Chapter 1
Automotive Development Processes

Product development in the automotive industry is driven by a highly complex series of market requirements that stem from a wide range of product variants and functionalities. Stagnating sales volumes in traditional markets and increased competition are leading to both growing product diversification and reduced time-to-market processes. Furthermore, the industrial globalization of development, manufacturing and distribution has resulted in new business models, which must consider several market-specific factors. Changes in boundary conditions, resulting from both legislation and customer orientation, and a growing realization of the finite nature of crude oil supplies are spurring a reorientation of individual mobility and a continuous introduction of new vehicle concepts. In order to develop lighter, more efficient cars driven by alternative propulsion technologies, common vehicle concepts will need to be revised and completely new vehicle architecture and styling solutions will need to be introduced. At the same time, increasing customer demands in terms of safety, comfort and fashion trends are driving the creation and implementation of new technologies. This technical evolution necessitates a reduction of investment risks throughout the entire product life cycle, which makes it essential to consider factors related to production, market conditions, and disposal throughout the entire development cycle.

Development processes in the automotive industry place high demands on the performance and flexibility of the development strategies and tools applied. Besides the standard prerequisites (e.g. design, simulation and production engineering), a number of enhanced requirements will present new challenges to the architects of future development cycles. Within the boundaries of a permanent cost and time reduction in engineering-based development, new strategies must support a smart connection between the working fields of project engineers, component designers, ergonomic specialists, safety and crash departments, designers and all other involved parties. These days, automotive development is driven by the interaction of virtual design and simulation methods in combination with physical development and testing procedures (Fig. 1.1). The trend is definitely going towards integrated virtual development processes which focus on the product function itself, but also take into account both the production and supplier situations, as well as lifetime-relevant factors that pertain

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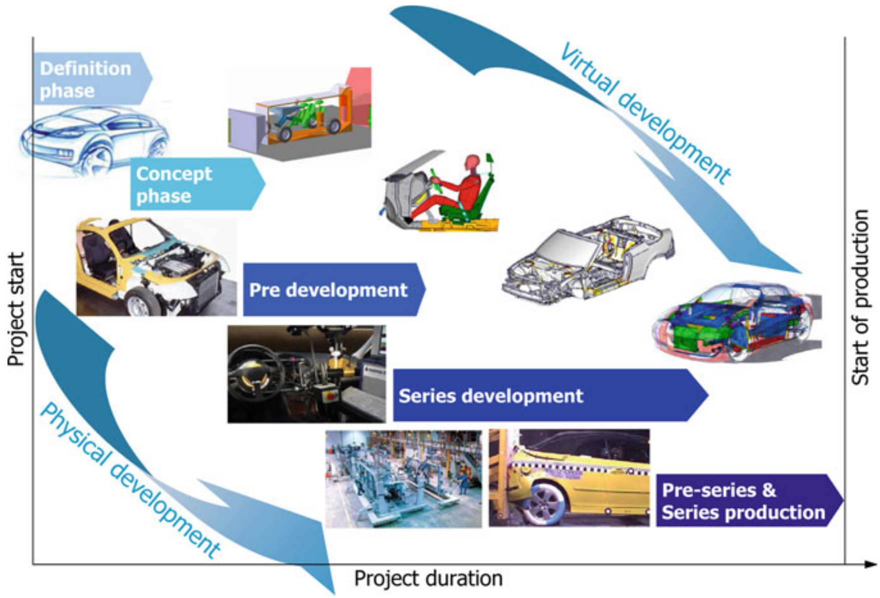

Fig. 1.1 Sample phases of an automotive full-vehicle development process [1]

to customer use, support, service and disposal. The increasing application of virtual methods is taking over several tasks formerly handled by physical development, where the focus is now shifting to data acquisition and verification procedures. This has led to a significant reduction in hardware-based test and prototype development in the last decades.

The manifold variants and characteristics of automotive products present a challenge for the entire development process chain. Unlike the limited model ranges that were typical in the mid twentieth century, the current range of personal automobiles is segmented into a wide variety of different vehicle categories, classes and configurations. New car types (e.g. MPV-multipurpose vehicles, SUV-sport utility vehicles), new body configurations (e.g. hatchback, roadster, coupe-convertible) and the development of new engine and transmission systems (e.g. supercharged gasoline and diesel engines, hybrid and electric drive, automatic transmissions, double clutch transmissions) have resulted in a significant increase in product variants and data. Besides the variety of car types, propulsion systems and chassis configurations, wide-ranging options for supplementary equipment have led to nearly endless product variations, which is good for the customers, but presents a challenge for data management in product development and throughout the product life cycle. At the same time, the development time for new automotive models has decreased from about seven years in the 1960s to about two years today (Fig. 1.2). This considerable reduction in development time has been significantly supported by virtual design, simulation and testing methods.

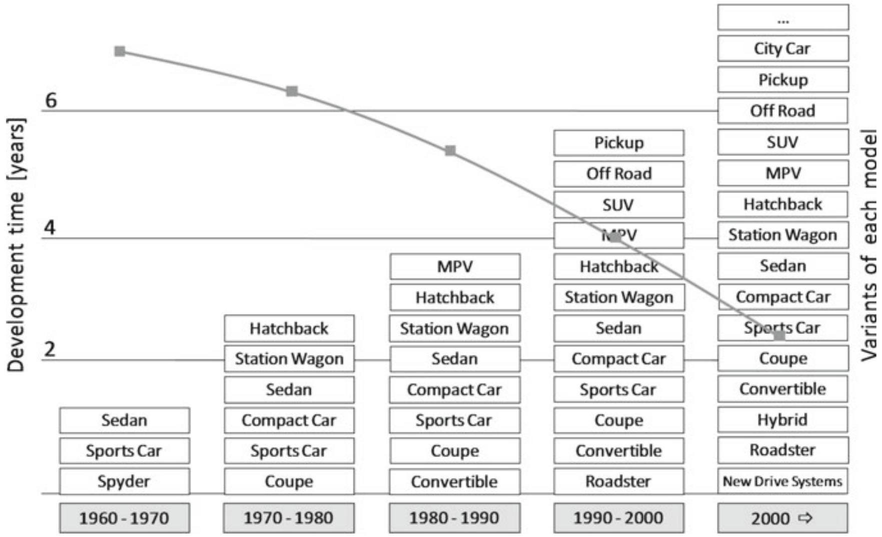

Fig. 1.2 Increase of model variants and decrease of development time in the last decades [2]

1.1 Manifold Requirements in the Past and in the Future

In addition to a brief overview of selected main topics in automotive development over the last 120 years, this chapter includes a discussion of the wide variety of development requirements for current and future cars.

More than a hundred years ago, at the beginning of automotive development, the inventors of new motorized vehicles built up their creations in simple workshops supported by a small group of specialists. Development processes were strictly problem oriented, and improvement cycles were mainly based on hardware testing procedures. Layout, design and optimization followed the functional aspects of the product itself. Figure 1.3 shows Gottlieb Daimler's first *Motorkutsche* from 1886. This vehicle was based on a coach from the Stuttgart Wagon manufacturer Wilhelm Wimpff and Sohn, which was adapted with a one-cylinder, four-stroke engine developed by Daimler. This early four-wheel automobile had a weight of 290 kg and a maximum driving speed of 18 km/h [3]. The development of the engine was completely separate from the development of the vehicle itself. Thus, people called early automobiles *horseless carriages*.

The early years were characterized by high creativity and many vehicle variants. In principle, each car was built up as an individual item. In that time, automotive development was completely hardware based and hierarchically structured. The heads of development were key people who possessed the main knowledge of construction, production and testing procedures. In many cases, the inventor, the chief of development and the business leader were one and the same person. The famous names from these early days of automotive development are well known,

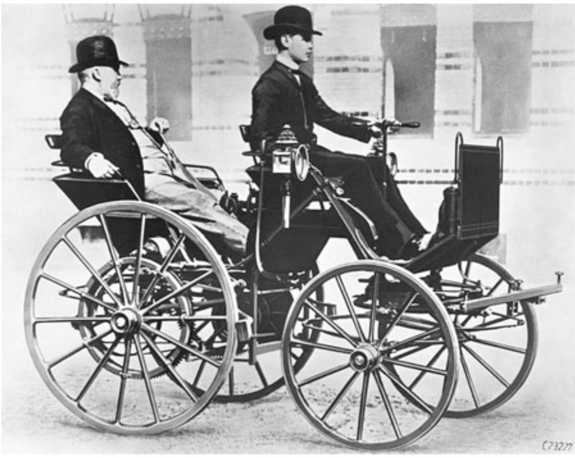

Fig. 1.3 Gottlieb Daimlers first *Motorkutsche* (1886) [4]

such as Nicolaus August Otto (1832–1891, Germany), Siegfried Marcus (1831–1898, Germany, Austria), Gottlieb Daimler (1843–1900, Germany), Henry Ford (1863–1947, USA), Ferdinand Porsche (1875–1951, Austria, Germany) and many others. At the beginning of the twentieth century, the production of the first series vehicles started. Besides product-oriented technical requirements, the development of series vehicles also had to take production-related aspects into account. In those days, production engineering and operation planning were driven by the low number of vehicles produced, meaning that the development process only partially considered the organization and necessities of manufacturing.

Henry Ford made the first steps in mass production development. He adapted assembly line manufacturing knowledge from simple products to the requirements of relatively complex products, such as those produced in the automotive industry. In this way, it was possible to produce large numbers of cars through only partially automated but strictly organized stages with a surprisingly low cost per unit. The introduction of assembly line production led to a modification of the principals of automotive development processes. Besides product-oriented technical requirements, the influences of manufacturing and assembly became more and more important. The first steps of production-line-oriented car development were strictly driven by the approaches of conformity. Initially, the Ford Model T was available in just one configuration, and new configurations were based on the same platform, assembled with a high degree of carryover parts.

Figure 1.4 shows a component assembly and a final assembly line of the Ford Model T, which was introduced in 1908. It had a robust vehicle setup and a four-cylinder engine. In the year it was introduced, the Model T was sold as a low-cost model for $825, a price which dropped in each subsequent year. Although the automobile was initially produced in a conventional way, under Henry Ford's directive, the manufacturing process was subsequently improved. Seeking increased

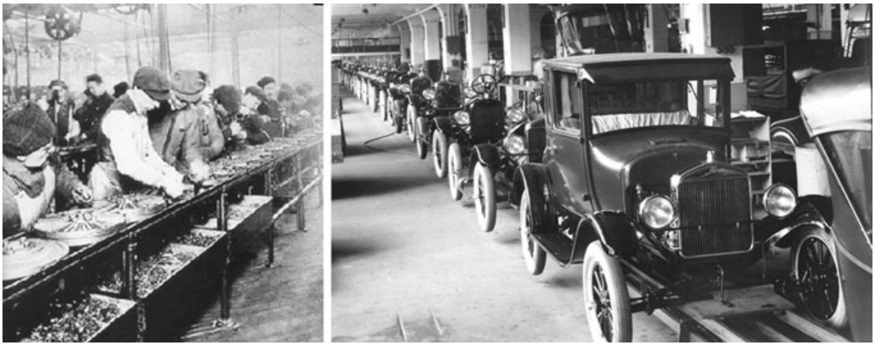

Fig. 1.4 Production of the Ford Model T in Detroit, Michigan [5, 6]

efficiency and lower costs, Ford introduced moving assembly belts into his plants in 1913, which resulted in an enormous increase in productivity. One key to success was the application of production-focused engineering in automotive development. The production of the Model T was continued until 1927, with about 15 million units sold within 19 years. The price of a basic model dropped to $290 in 1927 (which is equivalent to about $6,200 in the year 2012, based on the consumer price index), which made cars affordable for the middle class.

The increasing consideration of production-related aspects in the 1930s eventually had a significant influence on the products themselves. Growing production quantities led to the development of cost-optimized components, the use of building block units (non-variable part strategy) and the assembly of optimized structures. These measures helped lower costs, which supported the distribution of motorized vehicles into different social stratums in both Europe and North America.

At this time, the first stylistic aspects were also incorporated in the development of new cars. Stylists worked with drawings on paper and developed modeling procedures with clay. These so-called clay models can be used in different scales and levels of detail and are still an important part of the styling process today. Besides standard necessities, such as vehicle packaging and passenger space, the first influences on automotive styling came in the period between the World Wars from the aeronautic industry. As an example, Fig. 1.5 shows the famous Bugatti Type 57 SC Atlantic from 1937. Only four vehicles of this sports car were built, and it is currently one of the most valuable antique cars.

In the late 1930s and during the Second World War, the requirements of military armament influenced automotive manufacturers. Concerning automotive development methods, a breakthrough came in 1940 when Riekert and Schunk introduced a scientific approach for the calculation of the driving characteristics of a car, which were described by a series of equations and relations based on a simplified automotive model, the *single track model* [8]. The derivation of a simplified abstraction from a real vehicle to enable the general calculations of characteristic dynamic driving values represented an initial basic approach for the development of calculation and simula-

Fig. 1.5 Bugatti Type 57 SC Atlantic (1937) [7]

tion algorithms in a wide field of applications. Of course, the calculation itself was performed by hand; computer-supported simulation started more than two decades later. Today, the findings of Riekert and Schunk are still often used in different fields of vehicle dynamic simulation.

In the ensuing years, as social prosperity increased, the automotive industry was able to develop new products and to offer product variants. Mobility became more and more important, and car manufacturers offered various models in different price classes. The growing production quantity and the growing number of variants presented challenges for development departments. New development strategies and procedures arose, which led to the implementation of new departments and corporate structures. While communication had been easier in the time of compact development departments (and development targets), as task load and manpower requirements increased, it became necessary to develop new organizational structures for the organization of human resources and processes. In the early years, the development of a car was based on the definition of main vehicle modules, such as the engine module, transmission, suspension, chassis and body. Since individuals (or small groups) were assigned to each clearly defined module, information flow was relatively simple and consisted mainly of direct communication between the responsible parties. In addition, the simple setup of a car resulted in relatively short development times; in many cases, a car was developed in just a few months.

However, as the number of the development fields and people involved increased, new organizational procedures were generated for new car development. Figure 1.6 shows the Opel Record, which was introduced in 1957 and became a successful mid-class model in Europe. At that time, customers had begun to demand more comfort and performance. The development targets were therefore performance, durability and technical functionalities. In addition, styling and fashion became more important in the European automotive industry in the years following reconstruction. Thus,

Fig. 1.6 Opel Rekord P1 from 1957 [9]

styling aspects, comfort and additional customer benefits began to influence the development of personal cars.

In the second half of the 20th century, customer demands expanded to include increased safety and comfort functions, electronic features, brand identity and more. Due to growing product complexity, the automotive development became team oriented. The structured division of labor generated new jobs and areas of responsibility. In the 1960s, development processes were more strictly defined and organized. Driven by increasing responsibilities and resources, development departments were subdivided based on different tasks and requirements. The separation of automotive development into research, pre-development and series development followed. This made it possible to conduct research and develop new, future-oriented technologies without the boundary conditions of mass production and costs.

The growth in individual mobility also led to increasing numbers of traffic accidents, which forced manufacturers to take safety-relevant aspects into account. In 1968, the American Transportation Agency (DOT) started a research program for the development of vehicle safety technology. The European Enhanced Vehicle Safety Committee (EEVC) was founded in 1970, as European car manufacturers also began to intensify their commitment to crash tests and the development of passenger safety technology (Fig. 1.7). These new targets influenced the research topics in vehicle development. The vehicle body structure was analyzed in terms of stiffness and load paths in the context of different accident scenarios, and calculation and crash test procedures were added to the complete vehicle development processes. In later years, the introduction of computation technologies brought new possibilities for vehicle structure calculation. Computer-supported applications, first in simulation and later in design, led to the implementation of new organizational structures and procedures in development processes. The concern with safety continued into the 1980 and 1990s, which saw the introduction of both active and passive safety-relevant functionalities first into luxury cars, and later into all vehicle classes.

In addition to improving vehicle safety, two factors also contributed to a demand to improve vehicle efficiency. The first was a concern for the cost of operating a

Fig. 1.7 Mercedes Benz crash test 1959 [4]

vehicle, which was brought into start relief by the oil crises of the 1970s, as prices rose and availability declined. The second factor was a growing awareness of the environmental impact of the increasing number of automobiles that arose in the mid-twentieth century. This began in California, where geographic and climate factors led to heavy smog situations with serious air pollution, particularly in densely populated urban areas. Therefore, in the early 1960s, the government of Los Angeles introduced a limitation on carbon monoxide and hydrocarbon exhaust emissions for cars. In Europe, the first exhaust emission regulation was introduced in 1970 and has been continuously upgraded since then. In the 1980 and 1990s, strict exhaust gas legislation led to the implementation of exhaust catalyst systems and electronic motor management systems for gasoline engines. With the development of supercharged diesel engines with direct injection systems, diesel vehicles were introduced into many fields of application.

Along with safety and efficiency requirements, customer demands for better comfort also increased in the second half of the twentieth century. From ride comfort (e.g. enhanced suspension systems) and convenience (e.g. electric windows) to climate control and even on-board entertainment, developers and engineers were compelled to integrate ever more technologies and features into new vehicle designs. However, after a period of focus on improved comfort and performance, the end of the twentieth century saw a distinct shift in focus towards environmental friendliness and fuel efficiency. Low fuel consumption engines and alternative drivetrain concepts, such as natural gas engines and hybrid systems, emerged, as customers began to understand the direct dependency of their mobility on the availability of crude oil. For example, Volkswagen announced the series production of a car with a fuel consumption of one liter per hundred kilometers in 2013 (Fig. 1.8, right). The car bears a notable resemblance to a 1986 Volkswagen concept vehicle, which had already emphasized the requirements of a low-fuel-consumption vehicle, such as an efficient engine,

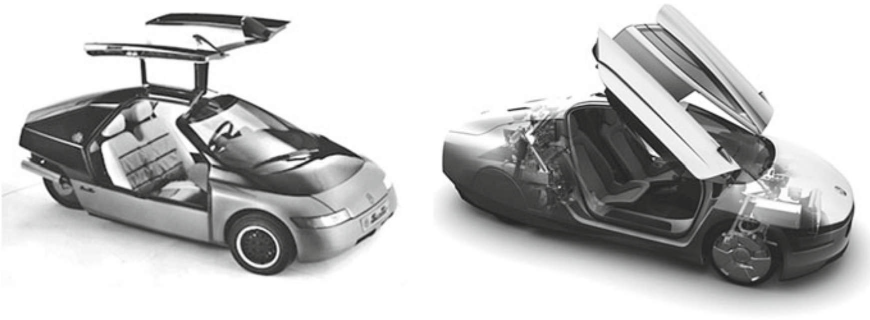

Fig. 1.8 Volkswagen concept cars: Scooter from 1986 and XL1 from 2013 [10, 11]

low weight and low driving resistance (Fig. 1.8, left). However, 20 years later, the time for this vehicle had definitely arrived. In fact, the emphasis on environmental friendliness has gone beyond simple fuel efficiency to include the use of recyclable products and sustainable materials, which is becoming increasingly widespread.

With all these different, constantly evolving demands, contemporary market researchers are constantly finding new market niches and variants to fulfill the customer requirements in terms of individualism and customizing. For example, Fig. 1.9 shows the Nissan Concept Car Pivo2, a prototype vehicle equipped with four electric hub engines, an example of a concept that is designed to meet the requirements of inner city traffic, such as an exhaust-emission-free drive unit, high flexibility for parking space, and the option of electronic supporting equipment. While such concepts represent real value for the consumers, it is important to recognize that all of these sometimes conflicting demands and the product variation that they have caused have presented significant challenges for vehicle engineers and developers.

Fig. 1.9 Nissan Concept Car Pivo2 (2007) [12]

To meet these challenges, fundamental changes had to be applied to both the vehicles themselves and the processes by which they are developed. For example, legislative limits on emissions and the growing impact of fuel costs led to the implementation of new engine concepts and exhaust gas aftertreatment systems. As the complexity of the tasks required for engine development increased, it became necessary to break the development process into separate, component-specific subprocesses, such as engine, transmission and others. One important side effect of this growing complexity was the resulting impetus to cooperate with specific key suppliers for particular components or systems. This led to the definition of new, shared development procedures, which integrated suppliers into the development processes and thereby brought in their knowledge of their respective business fields. One further result of this cooperation in development was the creation of know-how networks and collaborations between different car manufacturers in specific research fields, which play an important role in contemporary vehicle development.

Beyond the increased complexity of the vehicles themselves, the increased complexity of the automobile market has also had a significant influence on modern development strategies and methods. In particular, the globalization of automobile companies has had a significant impact on development processes [13]. On the one hand, there is pressure to meet the specific demands of different customer groups and legislative bodies around the world. On the other hand, there is a counter pressure to standardize as many production processes as possible, in order to achieve synergy between the production facilities in different countries around the globe. Thus, the organization and structure of global development has led to the implementation of global-network-based product data management systems and globalized development processes, which are supported by virtual product development.

In the coming years, automotive development will face significant challenges. New propulsion systems, energy storage media, tank systems and completely new vehicle concepts must be developed to provide continued individual mobility in the coming decades. New vehicle concepts call for new development methods and new engineering tools. Thus, the importance of virtual development in automotive engineering will increase in the next years, and the generation of flexible design and simulation methods will be an important key to success. Nevertheless, the main development targets remain the same as in previous decades - reduction of the costs and development time and increase in the quality and efficiency of development processes.

Figure 1.10 provides an overview of boundary conditions for the development of new car models in the near future. Four main areas influence the general requirements: the environmental impact of individual traffic, the influence of crude oil availability, safety aspects, and the increase in customer demands in terms of comfort and lifestyle.

Focusing on automotive engineering, these boundary conditions have a significant influence on the development targets and thus on the methods applied. The creation of new vehicle concepts that fulfill increasing demands requires careful planning and refinement of existing knowledge, as well as the generation of new ideas and techniques. The early phases of development, in particular, play an important role in conceiving, developing and evaluating new ideas and technologies.

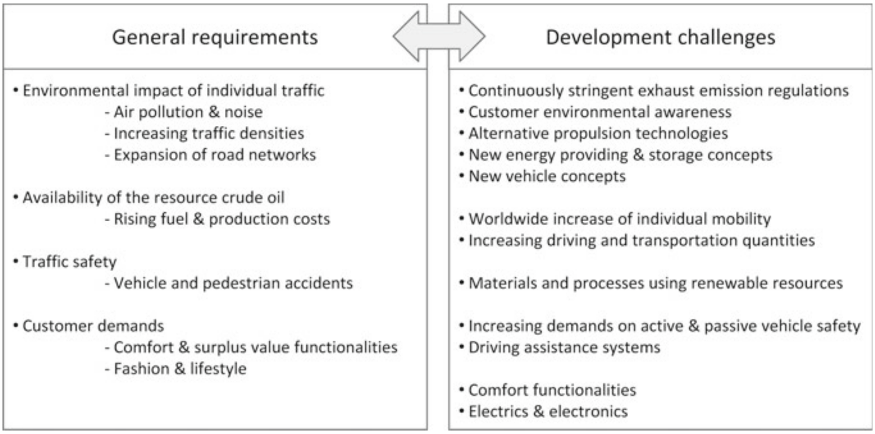

Fig. 1.10 Boundary conditions for the development of new cars

1.2 The Process of Automotive Development

Through the middle 1980s, automotive development processes were characterized by a high degree of hardware and prototype-based optimization cycles. Development projects were divided into individual tasks, which featured relatively little data sharing. Individual processes were performed in essential serial sequences, and data transfer was organized in rigid structures based on the completion of individual tasks. Computer-aided calculation methods were applied in specific areas only. For example, the application of the first computer-supported two dimensional drawing systems in the late 1970s represented a fundamental change in the way vehicles were designed.

At that time, full-vehicle development processes had a duration of about 6 years and included three prototype phases [14]. However, the integration of virtual, computer-aided methods into automotive development led to significantly revised processes. In the middle of the 1980s, computer-aided design and simulation methods began taking over engineering tasks that had formerly been done via hardware-based development. The pre-calculation of vehicle structures, durability and acoustic behavior in the layout phases supported product optimization without hardware tests, and growing design and calculation possibilities increased the influence of virtual computer-based development steps. Focusing on the design process, the introduction of parametric-associative methods pushed virtual modeling intensively.

In the closing years of the twentieth century, integrated CAD/CAE processes enabled network-based development in automotive engineering. Virtual prototypes were generated, which replaced at least one physical prototype generation. The application of virtual engineering in full-vehicle development fostered worldwide collaboration by bringing together partners and markets from different countries and regions. Today, a full-vehicle development project takes less than 3 years, and the trend is

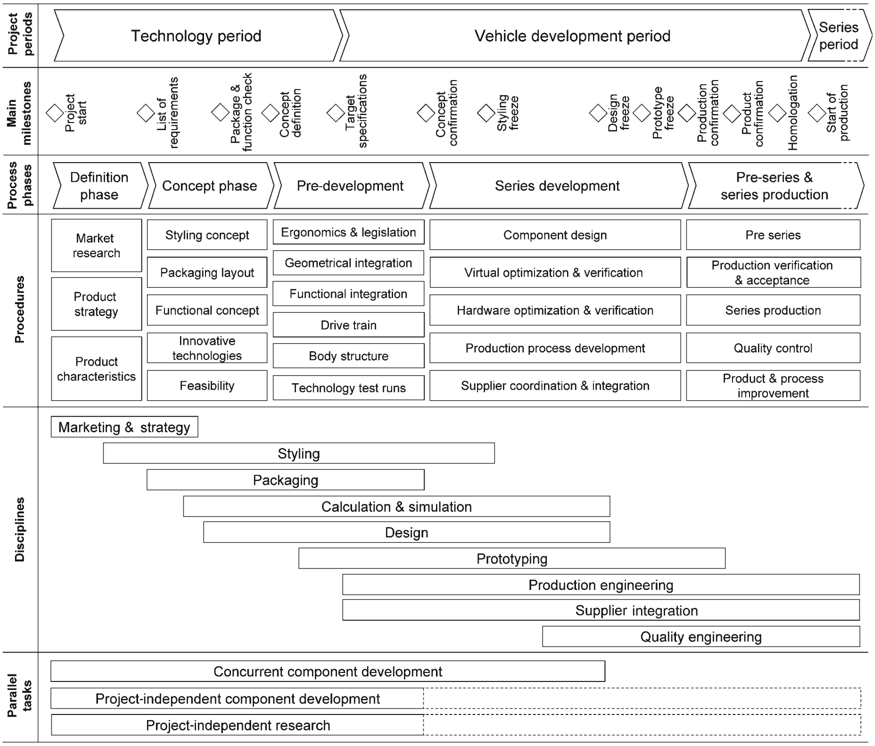

Fig. 1.11 Stages in a typical state-of-the-art full-vehicle development process

moving towards an additional decrease. Of course, since the product quality must be maintained, numerous virtual and physical test and acceptance procedures are applied throughout the entire development process.

Although the exact sequence of automotive development varies from one manufacturer to the next, in principal, the main fields of engineering can be found regardless of the specific company. Figure 1.11 shows a typical state-of-the-art automotive development process. The diagram displays the cumulative result of a detailed development process study that examined several car manufacturers and globally operating suppliers. The process depicted can be understood as a synthesized procedure which includes the main sections and milestones of a modern car development cycle. The nomenclature sometimes differs, but the major modules can be found in most development processes at car manufacturers around the world.

Therefore, the processes displayed serve here as a basis for the description and discussion of modern development cycles in the automotive industry, but do not reflect an actual development procedure from a specific company. The scheme describes the development sections of a new car model, without consideration of variants or model releases. In addition, concurrent component development and parallel project-independent research and development are not examined in detail. To support a clear illustration, the diagram is divided into different types of description. A general structure is provided by the division into three main project periods, the technology period, the vehicle development period and the series period, and an overview of the most important gates during each section is given by the definition of main milestones along the process progression. The process phases and the corresponding procedures describe the workflow, while a selection of comprehensive working disciplines points to the application of department-oriented tasks, which reflect the complex and extensively inter-linked procedures.

1.2.1 Project Periods

An automotive development process can be divided into three main periods. The technology period includes the product characteristics formulation, the vehicle concept and some initial pre-development steps. The technology period leads to the generation of a detailed target definition. This includes the definition of the vehicle layout and the drivetrain configuration from a series of production-related viewpoints. At the end of the technology period, variations pertaining to the drivetrain, transmission, special technical features and car body are considered and described, and innovations are defined and approved. Market-related research (from former models and/or competitors) is considered. The vehicle development period starts with a detailed planning of the subsequent vehicle-oriented development steps. At the beginning of this period, manufacturing-related tasks are considered, and suppliers are integrated into the development. Parallel to the design process, production engineering is performed and the influences on the detailed product design are considered. All production-related requirements have to be implemented before the concept confirmation. Technology test runs in the first section of the vehicle development period have to evaluate and optimize the interactions between the different modules in a car.

After finishing the pre-development phase (milestone: *Concept confirmation*), the series development phase takes the vehicle concept and develops the product until market-ability. During this period, the amount of production-related engineering tasks and working packages continues to increase. In addition, the influences of distribution and marketing are considered, while the product development itself decreases. There are a large number of linked processes in series development, which require an efficient project management. At the end of this period, the production, product confirmation and the homologation are completed, and the vehicle development period ends with the milestone *Start of production*.

As the consideration of manufacturing-related tasks increases, quality engineering is incorporated in the development process. Parallel to the aforementioned periods, additional responsibilities are taken into account. Project-independent research includes new technologies, strategic brand innovations and other fundamental research work. Project-independent component development is performed in the area of engine and transmission development for different vehicle types, platform development and/or development of components for the entire group. Project-related concurrent component development is performed to ensure the on-time functionality of delivered modules. This includes such tasks as parallel development, test and optimization of engines, and transmissions, which help to manage the working effort and time in the full-vehicle development process. In this way, different groups of departments and specialists work on new engines, transmissions, electronic devices and others. After completing the concurrent engineering processes, the tested and approved modules are implemented into the full-vehicle development process just in time.

1.2.2 Phases of Automotive Development

Besides the separation into three main periods, the product-generation process of a car can also be divided into process phases. Figure 1.11 shows the sequence of five main phases: the definition phase, the concept phase, the pre-development phase, the series development phase and finally the pre-series and series production phase.

The Definition Phase

The definition phase encompasses an initial characteristics estimation and evaluation of the car model which is to be developed. This phase is supported by far-reaching market research and trend prognoses to predict the requirements in target markets during the years of the projected product life cycle. In addition, the definition phase of a new car has to consider the overall product strategy of the manufacturer and boundary conditions related to the economic and financial situations. The product characteristics are set down in a *List of requirements*, which serves as a start-up schedule for the ensuing concept phase. Based on the definition phase, this list includes a description of the car classification (mini, compact, sedan, SUV, van, sports car, etc.), the main dimensions, the targeted driving behavior and other factors. In this phase, initial styling proposals are also submitted and discussed in the context of future styling trends and competing products.

The Concept Phase

The *Concept definition* milestone, one target of the concept phase, includes a detailed description of the vehicle concept itself. At this milestone, a rough approximation in terms of styling, packaging and functionalities is delivered, which provides an overview of the principal vehicle setup. Frontloading techniques support the working modules in the concept phase to enable the integration of knowledge from former project and research work.

One main working field in the concept phase is the execution of the styling process within given technical boundaries. In the initial phase, the generation of styling sketches and car body shape concepts is supported by initial packaging studies and ergonomic drawings. In later steps, the car styling has to take into account technical and legislative requirements in detail, such as space for the drivetrain and components, aerodynamics, passenger, pedestrian and crash safety. The task of the stylists is to find optimal solutions that meet the requirements of technical, economic, market and fashion trends. Benchmark studies assist in the evaluation of market trends and customer demands. In addition, typical brand characteristics have to be implemented and enhanced. Therefore, numerous styling proposals are produced to serve as a basis for discussions within the development team and in directive cycles.

The styling process is an important step in the concept phase, and even in the entire development process, because the car styling has a significant impact on customer perceptions and thus on the purchase decision. In modern vehicle development, computer-aided styling software (CAS) often supports the creation of exterior and interior styling surfaces. The styling software packages use several complex algorithms for the definition of high-quality surface models, which provide the basis for automotive styling development. The geometrical data are used for styling-related evaluation and representation within a virtual reality (VR) environment and serve as input information for subsequent engineering processes (e.g. vehicle packaging, ergonomic development, component design, module design). In most cases, styling data are transferred into the CAD-environment via neutral data formats.

In addition to styling, the packaging layout is another important task in the concept phase. It is carried out using digital mock-up (DMU) processes, which are based on a virtual assembling of the components and modules of a car. The geometrical description of these components is delivered by CAD and CAS. The working field of packaging layout handles the requirements of car module placement, such as drivetrain, tank, climate control, suspension, and others. The primary issue of the packaging investigations is the consideration of passenger and luggage space. In modern development processes, the packaging is built up around the passengers. In this context, the seating position plays an important role. Whether the passenger is sitting in a sports car, a sedan or an SUV makes a significant difference.

Besides the car class, brand-specific seating positions and space characteristics must be considered. Once the seating position, passenger's space requirements (e.g. head, elbow and knee clearance) and the luggage space have been designed, the vehicle packaging concept can be built up. This includes the placement of main modules, the review of compliance with legislative requirements and the definition of technical-based outline surfaces. All technical requests have to be double-checked with the styling surfaces of the car body to find an optimal solution that satisfies technical requirements without interfering with the car styling.

Alongside with packaging-relevant investigations, initial functional studies are performed. These studies examine the technical interaction of components and modules and also verify ergonomic functionalities. In this phase, technical modules are prepared and reviewed for their suitability for implementation into the vehicle concept. Technical modules include engine and drivetrain components, suspension and other supplied units. In addition, the functional concept includes early functional layout studies of components that must be newly developed, for example an initial estimation of the basic door kinematics and the window lifter mechanism (see also Sect. 3.13, p. 235). The package and functional check milestone includes a brief description of the vehicle architecture in terms of styling and technical requirements.

Of course, one main task in the concept phase is the consideration of innovative technologies, such as the implementation of new propulsion concepts (e.g. hybrid, electrical drive), new transmission systems (e.g. CVT, double clutch transmission), new vehicle concepts (e.g. convertible-coupe, micro city vehicles, one liter car) and others. Whether these new technologies influence the entire vehicle architecture (e.g. completely new vehicle types) or simply represent a part of the car (e.g. new transmission type) makes a significant difference. In both cases, the new technology has to be checked against the list of requirements for the new product, and its further development and applicability to the new car being developed must be verified. This can include concurrent, innovation-related virtual and hardware-based development cycles.

Finally, the concept phase concludes with a feasibility investigation of the vehicle concept. This section includes a description of different styling proposals that have been reconciled with the vehicle packaging. In addition, the functional concept is defined, and new technologies are approved for their principle usability in the new car model.

The Pre-Development Phase

Based on the concept phase, the pre-development phase includes a detailed definition of the vehicle layout taking into account all ergonomic and legislative boundary conditions. The packaging studies are enhanced by complete assembly and placement investigations, as well as functional optimizations. In addition to the definition of technical-related characteristics, comprehensive product decisions are made. This includes the integration of the new model into platform strategies, building block systems and the definition of model derivates. In many cases, new cars are based on predecessor models and carry over numerous technical features and components. In this case, the pre-development phase includes an assessment and evaluation of existing modules regarding their suitability for the new product.

The geometrical integration in the pre-development phase includes a detailed definition of the packaging, as well as of other geometrically based boundaries, whereby the knowledge from earlier models plays an important role. Brand-specific characteristics, such as the seating position, the drivetrain configuration, and suspension components, are implemented into the vehicle layout, which leads to a full-vehicle concept. This full-vehicle concept is represented as a detailed 3D CAD Model. In several steps, different specifications are adjusted in consultation with various development departments and decision makers. Styling is developed and adjusted in parallel, whereby the adjustments are performed in each department, focusing on both the styling and engineering.

In a parallel process, the functional integration verifies the technical functionalities and the interaction of all components and units. The ergonomic influences on the functionalities are investigated through ergonomic studies and simulation, for example entrance and seat position optimization, accessibility of switching devices, etc. The linkage of styling and engineering is performed in several steps, with a repeated data transfer between the departments. This procedure can sometimes be difficult, particularly when the wishes of stylists and engineers conflict. The functional integration also includes other areas, such as chassis and drivetrain, although some of these modules and components are normally developed separately because of their use in different car models. The drivetrain module can be seen as a delivered unit, but it must be considered in the vehicle setup from various viewpoints. For example, the engine packaging, an appropriate connection to the cooling system, the integration of the tank system, the development of the exhaust system (including exhaust gas aftertreatment), and the application of sensors and control units have to be adapted and approved for the new car model.

One important task of the functional integration is the full-vehicle layout related to driving performance and fuel consumption. The calculations conducted at this early stage are often based on former car models or by substituting simulation procedures because the necessary data are not yet fully available for the new model in this development phase. In many cases, there is an insufficient amount of data available for the full-vehicle simulation of future concepts. In these cases, a smart integration of existing data combined with pre-editing methods can improve the efficiency and accuracy in this important development phase in order to obtain the data necessary for simultaneous engineering.

Parallel to the general vehicle architecture development, the car body structure is defined and optimized. In the early phase, a rough estimation of supporting elements is defined and adjusted with styling and packaging. This initial structure is calculated in view of major load cases, such as different crash scenarios, stiffness and maximum stress. In many cases, the initial body structure is based on experience from former projects and/or benchmark studies. As pre-development proceeds, both the body structure design and its simulation begin to incorporate influencing factors to a higher degree. Detailed stress and durability calculations, full-vehicle crash simulations, weld spot pre-dimensioning and other production-related targets are considered and implemented.

At the end of this phase, a completely calculated design proposal for the series development is generated. In the case of a new body concept (e.g. new lightweight materials or design approaches), additional aspects have to be investigated and taken into account. In the last section of pre-development, a final styling concept is chosen and verified. This styling concept fulfills all engineering-based requirements, such as packaging, function, legislation, ergonomics, and aerodynamics. In most cases, a 1:1 hardware-styling prototype is built up to confirm the decision. Once the vehicle styling has been fixed, no subsequent modifications are allowed, due to the significant impact on the subsequent engineering steps. Parallel to the virtual development, different hardware test runs are conducted for both components and prototype vehicles to verify the functionalities.

In the course of investigating and assessing different technologies, the *Target specifications* milestone can be defined. This specification list includes a detailed description of the product characteristics and deliverables. The target specification list, which is based on the list of requirements, includes some adjustments and detailing resulting from the progress of the concept phase and the pre-development phase. The pre-development phase is completed with the *Concept confirmation* milestone. At this milestone, all product characteristics related to the target specifications have been fulfilled and verified. Modifications to the vehicle concept after the concept freeze have a significant impact on the further process timeline and the project costs. Due to the substantial influence that the initial development phases have on the product development cycle success and even on the product itself, it is necessary to apply highly flexible and efficient strategies. It is essential to use flexible tools, efficient methods and experienced engineers to identify the best product characteristics and technical solutions. In these early phases, the main facts of the entire product life cycle are defined.

Series Development

The series development phase includes a realization of the concept that takes into account process and production-related viewpoints. All of the engineering procedures in this phase are influenced by manufacturing-related boundary conditions. Thus, both the virtual and physical developments are performed in close cooperation with production engineering and with the supporting suppliers tightly integrated. In the series design process, the geometry of the components is described with a high accuracy within a CAD-environment. In this phase, the level of detail is significantly higher than during the concept phase or the pre-development phase. This precise generation of virtual models that take manufacturing processes into account requires special design methods and strategies. At present, the CAD models for series development feature a lower level of parameterization and thus less flexibility than the models created during the conceptual project phases.

The generation of new design methods, which enable a direct model transfer from highly flexible project phases into the rigid series development environment, offers substantial potential for increasing the efficiency of the entire development process. Besides component design, the virtual optimization and verification of parts and product configurations represent important steps in the series development. Digital mock-up procedures check and improve the interactions between modules in terms of functional aspects, assembly and tolerancing. Far-reaching simulation procedures ensure a failure-free performance and interaction. In the case of the vehicle body, structural investigations, virtual crash calculations and durability simulation are performed in detail under consideration of component design, materials and the applied connecting technologies. Especially in the case of modern lightweight body design, virtual preservation of failure-free operation during the product lifetime represents a significant challenge for all parties involved.

During series development, several concurrently developed components and modules are implemented into the full-vehicle architecture. Thereby, engine and drivetrain modules, brakes, suspension and electronic systems are included into the vehicle setup. One significant advantage of concurrent component and module development is the parallel generation and verification of enclosed units. These modules are optimized and tested in terms of their theoretical failure-free operation. During the integration process, they have to be verified in terms of suitability and failure-free operation within the complex vehicle system.

One example of the integration of concurrent developed modules is the engine unit. The development of internal combustion engines is a complex challenge and has to take into consideration not only engineering requirements, but also customer and legislative demands. Thus, a reduction of fuel consumption and exhaust emissions, increasing performance requirements, the implementation of alternative drivetrain concepts (e.g. hybrid power trains) and a high cost pressure influence the development of new engine technologies. The engine development process itself is divided into several sequences: design, mechanical and thermodynamic simulation, test bench and on-road application, and production-related development. Since this chapter focuses on the full-vehicle development process, it will not go into detail about engine or component development.

One important stage in the series development phase includes the mass calculation and mass management task. This task is addressed via virtual optimization and verification, as well as in hardware-related steps. The reduction of weight is an important target for the development of new models because of the direct influence of the vehicle's mass on driving dynamics, fuel consumption and exhaust gas emissions. Parallel to the virtual development, hardware optimization and verification take place. All the virtual development results are verified and fine tuned in the course of prototype test procedures. Hardware optimization and verification includes test cycles of components and modules, as well as work on full-vehicle prototypes on test benches and under different road conditions. Examples of hardware tests include tests of new propulsion concepts, engine and transmission tests, final aerodynamic and air flow (cooling) studies on hardware models, functional test benches for closures, suspension and brake tests, electronic test procedures, software tests, haptic and ergonomic studies, tests of sealing concepts, and many more.

Besides product-related hardware tests, manufacturing-related hardware optimization loops are performed in the course of the production process development. In addition, virtual manufacturing and plant engineering includes the simulation of production and assembly procedures to support the optimization of in-house processes, as well as integration with the supplier. One result of the series development is the complete generation of 3D CAD models and 2D workshop drawings. These product data are linked with different processes of data organization, supply and manufacturing. Parallel to component design, tools are designed and calculated in-house at the manufacturer, as well as in cooperation with suppliers. Detailed specifications of product quantity and quality, project schedule, logistics and manufacturing processes are defined.

When considering the main milestones of the series development phase, the dependency of product development and production engineering becomes evident. The exterior and interior styling process ends at the *Styling freeze* milestone. This target includes the complete definition of the vehicle styling under consideration of technical, production-related and, of course, aesthetic viewpoints. The *Design freeze* milestone marks the end of the design process, including all supporting calculation and simulation procedures. At this milestone, the product-influencing factors of production engineering have to be implemented. At the *Prototype freeze* milestone, the vehicle setup is confirmed across an extensive range. This includes mechanical and electrical confirmation, as well as hardware and software verification. The last milestone in the series development is *Production confirmation*. At this stage, the product is ready for production. Comprehensive workload in the area of production planning and control is frozen and approved, which includes the administration and organization of manufacturing-relevant data and procedures. The subsequent steps have to finalize the production process itself.

Pre-Series and Series Production

The production of the new car model starts with the pre-series. In this phase, although the series tools are used, the process is not performed on the ultimately planned time schedule. During the pre-series, the tooling and assembly procedures are tested and evaluated. This is performed with a reduced production rate to enable a detailed check of each individual step. Computer-controlled procedures are reviewed, and human resources are trained. Both the product itself and the production process are tested in terms of the quality guidelines. The *Product confirmation* milestone marks the acceptance of the product, including all aspects of development, production and process quality.

Due to the different market requirements, the homologation of the vehicle is a long-term process. Therefore, the homologation is carried out with pre-series vehicles or series-near prototypes. Of course, these vehicles have to fulfill the homologation-related specifications of series vehicles. The *Homologation* milestone denotes the end of the legal approval procedure. Product development ends with the *Start of production* (SOP) milestone. From this stage on, the manufacturing process is performed in the predefined time steps, and the targeted production volume is achieved. The delivery of supplied components and modules, the arrangement of the assembly line and the quality control function in the specified order. In most cases, suppliers have started their production a bit earlier, to ensure a failure-free start of the assembly process. During series production itself, continuous quality checks guarantee the predefined product features. Product and processes are checked continuously, and improvement steps are implemented into the production procedure. During the life cycle of a car model, further development and model upgrading include the implementation of new technologies (e.g. new engines and transmissions, new safety or comfort equipment) or slight styling modifications. These modifications are developed in parallel to the series production and implemented into the manufacturing process.

Once on the market, the product is maintained by a different kind of administration. Besides spare part delivery, selling centers are involved in the quality and improvement process. Feedback from the market provides important information for the current series, as well as for future development. Therefore, customer feedback data are collected and evaluated at markets around the world and collected for a detailed evaluation.

1.3 Application of CAD in Automotive Development

CAD is one of the central disciplines in modern automotive development. The efficient computer-aided creation of geometrical models provides the basis for a broad field of concerned engineering processes. The comprehensive CAD-based representation not only includes geometry data, but also provides extensive information about the product structure (e.g. bill of material - BOM), geometrical and functional interactions of components and modules, as well as much production-related information.

Section 1.2 introduced the sequences of a state-of-the-art automotive development process, including all its sub domains and areas of operation. A considerable number of working fields in this process are related to virtual product development and thus to the generation, modification and use of CAD-based information. With the goal of illustrating the main development targets and influencing factors, Fig. 1.12 shows several aspects of automotive engineering processes ordered in relation to six main areas. Economic-related aspects include the product strategy, influences from the market and of course cost management. Process-related aspects go hand in hand with production engineering, supplier integration and spare part management. Finally, traditional engineering-focused working areas contain the development of components and modules, as well as the consideration and implementation of full-vehicle-related technological parameters.

Since they are responsible for the generation of product data geometry within a virtual environment, CAD-processes are involved in development processes from the beginning. Market and product-strategy-related decisions are often influenced by fashion trends and lifestyle. In this way, a computer-aided creation and visualization of initial styling models plays an important role during assessment processes for the definition of customer requirements and market trends. In subsequent steps, the initially created styling surfaces serve as a basis for far-reaching optimization cycles, including several modifications and adaptations. The application of computer-aided styling (CAS) software supports the efficient creation of styling surfaces, data backup processes and evolutionary modifications of existing models.

Since cost calculation has an important influence on competitiveness, considerable effort is invested in the prediction, computation and evaluation of a wide range of product and production development processes in terms of their potential for cost savings. The provision of current information (including geometry, functions, materials, manufacturing and assembling related data), the implementation of components and modules from other models (COP), and providing information about the product structure throughout the entire product creation cycle offer significant support in the determination of cost-related aspects. Product data management (PDM)-based

Fig. 1.12 Development targets and influencing factors of automotive full-vehicle engineering processes [15]

organization of all the involved information supports a direct access of the concerned departments and working areas to cost-calculation-relevant information.

Production planning and manufacturing engineering, including the integration of supplier and logistic processes, involves automotive DMU structures for the computation of mounting and assembly procedures, the verification of production lines, and the development and evaluation of automated manipulation and transportation. Derived from CAD data, the assembly simulation addresses the optimization of mounting procedures regarding sequences, collision detection and ergonomics investigation of operators. In addition, the management of variants supports an efficient confirmation of production processes in the case of product modifications or variations.

Full-vehicle development goes hand in hand with the development of components and modules. These processes are traditionally known as product development and include all tasks necessary for the creation and verification of all geometrical and functional product characteristics. Whereas the development of component technologies is often focused on restricted functionalities, full-vehicle development processes have to consider the complete product structure, including complex geometrical and functional interactions and requirements. Both disciplines are based on virtual product development, as CAD plays a key role in the definition of both the product structure and the product creation. Due to their central position in automotive engineering, CAD data are managed in an extensive PDM structure and provided for several parallel and subsequent calculation and simulation processes for functional layout (e.g. kinematics simulation), structural dimensioning (e.g. body crash simulation) or other optimization and verification processes (e.g. aerodynamics simulation, weight computation).

Finally, process engineering handles the development and optimization of the applied processes, beginning with a structurization of the complete vehicle development (Fig. 1.11, p. 12). The derivation of sub-processes for detailed development steps and for the integration of external engineering partners and suppliers plays an important role in the integration of conception, design, calculation and simulation. An optimized interaction of different departments, including differing development disciplines, provides the foundation for successful product development. A special focus is placed on the correct planning of different sequences and development steps, in which the transfer of data plays an important role. Process engineering has to ensure that all required information is available just in time for different processes (e.g. geometrical information regarding components developed in design processes has to be provided for subsequent stress and fatigue simulation). In modern automotive development, the planning of development sequences and workflow faces challenges from simultaneous engineering and frontloading approaches, which are based on development steps that are partially performed in parallel and on the shifting of knowledge-based, product-related decisions into early development phases. The complex interaction of CAD, CAE and knowledge-based engineering has to be planned carefully because of its importance for successful product development.

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