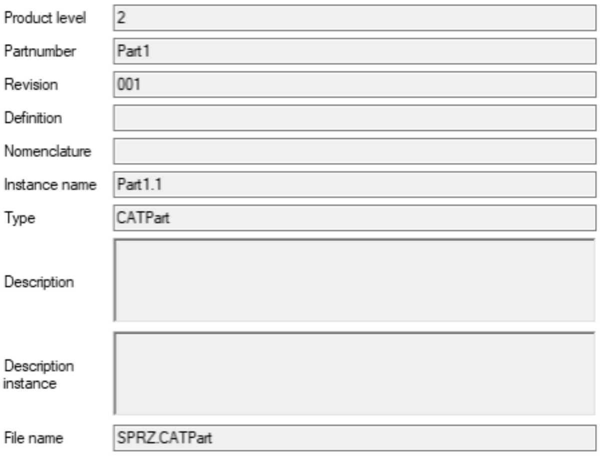


Fig. 76 - List of standard parts found according to the search criteria entered



Product level	2
Partnumber	Part1
Revision	001
Definition	
Nomenclature	
Instance name	Part1.1
Type	CATPart
Description	
Description instance	
File name	SPRZ.CATPart

Fig. 77 - Excerpt of parameters exported from the used standard parts in CAD

Fig. 78 exemplary shows the export of two standard parts – in this case of two weld nuts – in list format. Each weld nut is connected with exactly one sheet (weldnut_565 with B1237775654 and weldnut_12 with B0123458714). Besides this information, a coordinates vector (x-, y- and z-coordinates), the normal axis and normal axis vector (x-, y- and z-direction) and the superordinate assembly are exported as parameters.

name	sheet	coord. x	coord. y	coord. z
Part1 - weldnut:565	B1237775654	154.896	154.782	12.818
Part56-weldnut_12	B0123458714	-12.478	325.205	0

assembly product	normal axis	norm .dir. x	norm. dir. y	norm. dir. z
Assembly_00789_Part1	x	0.595	0.748	0
Assembly_002259_Part56	z	0	0	1

Fig. 78 - Exemplary output exported as a list format

In summary, the tool “Fastener Exporter” supports the optimized data exchange process by exporting the metadata and parameters of standard parts. This information is then used in the target CAx environment as well as for communication with standard parts suppliers.

5.5.3. Joining World – Joining Converter

The main function of the tool “Joining Converter” is to bi-directionally translate joining technology data available in one data format into another format (cf. Fig. 79). Joining technology data can be available in external sources either as CAD native format or as a list-based format. If it is a complete CAD dataset, no further modifications are necessary. In this case, it can be converted into an xMCF format without further processing. On the other hand, joining technology data can be delivered from external sources as different kinds of list formats. In this case, the tool “Joining Converter” is used to create the required internally-used xMCF format. In this way, native CAD joining technology data, as well as joining technology data in list format, can be converted into an appropriate output file. For export processes, joining technology data available in xMCF format have to be converted into different list formats, so that the external project partners receive the joining technology data in a format that corresponds to their data format specification. Another application of the tool includes conversion of joining technology data available in a list or xMCF format into joining technology CAD data, which are then imported directly into the CAD environment.

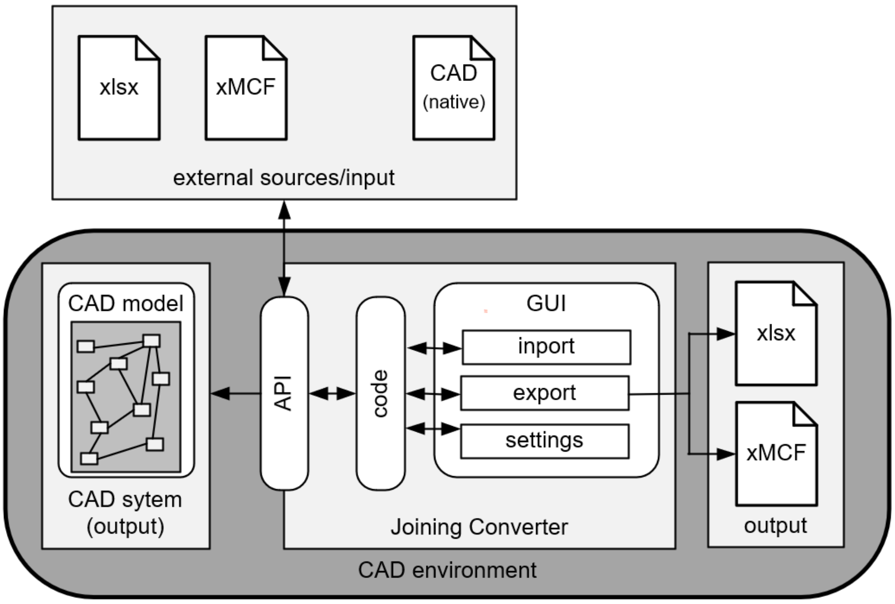


Fig. 79 - Embedding of the tool “Joining Converter”

Due to the requirement to handle data conversion in a multifarious way, the tool is designed flexible, so that various list-based data structures can be processed. Depending on the type of joining technology data and the data structure in a specific development project, the list formats contain different types of information. The type and number of information content have a direct influence on the structure of the file. The use of different structures (i.e. different customers work with different structures) requires that the headings of the columns or rows are different or that columns are arranged differently, which has to be handled by the tool “Joining Converter”.

name	coord. x	coord. y	coord. z	part 1	part 2	part 3	type	sub-type	norm. dir. x	norm. dir. y	norm. dir. z
conn 1	175.012	155.236	109.457	A00012123	A00013117	A00012912	spot weld	arc welding			
conn 2	-15.078	152.145	12.234	A00012124	A00013118		spot weld	arc welding			
conn 3	-15.078	152.145	22.234	A00012124	A00013118		spot weld	arc welding			
conn 4	265.123	65.140	98.887	A00012912	A17000222	A00022927	rivet	SPR	0	0	1

Fig. 80 - Exemplary selected list structure 1

name	part 1	part 2	part 3	coord. x	coord. y	coord. z	norm. dir. x	norm. dir. y	norm. dir. z	type	sub-type
conn 1	A00012123	A00013117	A00012912	175.012	155.236	109.457				spot weld	arc welding
conn 2	A00012124	A00013118		-15.078	152.145	12.234				spot weld	arc welding
conn 3	A00012124	A00013118		-15.078	152.145	22.234				spot weld	arc welding
conn 4	A00012912	A17000222	A00022927	265.123	65.140	98.887	0	0	1	rivet	SPR

Fig. 81 - Exemplary selected list structure 2

Fig. 80 and Fig. 81 show exemplary list structures of joining technology data exchange. Both lists contain the same information, but the structures of the lists are different. In this way, the tool “Joining Converter” is designed to offer flexibility, which can be adjusted by the user via the GUI. The tool is designed in a generic structure, which enables an adaptation to the structure of the corresponding lists (arrangement of columns, rows and cells). In the process of converting joining technology data from one data format into another one, both an input and an output file format are selected via the GUI. Subsequently, conversion and export processes are performed automatically.

5.5.4. Joining World – Connect Compare

The tool “Connect Compare” performs a delta-matching process between two different data sets, which have been created in different input sources (c.f. Fig. 82). In special cases, it may happen that joining technology data are available in both as native CAD file and as a list-based file (e.g. Excel-based).

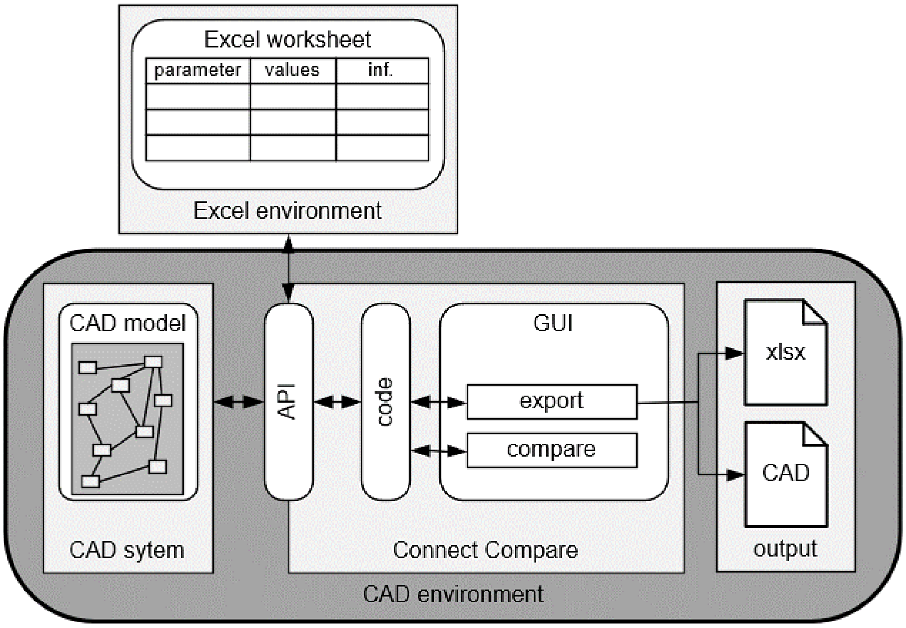


Fig. 82 - Embedding of the tool “Connect Compare”; CAD file as master

Since joining technology data are therefore available as native CAD format and as list-based format, these two data sets can be compared with each other by using a specifically designed compare function implemented in the GUI. If a joining technology element is found, both in CAD and in the list file, all parameters of the individual element are compared. If these parameters match, no changes are suggested. However, if a joining technology element is found in only one of the two input files, or if the parameters do not match, an error message is issued. At the end of the delta-matching process, a resulting list shows all deviations between the two input sources.

Another option of the tool is to set one of the two input sources as master source. This means that if deviations are detected during the delta-matching process, the selected master file is considered as to be correct. At the same time, the missing or wrong parameters are transferred to the second input source and a new so-called “delta file” (the delta file can be both a CAD native or a list-based file) is created. In the following example, the CAD file is defined as master source (cf. Fig. 83). This means that in the event of deviations, the corresponding parameters are transferred from the CAD source to the list-based format (cf. Fig. 84).

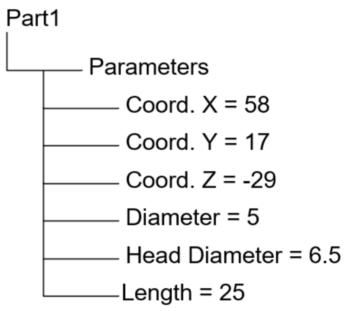
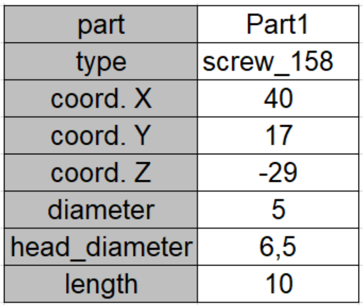
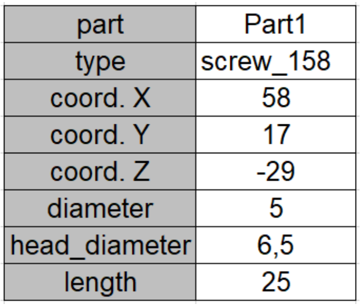


Fig. 83 - CAD master file



part	Part1
type	screw_158
coord. X	40
coord. Y	17
coord. Z	-29
diameter	5
head_diameter	6,5
length	10

Fig. 84 - List-based input file



part	Part1
type	screw_158
coord. X	58
coord. Y	17
coord. Z	-29
diameter	5
head_diameter	6,5
length	25

Fig. 85 - New list file

In the example it is recognized during the delta-matching process that the two parameters “coordinate X” and “length” do not match. Since the CAD file is defined as master, the two parameters are adapted in the list format (cf. Fig. 85).

6. Application of the Approach

The introduced approach of an optimized data exchange process to support the development of joining technology in automotive body design is applied to typical industrial use-cases to show the potentials. In the following, the optimized data exchange process is conducted on the basis of the project types presented in sub-chapter 5.3.

The applicability of the optimized data exchange process is illustrated by use of selected relevant quality factors, respectively, process-related requirements. In this context, Tab. 9 provides an overview of the tools, components and boundary conditions required to run the optimized data exchange process in the three mentioned project types.

Requirements	*Type I*	*Type II*	*Type III*
Applicability in several CAx environments	x	x	x
Applicability of different PDMS	x	x	x
Tool for exporting geometry data		x	x
Tool for creating geometry data		x	x
Tool for administration of geometry data		x	x
Tool for creating joining technology data		x	x
Tool for administration of joining technology data		x	x
Tool for exporting joining technology data		x	x
Tool for delta-matching, if two joining technology data sources are provided		x	
Tool for creating xMCF files	x	x	x
Tool for administration of xMCF files	x	x	x
Tool for creation of xlsx files	x	x	x
Exchange drive for data exchange between CAD and target CAx environments	x	x	x
Remote machines to connect with the customer-specific CAD environment	x		

Tab. 9 - Exchange process-related requirements for different project types

Note: If an “x” is specified for the various project types and boundary conditions, it means that this boundary condition/requirement must be considered. On the other hand, no “x” indicates that this boundary condition/requirement doesn’t occur in the associated project.

For the data exchange process, it is of central importance that different CAx environments and their tools can be integrated. In the following, the application of the approach is examined on the basis of the following cases, which result from the implemented project types:

- 1st case: Application of the approach in Type I projects
- 2nd case: Application of the approach in Type II projects
- 3rd case: Application of the approach in Type III projects

For the application of the optimized data exchange process in industrial projects, the following points are considered in all cases:

- Data are always exchanged from one CAD environment (placed internally or externally) to the internally provided target CAx environment, which could be a CAE or a CAM environment.
- It is always distinguished between geometry data and joining technology data (c.f. sub-chapter 1.2).
- Native geometry data are converted into the JT format before they are exchanged.
- The conversion of joining technology data into xMCF files is necessary for the exchange of joining technology data.
- Joining technology data are converted into the xMCF format before they are exchanged.
- The exchange process with external CAx environments, respectively with external PDMS, can be based on different data exchange formats.
- The creation of xlsx files is necessary for the distribution of joining technology data to suppliers.
- Use of two PDMS is necessary for the data exchange processes with external participants (Type I and Type II projects).
- Processed simulation results from pre-processing steps of the respective target CAx environment are transferred directly between the simulation environments (e.g. CAE, CAM) and the responsible CAD environments.

In the course of a typical BIW development project, the data exchange loops take place several times, depending on the workload of the project. Exemplary, in a full development project of a new vehicle, four to six loops (so-called simulation loops) are performed 2.3.3.

6.1. Application of the Approach in Type I Projects

Type I projects are driven by the OEM, which means that in view of data management, engineering suppliers perform the development tasks within clearly described boundary conditions. The engineering workload in regard to the creation of CAD-based data takes place in external CAD environments, more specific in the data management environment of the OEM. In this context, automotive suppliers must be able to use these prescribed processes and systems within their internal environment. CAD data structures and data transfer, as defined according to the OEM specifications (e.g. data formats, a varying number of metadata), is integrated into the internal target CAx environment according to the design and simulation tasks to be accomplished at the supplier company.

Fig. 86 shows the optimized data exchange process applied in a Type I project under consideration of the boundary conditions described in Tab. 9. The data exchange between the customer (e.g. OEM) specific CAD environment and the internally (e.g. supplier) used target CAx environment takes place as described below.

As already mentioned, the CAD environment for Type I projects is defined based on the customer-specific environment. This means that the workload for the complete creation, administration and management of CAD-based data is conducted in the customer-specific environment. As the customer aims to create and administrate CAD-based data in their own environment, the supplier-internal CAD engineers access the customer-specific CAD environment remotely. This strategy is applied in industrial processes to divide the workload in creating and managing CAD data between the customer (e.g. OEM) CAD engineers and internal (e.g. automotive supplier) CAD engineers. With Type I projects, the entire created CAD data are available exclusively to the customer in their own environment.

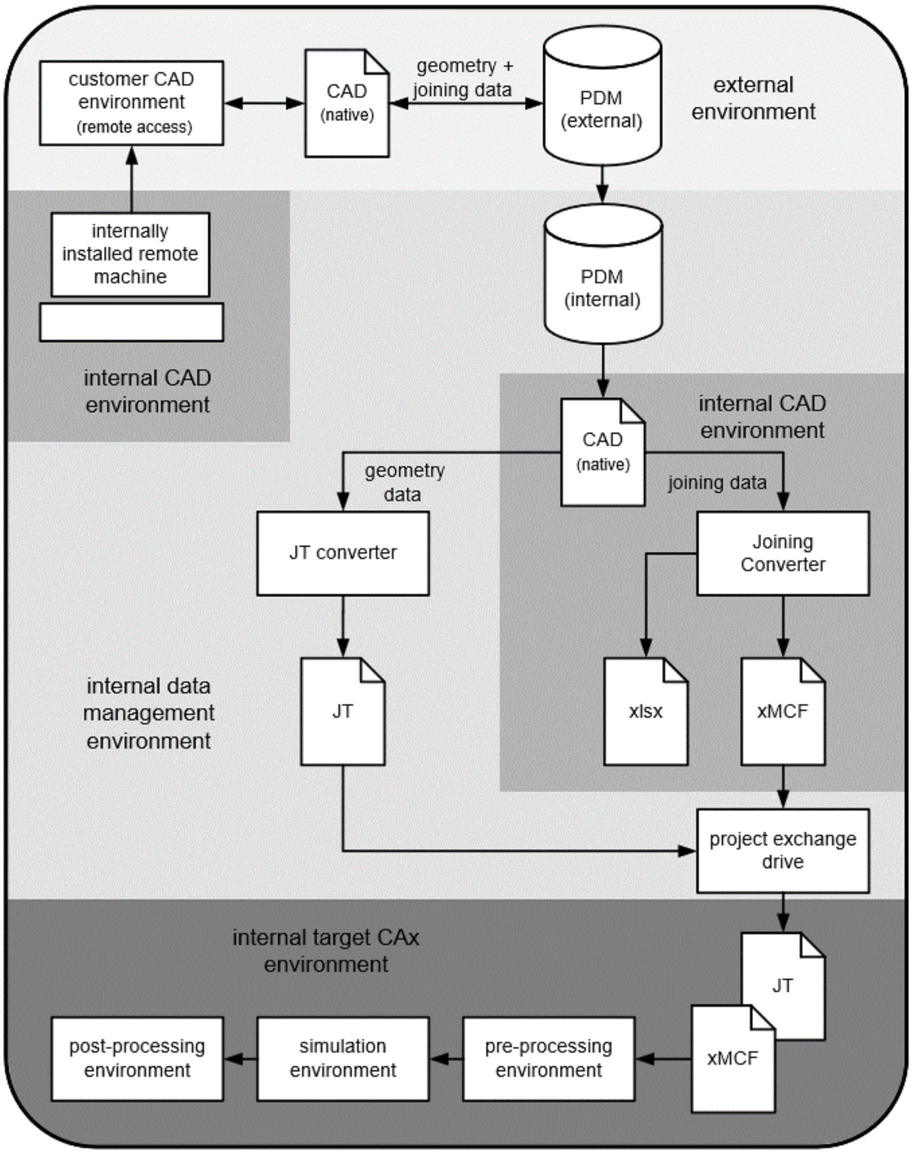


Fig. 86 - Application of the optimized data exchange process in Type I projects

As soon as the necessary maturity level of the CAD data has been created (determined by milestones), these data are saved in the customer PDM environment. From there, CAD data are exchanged between the customer PDM environment (“external”) and the PDMS installed in the supplier environment (“internal”). In most cases, the automotive supplier has no influence on the received data, data structure and data format (i.e. black box behavior). Usually, these data are transferred in different data formats. For the data exchange process, this means that suitable measures (e.g. flexible tools that can handle several data formats, converters) are used to ensure that all data and data formats are processed in a useful way. If data are already transmitted in the neutral file format JT (for geometry data) and in the neutral file format xMCF (for joining technology data), they are transferred to the target CAx environment without any further processing effort. In most cases, the native CAD data must be converted into a JT and xMCF file before further use in simulation environments, by application of the two tools “JT converter” and “Joining Converter” (c.f. Fig. 86).

The joining technology data can also be exported as xlsx file to enable evaluation measures and improved readability (necessary for the exchange of standard part with different involved parties). This export of joining technology data is processed by using the tool "Joining Converter". Once the JT and xMCF data formats have been created, they are transferred into the project exchange drive to provide access for CAE engineers. After completing all simulation steps, the results that exemplary provide information about crash and stiffness behavior of the BIW, are evaluated. In this step, results are discussed with the CAD engineers (both internal and external) responsible for the respective assemblies and parts. The CAD engineers can then consider the simulation results and modify the 3D-CAD models accordingly.

In summary, it can be concluded that in Type I projects, only the systems and tools of the customer are used for the creation of CAD-based data. The only exception (although not always necessary) are converters, which are used for the creation of the supplier internally-used data exchange formats (JT and xMCF). The complete CAD data creation takes place in the customer's CAD environment, while the simulation processes and evaluation of simulation results take place internally at the supplier. The approach of the optimized data exchange process provides a solution to handle Type I projects in the supplier's internal environment by a close connection to the data management structure of the customer.

Furthermore, it must be mentioned that by applying the optimized data exchange process in a Type I project, the effort for data exchange can be reduced significantly. This reduction results mainly from the fact that data reach the target CAx environment in an appropriate quality due to the support of tailor-made tools. These tools provide an improvement of data quality in the course of the data exchange process to the target CAx environments, which leads to less preparation effort for the creation of the simulation models (e.g. in pre-processing). This represents a significant improvement in comparison to conventional state-of-the-art approaches, where data are made available to the target CAx environments in different variants and different quality.

6.2. Application of the Approach in Type II Projects

While Type I projects are limited in the way of how data are created in CAD environments and exchanged between two or more CAx environments, the situation in Type II projects is more complex. Fig. 87 shows the application of the optimized data exchange process in a Type II project. As already mentioned, Type II projects are a mix of Type I and Type III projects. This means that the automotive supplier must be able to control all processes and tools specified by the customer (e.g. OEM) and include them in the data exchange process by use of specific, internal tools.

At the start of a data exchange process, 3D-CAD model data provided in an external environment are checked regarding correctness. Subsequently, the CAD data are transferred from the customer-specific CAD environment to the internal CAD environment by involvement of both PDMS. The existing CAD data in the customer environment are mostly so-called COP/COM, which are already used in other derivative vehicles. In the exemplary shown project in Fig. 87, the geometry and joining technology data are available in a native CAD file format. Additionally, joining technology data are available in a list-based format. Besides the advantage of better clarity of joining technology data in list-based formats, this also offers the possibility of collecting data from two different sources. A common problem in the automotive industry when obtaining data from two different data sources is that there may be differences in the data set. The reasons for these differences between the CAD-based and the list-based joining technology data sources can be manifold, e.g. because of an incorrect filling out of the lists by the CAD engineers or because only one of the two data sources is changed during design modifications.

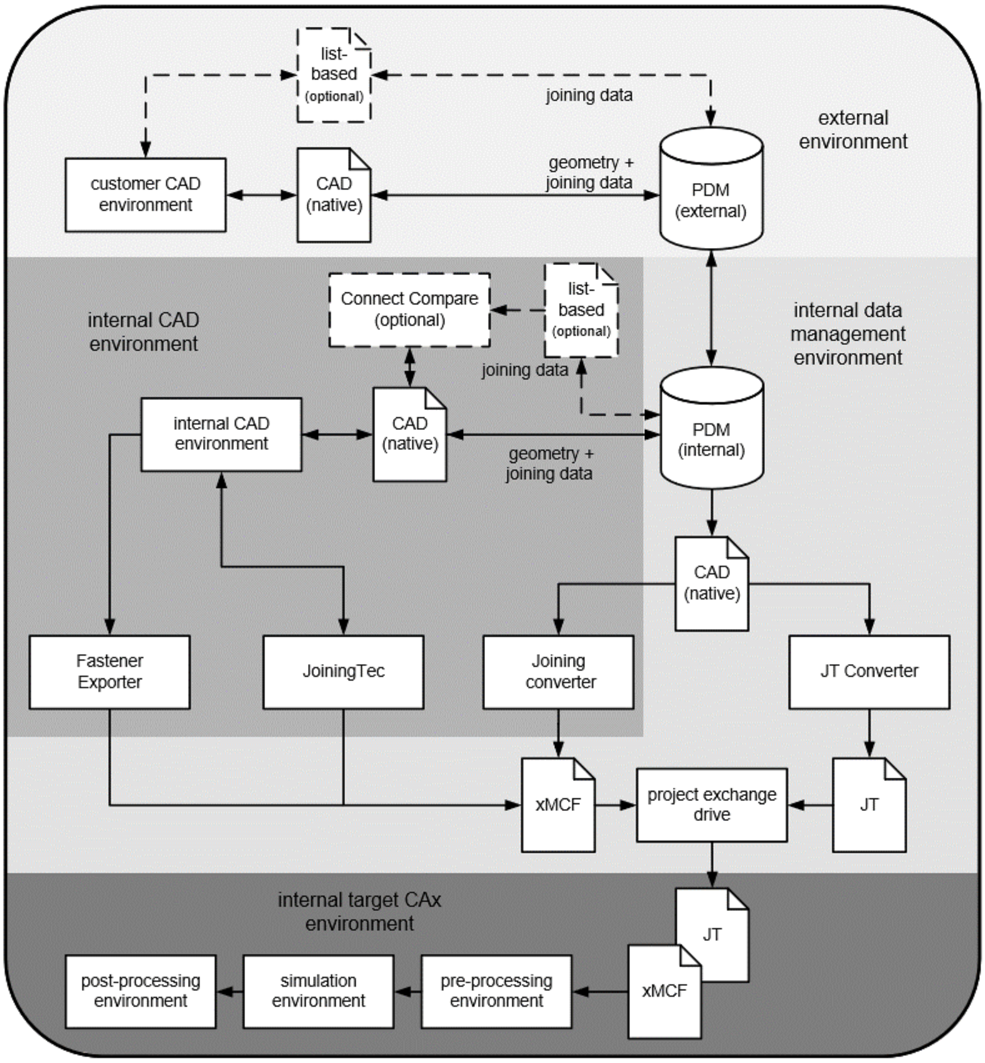


Fig. 87 - Application of the optimized data exchange process in Type II projects

However, by receiving two different data sources of joining technology, the correct data set has to be identified. To ensure that the correct data are used, the two data sources are matched and evaluated, which is performed in the specific tool “Connect Compare”. A more detailed description of the individual functions of the tool can be found in section 5.5.4. In the presented project (cf. Fig. 87), the existing list-based data are compared with the CAD-based data transmitted by the customer. As soon as differences are detected between the two data sources, the CAD-based data are processed further manually by internal CAD engineers. In this comparison procedure, an experienced CAD engineer makes the final selection in the event of errors. Subsequently, the two data files are combined into one that can be used further in the internal CAD environment. Usually, this comparison process is only applied for the first transmission of the customer data (so this path is displayed dash-dotted in Fig. 87), since from here on, the remaining CAD-based data are proceeded in the internally CAD environment. The developed native CAD-based joining technology data can then be directly converted into an xMCF file by using the tool “Joining Converter” or “JoiningTec”.

Since the first step, data retrieval from the external source and data evaluation and processing, is now completed, the rest of the data, including geometry and joining technology data, are created internally. During the development project, the internally generated data are transferred back to the external environment using the two involved PDMS. This means that CAD data are also made available to the customer in native form to enable the customer usage of the native CAD files in their own environment for further engineering processes. Since standard parts are also used in BIW development, these can be adopted directly by the standard part supplier in form of 3D-CAD models. Typically, standard parts are welding studs, bolts and screws. Due to the fact that standard parts are not created in the internal CAD environment, they are just inserted into the internal CAD environment and cannot be exported by using the tool “JoiningTec”. Therefore, the tool “Fastener Exporter” (cf. section 5.5.2) is applied. This tool offers the possibility to export standard parts in xMCF format to provide the corresponding information in the target CAx environment.

Since all joining technology data are now available in the appropriate data formats, the native geometry data (3D-CAD models) is converted. The tool “JT Converter” is used for this conversion process. After that, the entire file set, including joining technology data and geometry data, is transferred to the target CAx environments. The advantageous capability of the new approach of an optimized data exchange process to process different data sources as well as data formats, allows for the highly diverse Type II projects to transfer data from the participating CAD environments into the internal target CAx environments. In this way, the gap in the data exchange process between two parties of the automotive industry is closed in an effective way. In addition to an appropriate data quality that can be provided to the target CAx environment, multiple data sources are able to be handled by the new approach.

6.3. Application of the Approach in Type III Projects

Fig. 88 shows the application of the optimized data exchange process in a Type III project. Type III projects offer a high degree of leeway in the creation and transfer of CAD-based data between different CAx environments. On the one hand, this freedom means that the customer defines no or just a few specifications regarding management, creation, administration and exchange of the corresponding engineering data. On the other hand, it also means that the automotive supplier must be able to provide their own processes, including methods, systems and tools required for the creation, management and exchange of data. Today, Type III projects mainly occur in cooperative projects with OEM start-up companies that do not have their own systems, processes or methods yet. Another possibility for the application of Type III projects is that an OEM completely outsources an engineering project because of economic or resources-based reasons. In any case, the complete data generation takes place in the internal CAD environment of the supplier company.

In Type III projects, in most cases, it is usual not to make the internally generated CAD-based data available to the customers and external environments. Since these are so-called “internal projects” in which the entire workload and workflow is managed and handled in the company, the application of an optimized data exchange process is always performed in the same structure. This means that a commercial standard CAD tool (e.g. CATIA V5, Siemens NX) is used for the creation of all geometry data model sets. The creation of the corresponding joining technology data can be conducted in two ways. In case that standard parts (mostly fasteners, e.g. bolts, screws) are applied, the 3D-CAD model of the standard parts provided by the standard part suppliers are used. These standard parts are then exported in xMCF and xlsx format using the tool “Fastener Exporter” (cf. section 5.5.2). The second possibility to create joining technology data is by using the tool “JoiningTec”, which is embedded in the CAD environment. This tool not only generates the joining technology data but also administrates the created joining technology elements.

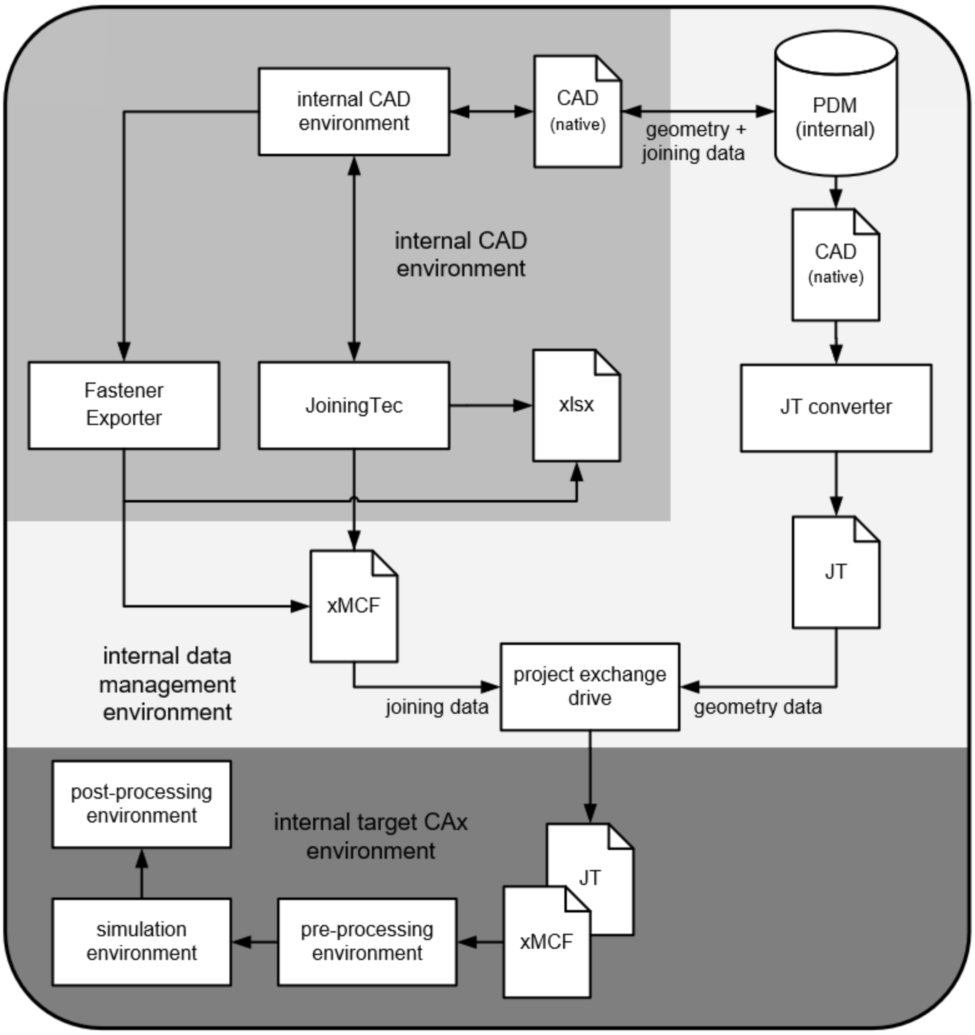


Fig. 88 - Application of the optimized data exchange process in Type III projects

Besides the creation and administration of joining technology data, the tool “JoiningTec” also offers the option of exporting joining technology data in both, xMCF and xlsx format. The data exported as xMCF format are used in the target CAx environments for further simulation steps, while the joining technology data exported as xlsx format is used for discussions with the suppliers of standard parts.

The geometry data are transferred from the CAD environment to the internal PDM environment. There, neutral JT geometry data files are generated from the existing native 3D-CAD geometry data. This conversion process is conducted at a certain time interval, usually shortly before a new simulation loop starts, as determined by milestones, c.f. section 2.3.3. The neutral JT files are, in turn, transmitted to the project exchange drive. From there, the simulation engineers can access the JT and xMCF data files for all further processes in the target CAx environment. After the pre-processing and simulation steps are finished, the simulation results are evaluated by the CAE and CAM simulation engineers in cooperation with CAD engineers. The resulting suggestions for improvement are incorporated back into the 3D-CAD model.

In summary, it can be stated that the optimized data exchange process approach provides all the methods, systems and tools necessary for the execution of internal Type III projects. This has the advantage that there is no dependency on external project partners, e.g. OEMs, with regard to tools, methods and processes. The introduced tailor-made tools, as well as the specific data exchange process for the internal exchange between different CAx environments can also be used in other projects (Type I, Type II), or in other external development projects. Since the procedure for creating and exchanging data in internal projects is always the same, the introduced optimized data exchange process offers an effective way to make required engineering data available to external suppliers and customers, involved in development projects.

7. Discussion of Results

The last chapter of this thesis gives an overview of the research findings and summarizes different aspects of engineering data exchange processes. Furthermore, benefits of the introduced optimized procedure are presented, including a delimitation from existing data exchange processes in the automotive industry. Finally, an outlook is given to further potentials of optimized data exchange, integrating various computer-aided engineering disciplines.

7.1. Summary

Constantly changing boundary conditions in the automotive industry as well as increasing requirements imposed in the automobile sector call for the development and implementation of new technologies, strategies and methods. Customization and optimization of automotive product development play a central role in this respect. In this context, the present thesis deals with the optimization of data exchange in the field of body design and the associated joining technology. The introduced optimized data exchange process pursues the goal of exchanging geometry and joining technology data between several computer-aided engineering environments in an efficient way.

To achieve this goal, processes and methods are introduced with the target to support the data exchange process by appropriate measures, like tailor-made tools and efficient data exchange file formats. One challenge was to design the optimized data exchange processes in such a flexible way that they are applicable in different types of automotive projects. In this thesis, the transfer of joining technology data in a different section of bodywork development is divided into an exchange of geometry data and an exchange of metadata, so-called joining technology data. With regard to geometry data exchange, the different boundary conditions require a consideration of exchange formats, including native CAD files as well as neutral data formats.

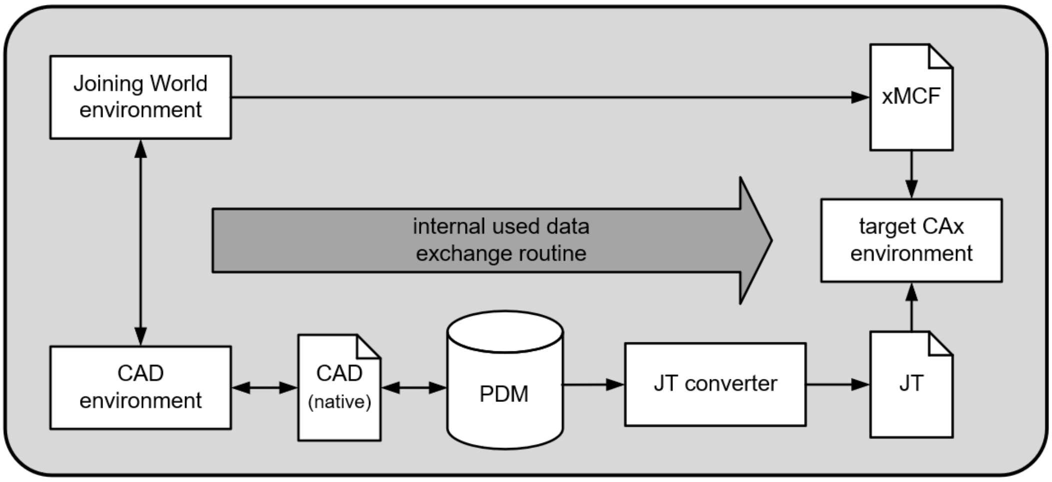


Fig. 89 - Company internal used data exchange routine

For the exchange of non-geometry joining technology data, the exchange processes with regard to file formats are more complex. In general, there are two main options how joining technology data can be exchanged. The first option is by using native CAD-based files, while the second and more common option is to exchange joining technology data in list-based file formats. Each of these data formats, geometry- and list-based formats, offer certain advantages and disadvantages. For data exchange between company-internal environments, the two neutral file formats JT (for geometry data exchange) and xMCF (for joining technology data exchange) have been chosen (c.f. Fig. 89). For data exchange with external environments, different formats come to use due to missing unique standards in this field.

In addition to the variety of different file formats involved, the introduced approach ensures that the complete data sets for both geometry data and joining technology data are available. In case that data are provided by external sources, specific data evaluation and conversion methods are introduced to ensure proper processability in the internal target environments – especially in view of data file formats and data structures. In the case of internal data sources, a flexible data exchange process provides effective transfer and conversion according to the requirements of the involved external target environments. For both cases, the application of different tailor-made tools in the optimized data exchange process guarantees a correct procedure.

The introduced tools are summarized in the software workbench “Joining World” and support the optimized data exchange process. Since different software tools for the creation and administration of geometry data are available from the shelf, the main focus of the present work was put on specific requirements of joining technology metadata. In this way, externally created joining technology data in any form (e.g. list-based formats or native CAD-based file formats) is converted into the internally required file formats. With the tool “Joining Converter” it is possible to bi-directionally convert native CAD-based, list-based or xMCF files. The “Fastener Exporter” is used for the export of joining technology data in xMCF format in projects, in which standard parts are used. The tool “Connect Compare” is used in the case that the customer provides joining technology data in two different data sources (e.g. native CAD-based files as well as in list-based files) to check both data sources and detect any kind of deviations.

In summary, all these tools are integrated into the introduced optimized data exchange processes to support the creation, administration and export of joining technology data. The application of the introduced methodology is shown by selected use cases from the automotive industry. In the meantime, the optimized data exchange process, including all tools and methods, has been implemented successfully at an automotive Tier 1 engineering and production supplier company.

7.2. Benefits and Delimitation of the Introduced Approach

The introduced optimized data exchange process is based on requirements of industrial development processes in the automotive industry. For this reason, industry-specific insights are considered in the development of the presented methods, strategies and tools. One important improvement achieved by the optimized data exchange process represents the saving-potentials in the fields of time, costs and man-hours. Firstly, the effort for manual conversion tasks, e.g. import of externally created data, conversion of native data into neutral file formats, has been reduced significantly. This results in lower data processing time and thus in cost reductions as well as shorter project cycle durations. Finally, the elaborated data exchange process provides improved data quality and reduced data quantity at the same time. The focus on two exchange formats (JT and xMCF) instead of a variety of different data formats reduces data format variety and delivers standardized data structures, which exactly correspond to the requirements of the involved target CAx environments. In this way, the pre-processing effort in the corresponding CAx environment is reduced significantly.

To express the improvement potential in figures exemplary, a reduction of preparation time of about one week for each simulation loop is achieved, which corresponds with about 25% of the duration of one simulation loop. A typical automotive body development project involves six simulation loops – in this way, the reduction of project time covers around six weeks in a vehicle development process. It should be stated, that this reduction is only based on the improved management and exchange of joining technology data.

This time, there are no standards defined for the data exchange of joining technology in automotive body development. This work provides an approach to close this gap by introducing a customized data exchange process that enables the exchange of joining technology data by the use of interfaces that are based on the neutral geometry format JT in combination with neutral list format xMCF. The data exchange process is designed flexible and involves specifically developed tools, so that the different boundary conditions, such as exchange formats, data structures, etc., can be handled comprehensively. In this context, the presented optimized data exchange process provides a good starting point for integration of enhanced KBE (Knowledge-Based Engineering) methods and design automation into the automotive body development process.

Delimitations of the research of the present work include aspects of integration of the findings into an actual industrial environment. Although industrial boundary conditions are considered in the development of the methods and tools, the application in actual automotive development projects has to consider the specific boundary conditions. This refers in particular to the tailor-made interfaces for the data exchange process with external environments. Different data external sources may require an extension or re-definition of the applied interface structure. In particular the following data source formats have been considered in actual version of the tools: CATIA V5 native, NX native, neutral JT, XML, xMCF and Excel-list. The specific software tools developed and implemented in the present works are fully applicable to CATIA V5 release 19-28 [24] and NX versions 8.0-11.0 [111]. If the tools should be used in different releases or CAD software, corresponding modification and testing are recommended.

7.3. Conclusion

Due to increasing globalization and competition in the automotive industry, it is becoming important to optimize the processes in every field of automotive engineering. This applies both to the entire development of vehicles as well as to specific engineering processes that involve computer-aided tools and their data environments. Because different computer-aided tools are incorporated, efficient exchange of data plays an important role in process optimization. In automotive body development, joining technology became increasingly important during the past decades due to an intensified application of new materials and material combinations. In addition, the development of joining technology explicitly involves different computer-aided tools and thus extensive data transfer. In this way, the optimization of the data exchange process of joining technology provides a considerable potential for improvement. One main issue influencing these exchange processes includes the different exchange strategies applied by car manufacturers and engineering suppliers. In this way, a variety of development methods, data formats, systems and tools must be integrated for different types of development projects.

The aim of the present research was to close the gap in management of joining technology data, so that a tailored data exchange process can be applied to all involved project partners. This goal is achieved by an optimization of existing data exchange processes to meet different customer requirements and the integration of tailor-made tools, which are flexible so that they can easily be adapted to the rapidly changing boundary conditions. In summary, it can be stated that the approach presented can be applied to different automotive bodywork development processes, while integrating car manufacturer and engineering supplier in an effective way. Within the scope of this thesis, a tailor-made approach for a data exchange process has been developed, which focuses on joining technology data. Furthermore, existing gaps in the exchange of joining technology data are closed and an optimization of automotive development processes is initiated.

Annex

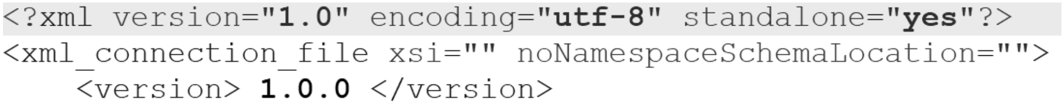
A.1. Structure of xMCF

The xMCF [29] file format, which is based on the XML [91] standard, is a standard for describing connections and joints in the automotive industry. Since it is a file format for the exchange of joining technology data, the structure is described in more detail here. In particular, the industry partner-specific structuring of the data exchange format is taken into account. In general, xMCF files contain the following scope:

- Header
- Area of “Connection group”
- Area of “Connected to”
- Area of “Connection list”

<u>Header</u>

The header is placed at the beginning of each XML file and includes some general information (e.g. XML version, encoding, version of exported data) related to the exported XML version. In addition, the tag <xml_connection_file xsi=““ noNamespaceSchemaLocation=““> serves as starting point of the file and includes the three areas of “Connection group”, “Connected to” and “Connection list”.

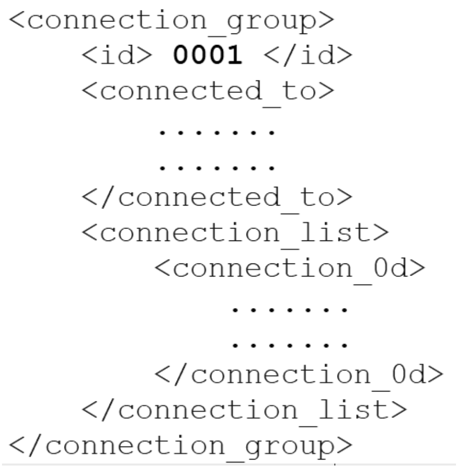


```
<?xml version="1.0" encoding="utf-8" standalone="yes"?>
<xml_connection_file xsi="" noNamespaceSchemaLocation="">
    <version> 1.0.0 </version>
```

Fig. 90 - “Header” structure of xMCF files

<u>Area of “Connection group”</u>

The tag <connection_group> contains the ID of the connection group, the area of “Connected to” and the area of “Connection list”. The ID is a consecutive number that increases with each new “connection group”. This section is closed by the tag </connection_group>.

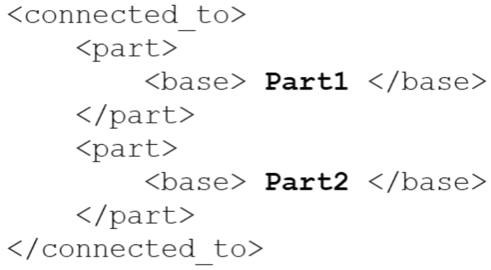


```
<connection_group>
    <id> 0001 </id>
    <connected_to>
        .......
        .......
    </connected_to>
    <connection_list>
        <connection_0d>
            .......
            .......
        </connection_0d>
    </connection_list>
</connection_group>
```

Fig. 91 - “Connection group” structure of xMCF files

Area of “Connection to”

The tag <connected_to> serves as the basis for all information of the connected sheets of one or more joining technology elements. This section contains all parts/sheets (e.g. Part1 and Part2) which are displayed with the tag <base> and is closed by the tag </connected_to>.

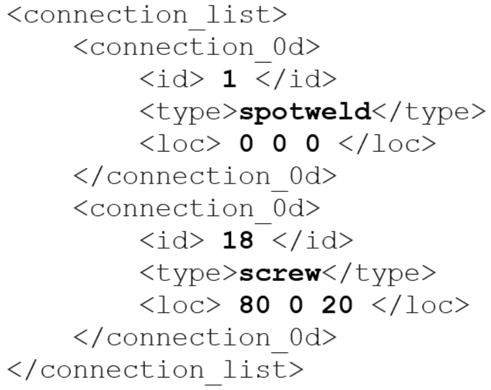


```
<connected_to>
    <part>
        <base> Part1 </base>
    </part>
    <part>
        <base> Part2 </base>
    </part>
</connected_to>
```

Fig. 92 - “Connection to” structure of xMCF files

Area of “Connection list”

The tag <connection_list> is used to transmit all information (e.g. location, id, type, additional parameters, e.g. diameter) related to the joining elements. Therefore, it does not matter if the joining element is a 0D-, 1D- or 2D-element. Each joining element is displayed separately by using the tags <connection_0d>, <connection_1d> and <connection_2d>. Further information regarding these three tags, is given in section A.3 of this annex. “Connection list” is closed by using the tag </connection_list>.



```
<connection_list>
    <connection_0d>
        <id> 1 </id>
        <type>spotweld</type>
        <loc> 0 0 0 </loc>
    </connection_0d>
    <connection_0d>
        <id> 18 </id>
        <type>screw</type>
        <loc> 80 0 20 </loc>
    </connection_0d>
</connection_list>
```

Fig. 93 - “Connection list” structure of xMCF files

A.2. xMCF-based Parameters of Joining Technology Elements

This section shows an excerpt of parameters of the most important types of joining technologies that are used in the automotive industry and gives a short description.

Spot welds

Spot welds are defined by a coordinate vector (x, y and z) and a diameter. Additional parameters (e.g. welding technology) can be used optionally.

Parameters	*Examples*	*Description*
loc (location)	125.7 98.6 876.89	three floating-point values to describe x-, y- and z-coordinates
diameter	5.0	any floating-point value in mm, describes the diameter of the spot weld
technology	resistance, laser, friction, brazing	any string value that provides, additional information about the welding technology

Tab. 10 - Excerpt of xMCF parameters for spot welds, referring to [29]

Gum drops

Gum drops are defined by a coordinate vector (x, y and z) and a diameter. Additional parameters (e.g. mass and material) can be used optionally.

Parameters	*Examples*	*Description*
loc	125.7 98.6 876.89	three floating-point values to describe x-, y- and z-coordinates
diameter	5.0	any floating-point value in mm, describes the diameter of the glue point
mass	1.0	any floating-point value in gram, describes the mass of the attached glue
material	CAD-material XY	any string value, describes the material of the glue

Tab. 11 - Excerpt of xMCF parameters for gum drops, referring to [29]

Rivets

Rivets are defined by a coordinate vector (x, y and z). Additional parameters (e.g. normal direction, different diameters, length) can be used optionally.

Parameters	*Examples*	*Description*
loc	125.7 98.6 876.89	three floating-point values to describe x-, y- and z-coordinates
shaft_diameter	5.0	any floating-point value in mm, diameter of the shafts
length	25	any floating-point value in mm, unmounted length of the rivets
head_diameter	5.5	any floating-point value in mm, diameter of the head of the rivets
head_height	1.0	any floating-point value in mm, height of the head of the rivets
head_type	dome	any string value, distinguishes between the different head-types of rivets (e.g. dome, countersunk)
sink_size	0.2	any floating-point value in mm, size of the head that is sunk
part_code	B_R_001247	any string value, describes the part code of the rivet
blind self-piercing solid swop	0 or 1	distinguishes between the different sub-types of rivets, only one can be chosen
normal_direction	0.99 0.78 0.54	three floating-point values separated by one blank space to describe x-, y- and z-direction of the normal direction

Tab. 12 - Excerpt of xMCF parameters for rivets, referring to [29]

Depending on the chosen sub-type of rivet, there are some further parameters (cf. [29]) that can be used, e.g. min_grip, max_grip, clearance (for blind rivets) or hardness, head_label, shaft_label, die_label, die_diameter, die_depth (for SPR).

Clinches

Clinches are defined by a coordinate vector (x, y and z). Additional parameters (e.g. clinch type, button diameter, die type) can be used optionally.

Parameters	*Examples*	*Description*
loc	125.7 98.6 876.89	three floating-point values to describe x-, y-and z-coordinates
clinch_type	TOX	any string value that describes the clinch type (based on supplier clinch codes)
strength_class	HD (heavy duty), MD (medium duty)	any string value that describes the strength class
shear_strength	890	any floating-point value in Newton (N), peel strength is defined as the maximum force that occurs during the test process (shear)
peel_strength	356	any floating-point value in N, peel strength is defined as the maximum force that occurs during the test process (tension)
punch_diameter	5.5	any floating-point value that describes the punch diameter, Fig. 94 shows the punch diameter (BD)
die_type	round, rectangular	any string value that describes the die type

Tab. 13 - Excerpt of xMCF parameters for clinches, referring to [29]

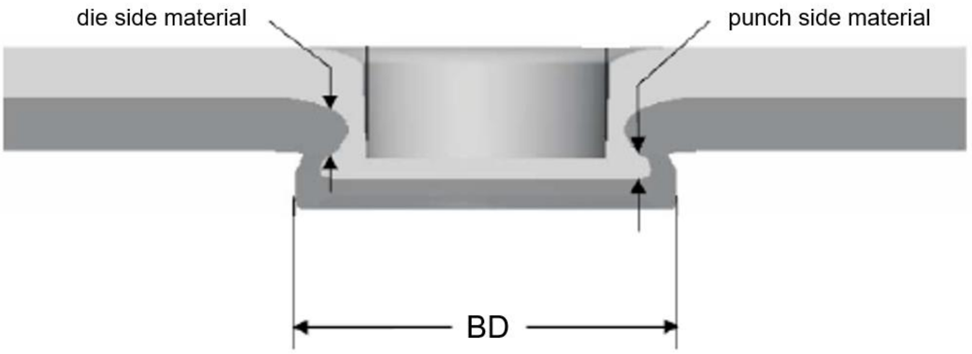


Fig. 94 - Clinch dimensions, referring to [29]

Bolts and screws

Bolts and screws are summarized in the xMCF standard. They are defined by using coordinates vectors (x-, y- and z-coordinates) and additional parameters can be optionally chosen.

Parameters	*Examples*	*Description*
loc	125.7 98.6 876.8	three floating-point values to describe x-, y- and z-coordinates
diameter	5.0	any floating-point value in mm
length	10.0	any floating-point value in mm, describes the length of the joining element
thread_length	5.0	any floating-point value in mm, describes the thread length of the joining element and must be smaller than the (total) length
head_diameter	5.0	any floating-point value in mm, describes the head diameter of the joining element
head_height	2.0	any floating-point value in mm, describes the head height of the joining element
head_type	hexagon	any string value in mm, describes the type of the head of the joining element
sink_size	0.5	any floating-point value in mm, size of the head that is sunk
pitch	0.1	any floating-point value in mm
lead	0.5	any floating-point value in mm, describes the distance along the axis of the joining element for one complete rotation
torque	4	any floating-point value in Nm, describes the maximum torque applied on the joining element during the fastening process
angle	30	any floating-point value in degrees, describes the maximum turning angle of the joining element during the fastening process
pretension	1.200	any floating-point value, describes the occurring pretension during the fastening process
static_friction kinetic_friction	0.8 0.5	any floating-point value, describes the static/kinetic friction between the joining element and the adjacent element
part_code	M10x50 12.9	any string value, describes the part code of the joining element, in most cases a unique code
normal_direction	0 0 1	three floating-point values separated by one blank space to describe x-, y- and z-direction of the normal direction
nut	0 or 1	0 or 1 to select if a nut is used
washer	0 or 1	0 or 1 to select if a washer is used

Tab. 14 - Excerpt of xMCF parameters for bolts and screws, referring to [29]

Due to the variety of different bolts and screws used in the automotive industry, various parameters are transferred. When the bolt or screw connection uses a washer or a nut, additional parameters can be chosen.

Parameters	*Examples*	*Description*
outer_diameter	10.0	any floating-point value in mm, describes the outer diameter of the washer
inner_diameter	3.0	any floating-point value in mm, describes the inner diameter of the washer
thickness	2.5	any floating-point value in mm, describes the thickness of the washer
attached	false, true	Boolean value (false and true), if the washer is directly connected to the joining element → true
static_friction, kinetic_friction	0.8	any floating-point value, describes the static/kinetic friction between the joining element and the washer or nut
height	2.0	any floating-point value in mm, describes the height of the nut
torque	4	any floating-point value in Nm, describes the maximum torque applied on the nut during the fastening process
angle	30	any floating-point value in degrees, describes the maximum turning angle of the nut during the fastening process
fixed to	bolt_02341	any string value, defines the fastener to which nut is attached
part code	M10x8.8	any string value, describes the part code of the washer or nut, in most cases a unique code

Tab. 15 - Excerpt of xMCF parameters for nuts and washers, referring to [29]

Clips

Clips are defined by a coordinate vector (x, y and z). Additional parameters (e.g. clinch type, button diameter, die type) can be used optionally.

Parameters	*Examples*	*Description*
loc	125.7 98.6 876.89	three floating-point values to describe x-, y- and z-coordinates
clip_type	Strap 5-45X8X.9-4.1 PNL".	any string value, describes the name of the clip (based on supplier clip codes)
attachment_type	push into round hole	any string value, describes how the clip is mounted
hole_diameter	5.0	any floating-point value in mm, describes the diameter of the hole into which the clip is pushed, 0.0 means no hole
hole_length	10.0	any floating-point value in mm, describes the length of the hole
pin_diameter	3.0	any floating-point value in mm, describes the diameter of the clip's pin
pin_width	5.0	any floating-point value in mm, necessary if the clip is pushed into a non-round hole
pin_length	3.0	any floating-point value in mm, describes the length of the clip's pin
clipped_to	Clip_00245	any string value, describes the element the clip is fastened to
material	polyamid	any string value, describes the material of the clip
normal_direction	0 1 0	three floating-point values separated by one blank space to describe x-, y- and z-direction of the normal direction
part_code	Clip_25x5_DK	any string value, describes the part code of the clip, in most cases a unique code

Tab. 16 - Excerpt of xMCF parameters for clips, referring to [29]

Besides to the parameters above, a distinction can be made as to which sub-type of clip is used, e.g.:

- Terry clip
- Hairpin clip
- R-clip
- Circlips

This information is transmitted in xMCF files by using the parameters respectively tags <label> or <info>.

Nails

Nails are defined by a coordinate vector (x, y and z). Additional parameters (e.g. clinch type, button diameter, die type) can be used optionally.

Parameters	*Examples*	*Description*
loc	125.7 98.6 876.89	three floating-point values to describe x-, y- and z-coordinates
nail_type	N344x33	any string value, describes the name of the nail (based on supplier nail codes)
shaft_diameter	5.0	any floating-point value in mm, describes the diameter of the shaft of the nail
length	10.0	any floating-point value in mm, describes the length of the joining element
cylinder_length	0.5	any floating-point value in mm, describes the length of the cylindrical part of the nail
head_diameter	3.0	any floating-point value in mm, describes the diameter of the head of the nail
head_length	2.0	any floating-point value in mm, describes the length of the head of the nail
shear_strength	5.2	any floating-point value in kN, peel strength is defined as the maximum force that occurs during the test process (shear)
peel_strength	5.0	any floating-point value in kN, peel strength is defined as the maximum force that occurs during the test process (tension)
material	aluminum 6xxx	any string value, describes the material of the nail
normal_direction	0.997 0.543 0.973	three floating-point values separated by one blank space to describe x-, y- and z-direction of the normal direction of the nail
part_code	N344x33	any string value, describes the part code of the nail, in most cases a unique code

Tab. 17 - Excerpt of xMCF parameters for nails, referring to [29]

Seam welds

Since the weld seam is a linear joining technology, it is discretized into several points to be clearly described in the xMCF format. This means that it is necessary that more than one coordinate vector is known. The coordinate vectors are summarized to a list, which represents the minimum information that must be known to define a seam weld. All other parameters can be provided optionally in xMCF files.

Parameters	*Examples*	*Description*
loc	125.7 98.6 876.89	three floating-point values to describe x-, y- and z-coordinates
loc_list	loc1, loc2, loc3	summarizes all loc parameters, describes the curve progression of the seam weld
height	2.0	any floating-point value in mm, describes the height of the seam weld
width	3.0	any floating-point value in mm, describes the width of the seam weld
technology	resistance welding, arc welding, friction welding, brazing	any additional information regarding the welding technology

Tab. 18 - Excerpt of xMCF parameters for seam welds, referring to [29]

Adhesive lines

Since this is a linear joining technology type, the curve is divided into several points, so that the adhesive line can be defined in xMCF format.

Parameters	*Examples*	*Description*
loc	125.7 98.6 876.89	three floating-point values to describe x-, y- and z-coordinates
loc_list	loc1, loc2, loc3	summarizes all loc parameters, describes the curve of the adhesive line
width	2.0	any floating-point value in mm, describes the width of the adhesive line
thickness	5.0	any floating-point value in mm, describes the thickness of the adhesive line
material	CAD-material XY	any string value, describes the material of the glue

Tab. 19 - Excerpt of xMCF parameters for adhesive lines, referring to [29]

Adhesive surfaces

Besides the element “loc”, the adhesive surfaces need an additional list “faces” to define the joining element. This means that xMCF file includes “loc”, “loc_list”, “face” and “face_list” as well as all other optional parameter.

Parameters	*Examples*	*Description*
loc	125.7 98.6 876.89	three floating-point values to describe x-, y- and z-coordinates
loc_list	loc1, loc2, loc3	summarizes all loc parameters, describes all points of the adhesive surface
face	0, 1, 2, 4	four integer values, describes a square in the order in which the numbers appear.
face_list	face1, face2, face3	summarizes all face parameters, describes all faces of the adhesive surface
thickness	2.0	any floating-point value in mm, describes the thickness of the attached adhesive
material	CAD-material XY	any string value, describes the material of the glue

Tab. 20 - Excerpt of xMCF parameters for adhesive surfaces, referring to [29]

A.3. Examples of xMCF files

This section shows examples of how data of different joining technology elements can be transmitted in xMCF files.

Example 1 – Spot weld and adhesive line connecting two sheets

In this case, the two sheets “CVT0000002” and “CVT0000003” are connected by one spot weld and one adhesive line. The ID of the “Connection group” is “0025”, the ID of the spot weld is “1” and the ID of the adhesive line is “2”.

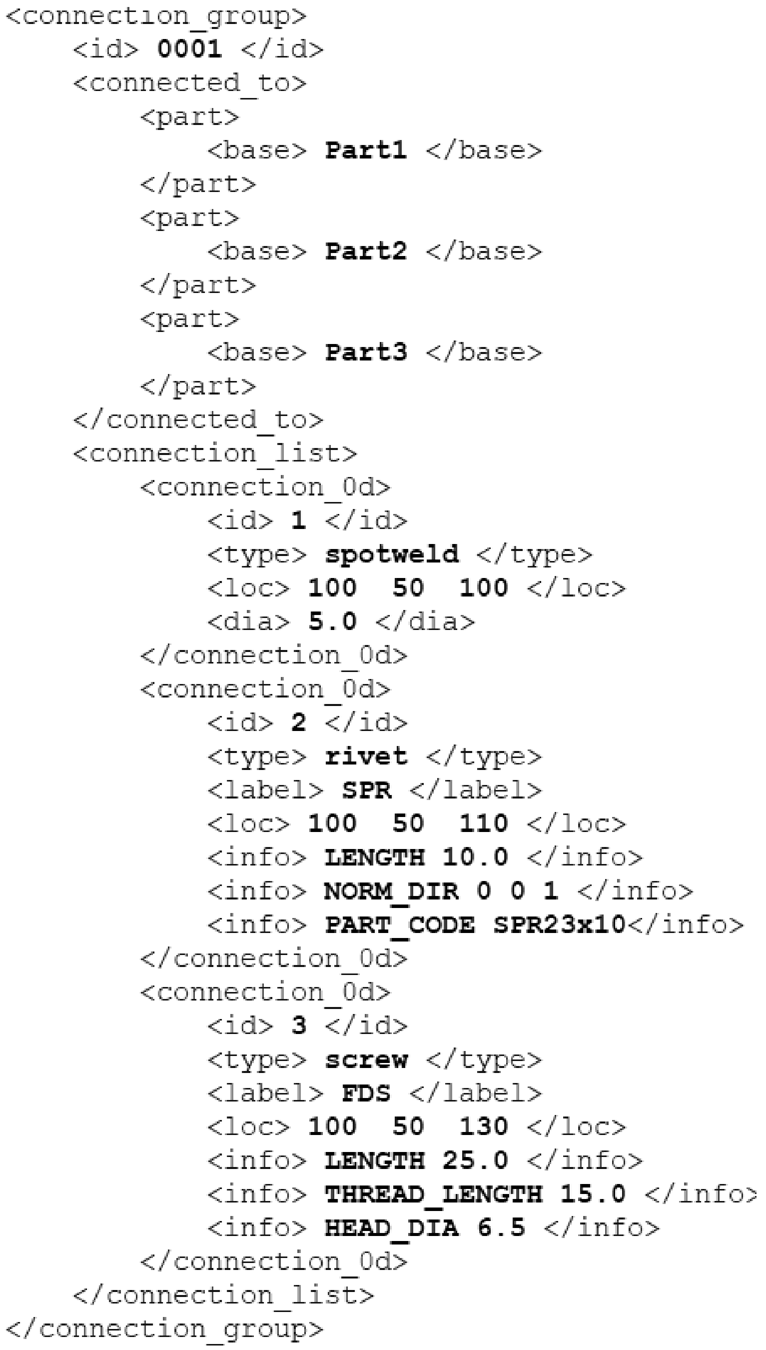
```
<connection_group>
    <id> 0025 </id>
    <connected_to>
        <part>
            <base> CVT0000002 </base>
        </part>
        <part>
            <base> CVT0000003 </base>
        </part>
    </connected_to>
    <connection_list>
        <connection_0d>
            <id> 1 </id>
            <type> spotweld </type>
            <loc> 3982.344 672.774 351.601 </loc>
            <dia> 5.0 </dia>
        </connection_0d>
        <connection_1d>
            <id> 2 </id>
            <type> adhesive </type>
            <loc_list>
                <loc> 3992.344 672.774 351.601 </loc>
                <loc> 3992.344 682.774 351.601 </loc>
                <loc> 3992.344 692.774 351.601 </loc>
                <loc> 3992.344 702.774 351.601 </loc>
            </loc_list>
            <info> WIDTH 10.0 </info>
            <info> HEIGHT 2.0 </info>
        </connection_1d>
    </connection_list>
</connection_group>
```

Fig. 95 - Example of connecting two sheets by one spot weld and one adhesive line

The spot weld connection has a diameter of 5.0 mm and is located at the above shown coordinates (<loc>). The adhesive line is discretized in four points. Therefore, four coordinate vectors are necessary to determine the location. Additionally, the width (10.0mm) and height (2.0mm) of the adhesive line is transmitted.

Example 2 – Several 0D-elements connecting three sheets

Example 2 displays a three-sheet connection (“Part1”, “Part2” and “Part3”) by using several 0D-joining elements (one spot weld, one rivet and one screw) for the joining process.



```
<connection_group>
    <id> 0001 </id>
    <connected_to>
        <part>
            <base> Part1 </base>
        </part>
        <part>
            <base> Part2 </base>
        </part>
        <part>
            <base> Part3 </base>
        </part>
    </connected_to>
    <connection_list>
        <connection_0d>
            <id> 1 </id>
            <type> spotweld </type>
            <loc> 100  50  100 </loc>
            <dia> 5.0 </dia>
        </connection_0d>
        <connection_0d>
            <id> 2 </id>
            <type> rivet </type>
            <label> SPR </label>
            <loc> 100  50  110 </loc>
            <info> LENGTH 10.0 </info>
            <info> NORM_DIR 0 0 1 </info>
            <info> PART_CODE SPR23x10</info>
        </connection_0d>
        <connection_0d>
            <id> 3 </id>
            <type> screw </type>
            <label> FDS </label>
            <loc> 100  50  130 </loc>
            <info> LENGTH 25.0 </info>
            <info> THREAD_LENGTH 15.0 </info>
            <info> HEAD_DIA 6.5 </info>
        </connection_0d>
    </connection_list>
</connection_group>
```

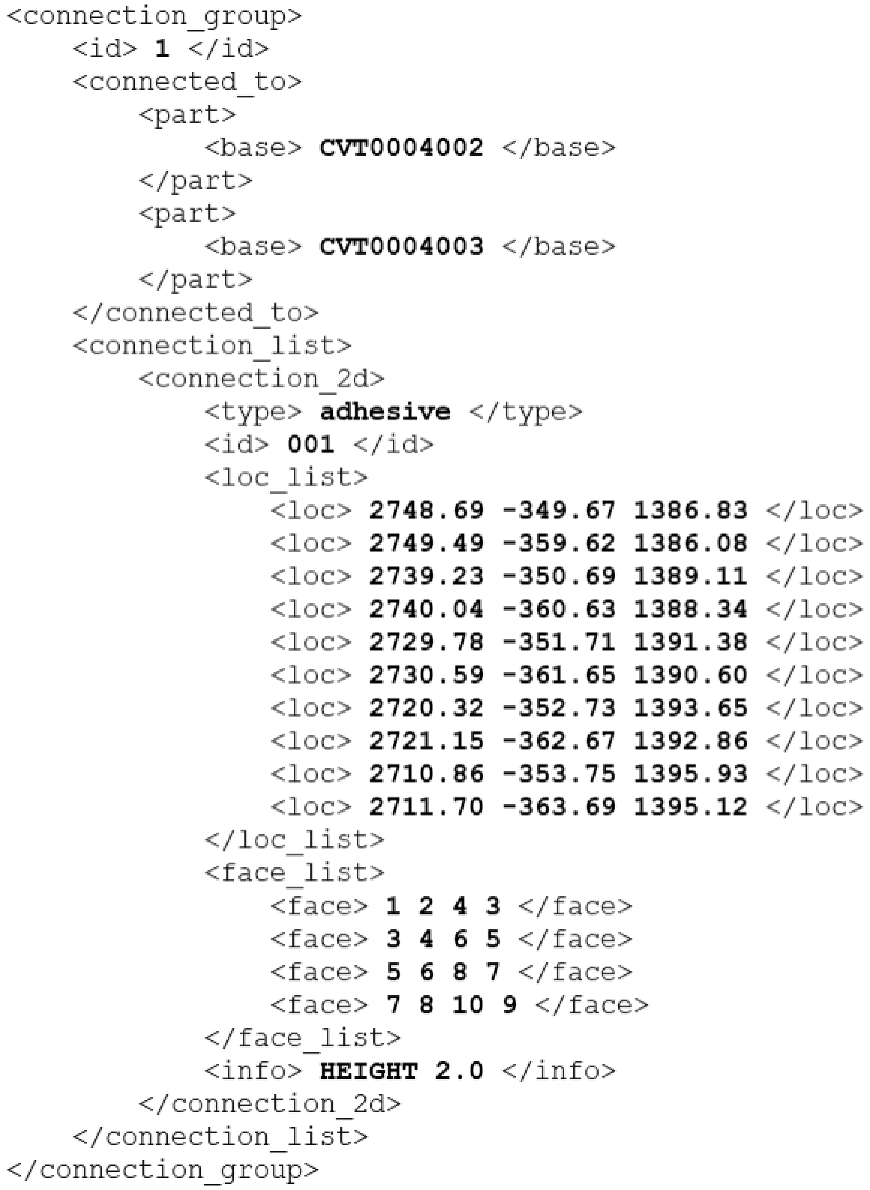
Fig. 96 - Example of connecting three sheets by several 0D-joining elements

The spot weld is defined by a coordinate vector and a diameter. In this case, the diameter is 5.0 mm. On the other hand, the two joining elements, rivet and screw, need more information to be fully defined. Fig. 96 shows that both, the rivet and screw, use the tag <label> to transmit the sub-type information. The rivet, in more detail SPR, has a length of 10.0 mm, is located at the above-mentioned coordinates and has a normal direction, which is displayed by using the tag <info>. Furthermore, the part code is provided, which identifies the SPR uniquely. The third element is a FDS (Flow Drill Screw) which is more precisely described by the three info tags.

The used FDS has a length of 25.0 mm, a thread length of 15.0 mm and a head diameter of 6.5 mm. This information is sufficient to clearly describe the FDS.

Example 3 – Adhesive Surface connecting two sheets

This example shows the connection of the two sheets “CVT0004002” and “CVT0004003” by using a 2D-element. The type of the 2D-joining element is an adhesive with the ID “001”.



```
<connection_group>
    <id> 1 </id>
    <connected_to>
        <part>
            <base> CVT0004002 </base>
        </part>
        <part>
            <base> CVT0004003 </base>
        </part>
    </connected_to>
    <connection_list>
        <connection_2d>
            <type> adhesive </type>
            <id> 001 </id>
            <loc_list>
                <loc> 2748.69 -349.67 1386.83 </loc>
                <loc> 2749.49 -359.62 1386.08 </loc>
                <loc> 2739.23 -350.69 1389.11 </loc>
                <loc> 2740.04 -360.63 1388.34 </loc>
                <loc> 2729.78 -351.71 1391.38 </loc>
                <loc> 2730.59 -361.65 1390.60 </loc>
                <loc> 2720.32 -352.73 1393.65 </loc>
                <loc> 2721.15 -362.67 1392.86 </loc>
                <loc> 2710.86 -353.75 1395.93 </loc>
                <loc> 2711.70 -363.69 1395.12 </loc>
            </loc_list>
            <face_list>
                <face> 1 2 4 3 </face>
                <face> 3 4 6 5 </face>
                <face> 5 6 8 7 </face>
                <face> 7 8 10 9 </face>
            </face_list>
            <info> HEIGHT 2.0 </info>
        </connection_2d>
    </connection_list>
</connection_group>
```

Fig. 97 - Example of connecting two sheets by one adhesive surface

The special thing about 2D-elements is that in addition to the coordinate vectors, faces are used to define the joining element. Fig. 97, shows ten coordinate vectors, which symbolize the ten discretized points. The faces are necessary to get the information about how these points are connected (e.g. four faces mean four rectangular connections). Besides locations and faces, the additional parameter “height” is transferred.

A.4. Structure of JT

The file format JT is widely used in the automotive industry for the exchange of geometry data. It offers various possibilities to transfer either exact forms of geometry (BREP) or tessellated geometry (different LODs) and additional information, e.g. PMI. The range of possible settings is also visible in the structure (c.f. Fig. 98.) of the JT file format. These different setting options are explained below.

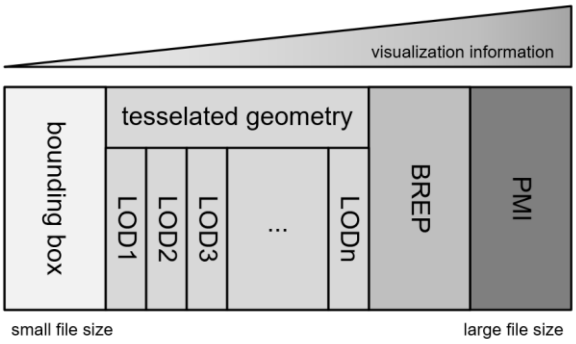


Fig. 98 - Structure of JT

Bounding boxes:

Bounding boxes deliver a coarse geometry description. They use the smallest possible box in which all the objects fit in. This can be used to show a rough depiction of the extension of the geometrical bodies (cf. Fig. 99). The dimension for the size of the bounding box are the maximum width, height and depth, for displaying 3D-objects. The significant advantage of using this method is that the file size can be kept very small, but the visualization information is limited. In Fig. 99 a bounding box is displayed by a 3D-cuboid [116].

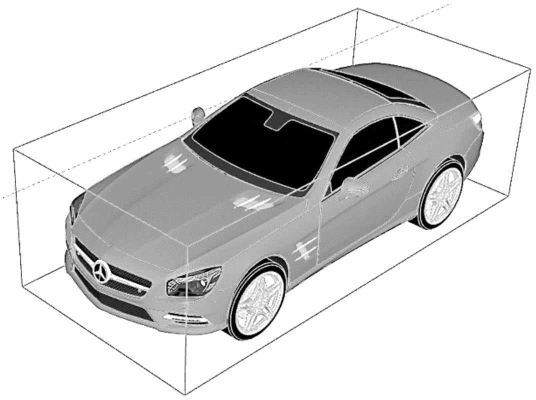


Fig. 99 - Bounding box exemplary shown on a vehicle [116]

Tessellated geometry:

A more precise way to display and exchange geometry information, is the use of tessellated triangles, especially if several LODs are included. Normally, three different LODs are used in the standard settings of JT files. Between these three levels, a distinction is made by a rough, middle and high resolution. This has the advantage, especially for viewing operations, that interesting areas (e.g. all objects in the foreground) get a high resolution and less important areas get a lower resolution (e.g. background information). As mentioned, the resolution of the LODs is changeable. This can be done by a variety of settings, which are shown in Tab. 21.

Settings	*Level 1*	*Level 2*	*Level 3*
Label	DMU fine	DMU	Factory
Chordal [mm]	0.22	0.6	3.0
Angular [°]	28	52	0
Length [mm]	0	0	0
Feature suppression [mm]	0	0	0.5
Simplify	1	1	0.4

Tab. 21 - Exemplary LOD settings

The example in Tab. 21 includes a JT file with three different LODs. The first LOD “DMU fine” is rather accurate (maximum chordal distance of 0.22 mm and maximum angle of 28°), the second one “DMU” has a middle accuracy (maximum chordal distance of 0.6 mm and maximum angle of 52°) and third one “Factory” a rough resolution (maximum chordal distance of 3 mm and no specification about the maximum angle between two lines). In this example, the first LOD is used for DMU activities, e.g. space analyses. The third LOD is used for those types of factory planning, which do not require accurate resolution. This statement can also be illustrated in the setting options “Chordal”, “Angular”, “Length”, “Feature Suppression” and “Simplify” which are shown in Fig. 100.

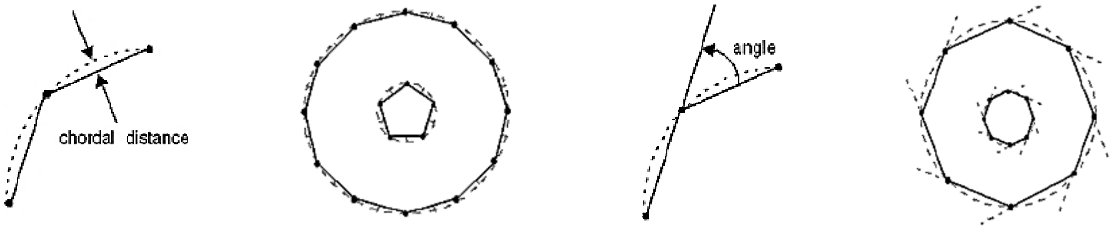


Fig. 100 - Explanation of the LOD settings “chordal” and “angular” [112]

The maximum deviation between the original object (circle) and the tessellated element is referred to as “Chordal” and the maximum angular deviation between them is referred to as “Angular”. The larger these two values are defined in Tab. 21, the rougher the resolution. The same statement is valid for the “Length”, which represents the maximal length of a tessellated line. If any adjusted value is 0, it is not considered. The setting “Feature Suppression” suppresses all holes and arcs that are smaller than the selected value.

For example, the value in the third column is 0.5, which means that all curves that have a radius smaller than 0.5 mm are suppressed. The last presented setting option “Simplify”, means that the number of tessellated surfaces related to the first LOD is reduced down to 40% in the shown example. (e.g. the value 0.4 in column three means that if there are 100 triangles in LOD 1, LOD 3 uses a maximum of 40 triangles). These are some settings to limit the LODs but depending on the tool used to create the JT, there may be several more. It has to be considered that LODs are based on non-exact geometry and deviations are accepted for smaller file size.

BREP:

Another way to describe geometry in JT format is offered by BREP, which represents a mathematical approximation of the exact geometry (c.f. section 4.4.2). When BREP is used, the file size increases in addition to the higher quality of visualization-related information.

PMI and attributes:
The last component of the JT structure are the so-called PMI and attributes. PMIs deliver production-relevant information, like tolerances, annotations, surface finish, geometric dimensions. Attributes are containing physical properties like material information or density [20]. However, using the PMIs increases the file size.

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