The Vehicle Development Process Where Engineering Meets Industrial Design

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Abstract—*It is not only the car as a product that is experiencing a significant process of change at present; the development process behind cars is also facing up to new challenges. To adapt to these emerging situations, we need to introduce new methods that bring dynamism to design processes. Creating those methods requires sound knowledge of actual vehicle development processes and activities. Existing reference works provide either highly selective insights into real-world experience or very abstract processes. We have, therefore, conceived this article as an expert-based assessment of the current development situation. It presents a scientifically reasoned reference process—building on practical experience—for the early phases of vehicle development, in particular the interplay of engineering design and industrial design.*

Key words: Automotive development process, design-technology convergence (DTC), industrial design process, project and R&D management, R&D management, transportation design.

1. INTRODUCTION

THE product development process (PDP) is the subject of countless academic studies (Birkhofer, 2008; Beier, 2013). The myriad studies and publications range from detailed observations of individual process steps to holistic interpretations and adaptions of familiar standards. These mostly theoretical and methodological considerations are complemented by insights and case studies from industry.

When it comes to the PDP in the automotive industry—i.e., general PDPs applied to this specific sector—a degree of vagueness exists. This stems primarily from the high level of secrecy in the automotive industry, as well as from the competitive pressure. Nevertheless, it is still possible to find well-judged overviews of the vehicle development process (see Section 2.1). Abstract and generic flowcharts have been developed on the theory side which describe the ideal scenario for the processes generally involved in the development of a vehicle.

The car as a product is facing a raft of new challenges and requirements, and that is reflected in the tasks facing PD teams. Here, both academic research (Gerhard et al., 2008; Bennett & Lemoine, 2014; Engeln, 2020; Reichelt et al., 2021; Reichelt et al., 2022) and practical applications have flagged up the importance of improved interdisciplinarity, greater flexibility, and a stronger customer focus, as the overall appearance and experience of a vehicle determines the differentiation between the brands and models, especially in terms of the currently increasing alignment of technical features and functions.

As we will explain in more detail in the following section, in the specific context of the early phases of vehicle development there is a knowledge gap when it comes to the relationship between designers and engineers—the "design-technology convergence" or DTC. However, these embryonic stages of the creative process are critical in product design, as the fundamental properties of the car, and above all its shape, are determined during this phase.

Therefore, we have carried out workshops with experts engaged in the early phases of automotive development. These workshops have yielded a well-thought-through, holistic, and universally valid description of the logical convergence steps that happen in the early phases of vehicle development. With our research, we build a proper basic understanding of the automotive development process in the crucial early phases with a special focus on the interplay of industrial design and technology. The derived reference process can on the one hand, therefore, serve as general understanding for building a unified understanding of the process. On the other hand, this first academic description can be seen as a basis for further research, especially with regard to evolving the process according to current challenges on process and product.

2. Literature Review

In this section, we outline the knowledge currently available from academic research and practical insights on development projects in the automotive industry. Here, we deal only with the key fundamentals and basic understandings. Table 1 contains a detailed overview with additional references.

According to Meboldt (2008), research on engineering development processes started in the 1980s with the first process model descriptions. Afterward, the development process for products (especially technical products) has often been the focus of research (Birkhofer, 2008; Beier, 2013) and many descriptions outlined in reference works model the procedure for technical PD (Meboldt, 2008). Here, different perspectives can be identified (Clarkson & Eckert, 2005; Birkhofer, 2008): The description of development stages, development activities, general problem-solving steps, basic steps of development activities, or process-focused models.

A process-focused model is mostly used to describe the global context, as here the essential key steps of PD can be described in abstract terms (Clarkson & Eckert, 2005). The more complex the product to be developed, the more this abstract description is subdivided into module-, component- or individual part-specific development processes—so-called subprocesses or subprojects (Kraus, 2007; Rudert & Trumpfheller, 2015; Feldinger et al., 2017; Widmann et al., 2021). This breakdown allows the process-based descriptions of the overall approach to be carried over more effectively on a subprocess level, as well as mapping interconnections and essential interfaces between the sub-processes more effectively. This type of process-based description is therefore discussed in more detail below.

Numerous process models exist for general PD. A large amount of material on development processes has been published in Germany, in particular, over recent decades (Clarkson & Eckert, 2005). The VDI 2221, VDI 2206, and VDA (2017) standards and reference works by Wallace & Blessing (2007), Lindemann (2009), Gausemeier et al. (2013), and Albers et al. (2002) may be referred to here as key process descriptions.

In the international context, we should mention above all the approaches contained in the stage-gate process described by Cooper (2007 & 2022) and the general development process outlined by Ulrich et al. (2020) as central process descriptions for technical PD. A larger selection of reference works containing descriptions of development processes can be found in Table 1.

What these all models have in common is that they primarily serve as visual orientation and, therefore, show the various relationships and key tasks (Clarkson & Eckert, 2005). Ulrich et al. (2020) maintain that this orientation can ensure better quality assurance, coordination, planning, and management, as well as continuous improvement.

The development process links all key tasks in superordinate phases (Meboldt, 2008). The structure of the process can be described as a linear approach in which certain development activities within a phase are iterative, i.e., they can be run through several times (Tovey, 1997; Hacker, 2002; Engeln, 2020). The key characteristic of the activities in this process is that design and evaluation cycles alternate (Tovey, 1997; Hacker, 2002).

The different process-related reference works covering technical PD are used as the basis for the description of sector- and company-specific process models (Clarkson & Eckert, 2005; Gusig & Kruse, 2010; VDI 2221; Widmann et al., 2021). This is primarily due to the fact that, given the complexity of the various activities and areas involved, only an abstraction is described. This removes practical application from the equation, especially where scientifically approved models are available (Clarkson & Eckert, 2005; Meboldt, 2008).

The key differentiator here is the complexity of the product being

Table 1. Classification of the Researched Sources Re. Overall PDP, Design Process, and DTC.

	Overall PDP			**Design process**			**DTC**	
	Theorem / model	**Norm / directive**	**Practical examples**	**Principles / theorems**	**Norms / directives**	**Practical examples**	**Theories / papers**	**Practical examples**
Source								
Audi (2017)						X		(X)
Balasubramanian et al. (1998)			X					
BMW (2012)						X		(X)
Böhme (2012)	X			X			X	
Braess & Seiffert (2007)				X			(X)	
Broy (2010)	X							
Bryant & Wringley (2014)								
Clark et al. (1995)	X		(X)					
Clarkson & Eckert (2005)								
Cooper (2007)	X							
Cooper (2022)	X							
Cross (2007)				X				
Da Silva & Kaminski (2017)	X		X					
Daecke (2009)	X							
Design Council (2007)				X		X		X
Ebel et al. (2014)				X			(X)	
Ehrlenspiel (1995)			X					
Engeln (2020)	X			(X)				
Gausemeier (2013)	X							
Gericke & Blessing (2012)				X				
Gusig & Kruse (2010)	X		(X)					
Haase (2012)						X		
Herrmann (2000)			X					
Hugentobler (2004)				X				
IDEO (2012)				X				
Kraus (2007)				X				
Kraus et al. (2021)				X		(X)		
Kurz (2008)				X			X	
Lindemann (2009)	X							
Macey & Wardle (2014)				X		(X)		
Meadows (2017)						X		
Mercedes-Benz (2017)						X		
Rudert & Trumpfheller (2015)			X			X		
Schmid & Maier (2017)				X			X	
Sörensen (2006)								
Tecklenburg et al. (2009)	X			(X)			(X)	
Tovey (1997)				X				
Ulrich et al. (2020)	X						(X)	
VDA (2017)		X						
VDI 2206		X						
VDI 2221		X						
VDI 2424					X		(X)	
Wallace & Blessing (2007)	X							
Weber (2009)	X		X					
Widmann et al. (2021)			X			X		X

developed (Clarkson & Eckert, 2005; Gusig & Kruse, 2010). Further, we focus on descriptions for the vehicle development process.

Table 1 provides an analysis of various literature sources. The sources were examined in relation to the processes covered. A distinction was made between the following points of focus: overall PDP, industrial design process, and DTC. Furthermore, it was analyzed whether the content comprised basic, theoretical process descriptions, or practical examples. If the sources contain clear descriptions, they are marked with an X; if only certain insights are given, these are marked with (X). Due to the large number of publications on PDP, the list does not claim to be complete.

2.1. Vehicle Development Process

Only a small number of sources are available on the actual vehicle development processes in an industrial context that go beyond a general, abstract description of the key stages to depict the activities that have to be performed in each stage. The vehicle development process is basically organized into stages and milestones (Meboldt, 2008; Gusig & Kruse, 2010; Rudert & Trumpfheller, 2015; Widmann et al., 2021). The main idea behind this stage-based procedure is to gradually increase the level of detail, avoiding or minimizing any modifications as the process advances (Gusig & Kruse, 2010).

The full development process encompasses all key stages here, from the initial product idea through to the start of production (SOP) (Weber, 2009; Gusig & Kruse, 2010; Da Silva & Kaminski, 2017). There are varying figures for the number of stages. Examples of published processes from both academic research and practice can be found in Table 1.

The number of stages and milestones very much depends on the basic type of development project (Weber, 2009; Raabe, 2013; Engeln, 2020). New designs represent the most complex type of project, meaning the processes involved are more extensive compared to updated designs (facelifts). Besides this strategic impact on the type of development process and its extent, processes are also subject to overarching trends (Clarkson & Eckert, 2005). For example, the general trend toward sustainable products is currently having a substantial influence over process design.

Notwithstanding trend-driven adjustments, the development process is underpinned by a standardized structure to ensure the vehicle meets the expected quality requirements, with milestones or quality gates needed as decision points between the various key stages. To maintain high levels of product safety and quality, the milestones are based on established quality standards and compulsory testing for vehicles, such as ISO 26262, ISO 9000, or the NCAP programme (Clarkson & Eckert, 2005; Reichelt et al., 2022). At each of these gates, the results obtained so far are checked against the external quality requirements and decisions are taken regarding further development based on the outcome (Clarkson & Eckert, 2005; Gusig & Kruse, 2010; Reichelt et al., 2022). In some cases, the number of evaluations and tests is stipulated by laws or other regulations and is not a matter for the OEMs to decide (Clarkson & Eckert, 2005). The test results are incorporated straight into the product's development, producing an iterative web of design, component testing, and prototype testing (Engeln, 2020).

As well as these general requirements of the vehicle development process, the product complexity of cars poses a further challenge. Vehicles are completely styled and highly complex products, so development is split up by breaking down the overall PDP into various specialist tasks allocated to different development teams (Clarkson & Eckert, 2005; Kraus, 2007; Gusig & Kruse, 2010; Feldinger et al., 2017; Meadows, 2017; Widmann et al., 2021). The numerous modules and components are generally structured and managed as individual subprojects. These are governed by their own, specific sequences of processes, which are, however, always aligned with the overall PDP (Gusig & Kruse, 2010; Feldinger et al., 2017; Meadows, 2017; Engeln, 2020; Ulrich et al., 2020). Development is usually divided into the core modules and components described by Widmann et al. (2021). Individual subprocesses have occasionally been published in dissertations and other publications. There have not been any publications to date describing the interrelationships between the different development units or the individual tasks and activities in the subprocesses, including industrial design.

2.2. Early Phases of Vehicle Development

The first stages of the vehicle development process are also referred to as the "early phases." Raabe (2013) subdivides these fundamental initial phases into the "*early stage*" and the "*concept stage.*" The main aspect to note about these stages is that the exact requirements of the vehicle and potential solutions are not yet complete or still need to be elaborated, meaning there exists a high degree of complexity, risk, and uncertainty (Lévárdy, 2006; Cooper, 2014; Albers et al., 2017; Cooper & Sommer, 2018; Engeln, 2020; Ulrich et al., 2020).

These characteristics often result in this section of the development process being referred to as the *"fuzzy front end"* (Cooper, 2014), *"Advanced Concept Design Process,"* (Macey & Wardle, 2014) or *"concept process"* (Ulrich et al., 2020). Besides identifying technical solutions and risks, and minimizing those risks, these stages also focus on the development of the vehicle's styling (Tovey, 1997; Kurz, 2008; Rudert & Trumpfheller, 2015; Feldinger et al., 2017; Ulrich, et al. 2020). Converging the technical and aesthetic solution spaces in the process is one of the fundamental conceptual tasks in the early phases (Feldinger et al., 2017).

There is virtually no information available about the exact processes in these early phases in the automotive industry (Kraus, 2007, Reichelt et al., 2022), other than about the basic characteristics of development work in these stages and general implications for the design process (cf., Reichelt et al., 2021; Reichelt et al., 2022).

2.3. The Role of Vehicle Design

There is no disputing the importance of product design: a product can only be marketed successfully if it has been well designed, making product design an intrinsic part of strategic PD (Oakley, 1990; Tovey, 1997; Kraus, 2007; Kurz, 2008; Meadows, 2017; Schmid & Maier, 2017; Engeln, 2020; Kraus et al., 2021; VDI 2424). Here, the general term "design" is understood to mean the complete development of a product, taking into consideration all aesthetic, functional, technological, economic, statutory, quality assurance, and homologation-related requirements (Oakley, 1990; Tovey, 1997; Cross, 2007; Kurz, 2008; Engeln, 2020).

Although it is not possible to split the content into aesthetic and functional PD (Kurz, 2008; Meadow, 2017), technical PD can be broken down into engineering design and industrial design (Ulrich et al., 2020). *Engineering design* primarily deals with the technical and economic aspects of function development (Feldinger et al., 2017; Ulrich et al., 2020), whereas *industrial design* focuses on shaping product perception (Tovey, 1997; Kraus, 2007; Kurz, 2008; Engeln, 2020; VDI 2424). A product's appearance creates an emotional bond between user and product, enabling it to be differentiated from competitor products and positioned in the market—which is achieved first and foremost by epitomizing corporate and brand values (Tovey, 1997; Kurz, 2008; Schmid & Maier, 2017; Engeln, 2020; VDI 2424).

No public or academic studies into the connections between the actual activities—in particular the interfaces and decision-making processes—are available. As far as the approach for industrial design development is concerned, only generally applicable methods can be found, such IDEO (IDEO, 2012), FROG design (Bobbe et al., 2016), or the double diamond (Design Council, 2007). The new VDI 2424 standard outlines a universal process without, however, describing the exact activities of the tasks involved in either vehicle design or DTC in detail. The general sequences of the process steps basically coincide with the generic descriptions found in the corresponding literature: The general approach used in industrial design is seen as an iterative procedure where design drafts are created then evaluated, decisions are taken, compromises are found, and modifications are made to the designs (Tovey, 1997; Cross, 2007; Kurz, 2008; Feldinger et al., 2017; Meadows 2017; VDI 2424).

According to Tovey (1997) and Kurz (2008), industrial design in the automotive industry is only governed by the basic understanding that it means styling the vehicle's appearance. Vehicle styling is normally carried out in a separate process, mainly involves defining the vehicle's shape as a fundamental activity of product design, and takes place independently of engineering design in the early stages (Kraus, 2007; Kurz, 2008; Feldinger et al., 2017; Engeln, 2020).

The industrial design process is essentially a subprocess and is integrated into the overall vehicle development process, particularly with respect to the milestones (Kurz, 2008; Meadows, 2017; Engeln, 2020; VDI 2424). This subprocess occurs in the early stage and concept stage. There is little validated academic knowledge about the exact work carried out as part of industrial design in general (Kurz, 2008).

There is an even more lack of academic knowledge when it comes to analyzing the automotive design process in particular, as very little detailed information is available externally (Krzywinski, 2011; Meadows, 2017). There is no reference process depicting the tasks of vehicle design (Kraus, 2007). This is mainly down to the fact that, although—according to Tovey (1997) and Cross (2007)—there is a common understanding among designers about how to design a vehicle, it is difficult to convey this process in the form of clearly worded descriptions or illustrations. There is only the occasional insight based on practical experience at the OEMs, as design work represents a core competency and as such is classified as top secret. The few insights that are offered either describe the basic steps of design development, particularly in terms of how it fits into the overall vehicle development process (e.g., Rudert & Trumpfheller, 2015), or they present individual elements of the design process (e.g., BMW, 2012; Audi, 2017; Mercedes-Benz, 2017).

2.4. Design-Technology Convergence

As Tovey (1997) points out, the collaboration between engineering and industrial design during car development is something of a special case. At the start of the development project, the two areas are primarily focused on their own targets and tasks, initially resulting in a separation between the work carried out by the engineers and that of the designers. This is mainly because the two disciplines work in opposing directions while developing (Engeln, 2020): engineering designers start off by developing smaller details at the module and component level and finally put these together to form a complete product, whereas industrial designers first develop the vehicle's overall look and then turn their attention to the smaller details over the course of the early phases.

This division tends to be overstated though and in actual fact the two areas constantly liaise with one another within the applicable development and decision-making units in order to ultimately develop a satisfactory product (Braess & Seiffert, 2007; Beier, 2013; Feldinger et al., 2017; Engeln, 2020).

This process is known as DTC and refers to the progressive amalgamation of styling and technological developments (Braess & Seiffert, 2007; Kurz, 2008; Feldinger et al., 2017). This joint work forms the core task of the concept stage and leads to some conflicting objectives that have to be resolved (Bryant & Wrigley, 2014; Feldinger et al., 2017; Meadows, 2017; Engeln, 2020). Current automotive developments, such as powertrain electrification or automation of vehicle functions, have the effect of altering the vehicle's proportions (Luccarelli et al. 2014; Holder, 2021), requiring particularly close communication during the DTC process.

In order to drive this convergence between the two areas of development, an iterative approach is used (Kurz, 2008; Feldinger et al., 2017; VDI 2424). Design drafts are produced, usually by the industrial design team, which are then checked and evaluated by the engineering design units for technical feasibility and fulfillment of boundary conditions. These feedback loops and efforts to find compromise solutions ultimately serve as the basis for ongoing refinement of the vehicle design (on both an aesthetic and technical level). However, there is no information available in the literature about the exact activities or the timing and content of processes (Braess & Seiffert, 2007; Kurz, 2008; Krzywinski, 2011; Meadows, 2017)

2.5. Research Gaps

The procedural descriptions of vehicle development outlined above illustrate how development basically follows a set sequence of activities. These are aligned with central decision gates intended to guarantee standards of product quality.

Producing a depiction of the interaction between all the departments involved poses a challenge due to the car's high level of complexity. There are additional gaps in the knowledge required for describing vehicle development—the interrelations between the individual units involved in automotive development have either not been studied at all in the past or there has only been a focus on very specific content. There have not been any academic publications so far on the interrelationships and procedures of industrial design. At the same time, the worlds of theory and practice agree that product design is a fundamental factor in achieving product success. These tightly interwoven procedures are some of the most important steps in the early and concept stages and determine whether a vehicle will be a success or not. The process of DTC has not yet been systematically examined from the viewpoint of the players involved.

Making lasting changes and improvements to a process requires an exact understanding and detailed knowledge of the procedures, activities, and influencing factors (Clarkson & Eckert, 2005). As a great deal of uncertainty exists regarding the exact processes and procedures in the early phases of vehicle development, particularly about DTC, our study addresses this research gap. We will provide academic insight into these key stages of vehicle development and the collaboration between engineering and industrial designers.

3. Methodology

Based on the results of a systematic study of literature (Section 2), the following research questions (RQ) were formulated.

> *RQ1: What is the actual sequence of steps carried out when developing a vehicle in the early phases of the process, as experienced in practice?*
>
> *RQ2: How does the industrial design process work in practice in the automotive industry?*
>
> *RQ3: How does convergence between engineering and industrial design work in the early phases of vehicle development?*

An expert workshop was devised to harvest their real-world knowledge and answer these RQs. The fundamental principles researched in the literature served as the starting point for planning the workshop. The workshops were divided into two parts: an interview and an interactive workshop.

The interview was a structured interview (Döring et al., 2016) during which open-ended and closed-ended questions were asked. Two fundamental elements of the interview involved recording demographic data and appraising personal expertise regarding vehicle development or, more specifically, the areas of design, ergonomics, and technological development. The experts were also asked general questions about their knowledge and understanding of project management. Regarding evolution of the design process, particularly in terms of DTC, targeted questions were put to the interviewees to characterize the current state of the design process.

According to Cross (2007), it is important to speak to the players directly involved in the development process, especially in the field of industrial design, to obtain genuine insights. A generic, noncompany-specific vehicle development process was, therefore, modeled in the interactive workshop together with the experts in order to harvest their

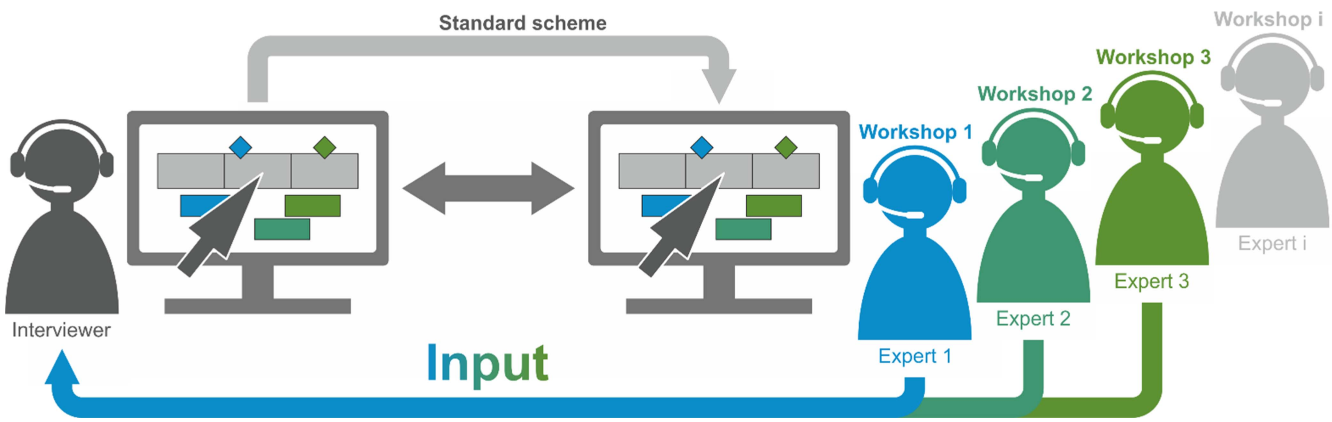

Figure 1. Visualization of the procedure for the workshops.

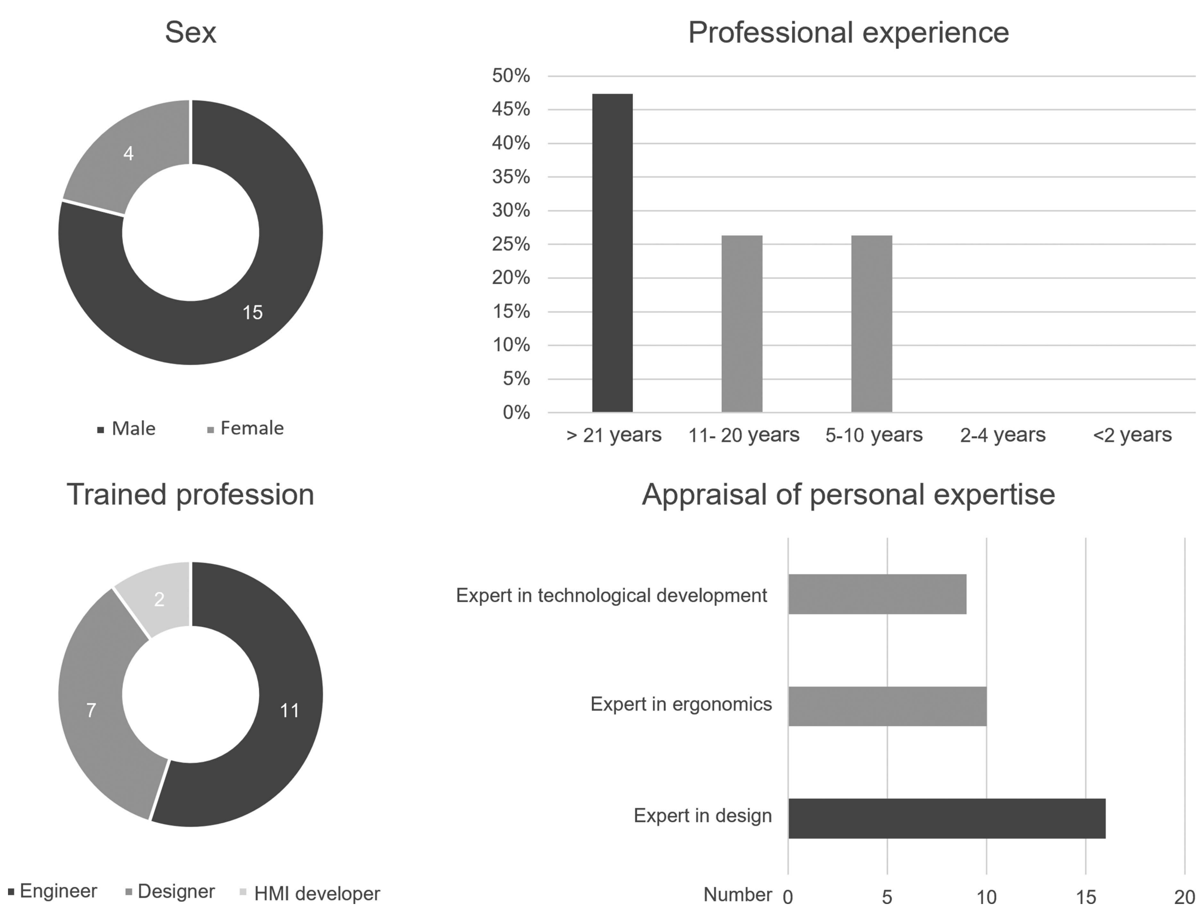

Figure 2. Overview of demographic data for the experts.

practical know-how and map out their knowledge of the subprocesses and design process. To this end, a virtual whiteboard was used to create a reference procedure from the viewpoint of each expert with the help of building blocks and templates. The interviewer and the expert worked on various key questions together on the virtual board. However, these key questions merely served as a starting point for a free discussion about the respective processes. These questions included general information regarding the starting and ending points of each process, as well as central milestones during the process. To gather more real-world impressions especially the interaction between different areas of design, ergonomics, and technological development was discussed. At the end of each interactive process modeling workshop, the focus lied on the involvement of the users during the different processes.

The expert's stated fields of expertise were used to always model precisely those (sub-)processes in which the expert could demonstrate appropriate practical knowledge.

Once the interviews had been completed, the individual reference models produced in each interview were categorized and compared with one another in terms of the (sub-)processes in order to ultimately derive a generally applicable procedure.

The workshops took place between July and November 2021. Experts were chosen who offered at least one of the required areas of expertise as a result of their education/professional training or their occupation. A total of 21 workshops were held.

All the experts could be assigned to one of the three focal points of the study (design—ergonomics—technological development). Incomplete data meant that only 19 of the datasets obtained were suitable for evaluation.

The workshops took the form of individual appointments in Microsoft Teams. The questionnaire for the interview was completed with each expert using the screen-sharing functionality. The interviewer made a note of what was said by the expert, who was able to follow what was being written. All workshops were hosted by the same investigator with compulsory guidelines to ensure they were all staged in a consistent, comparable form, especially the interactive workshop section. Figure 1 shows the procedure for the workshops as a diagram.

As shown in Figure 2, four of the 19 experts were female (21%). All experts had at least five years of professional experience in their specialist area. A total of 47% of the experts actually had over 20 years of professional experience (most experience was 38 years). Based on their own appraisals, experts from the field of design (84%) could be seen to predominate slightly. It is important to note here that it is possible to be an expert in multiple areas. According to this distribution of the different expertise at least 9 processes of the typical technological development, 10 ergonomic processes and 16 design processes could be noted and are considered in the final derivation of the reference process.

4. Results

The results of the workshops conducted have been transferred into the generally applicable procedure for the early phases of vehicle development presented below with the key milestones incorporated into the overall process. The various areas of the early phases on which this article concentrates are then explored in greater detail: design process, design models and tools, ergonomics, and DTC.

4.1. Basic Vehicle Development Process in the Early Phases

The process described below is primarily based on the workshops conducted. Some of the individual elements coincide with the theorems outlined in Section 2 or published examples from industry.

The process presented here is a generalization and describes the fundamental stages and milestones in the early phases of automotive development. Here, "early phases" is taken to mean all activities carried out from the initial product idea through to the handover to production development. These activities, therefore, encompass the "early stage" and "concept stage."

The process sequences, terms, and content furthermore only refer to vehicle development procedures in general. Each OEM has its own individual procedure adapted to its company. Only the basic elements and processes are described here and not an OEM-specific procedure.

It was necessary to synchronise the varying chronological sequences when compiling the overall PDP. For this reason, it was decided to dispense with the custom of stating the months until SOP. Each development project is unique in terms of the set task, organization, employees involved, etc. The type of development alone (new/variant/updated design) results in varying requirements and, therefore, also has an impact on the project's organization, resources, financing, and methodology. We, therefore, describe the general procedure for a new design here as this involves completing most processes and stages.

As illustrated in Figure 3, the early phases of the automotive development process can be broken down into four stages and six milestones. In contrast to traditional stage-based models, we have used overlapping stages to reflect what occurs in practice: Work on the content of each stage commences before key milestones are reached and does not automatically finish at a particular milestone. The procedure is often assumed to have a strict, linear structure but this is not workable in practice. This does not, however, diminish the meaning and importance of milestones as chronological and content-related reference points for various development departments.

The vehicle development process in general can be split into the early stage, the concept stage, and production development (see Section 2.1). In the period prior to the project's official start, all fundamental questions relating to the upcoming project are clarified in the "early stage" as it is known.

In this *strategy stage*, a strategic orientation is derived for the vehicle being developed based on corporate strategy. Strategic questions covering all relevant aspects from the areas of finance, procurement, corporate development, technology, and sales are also addressed. This is then used as a basis for making initial assessments of the strategy to use for vehicle architecture, platform, technology, design, and brand.

In order to clarify or weigh up these questions, "pre-development projects" are started on subaspects or conceptual overall solutions, while also factoring in results from previous projects. These predevelopment projects usually have a duration of 12 months and focus on new technologies, architectures, or platforms. The results can be applied to multiple products. It is, however, not uncommon for predevelopment projects to be set up with a concrete connection to a reference product. This may lead to the creation of a show car, which could combine a series of innovative results from several different predevelopment projects or build on a single project. The objective of these show cars is to gauge public reaction and the innovation's potential for success. Show cars can range in their level of feasibility from fully functional prototypes to styling models. Another objective of pre-development projects is to showcase the industrialization of new technologies and the evaluation of inventions both from a conceptual and an economic perspective.

In addition, new requirements are compiled from the current models on the market or feedback from the market. Parallel to this, user

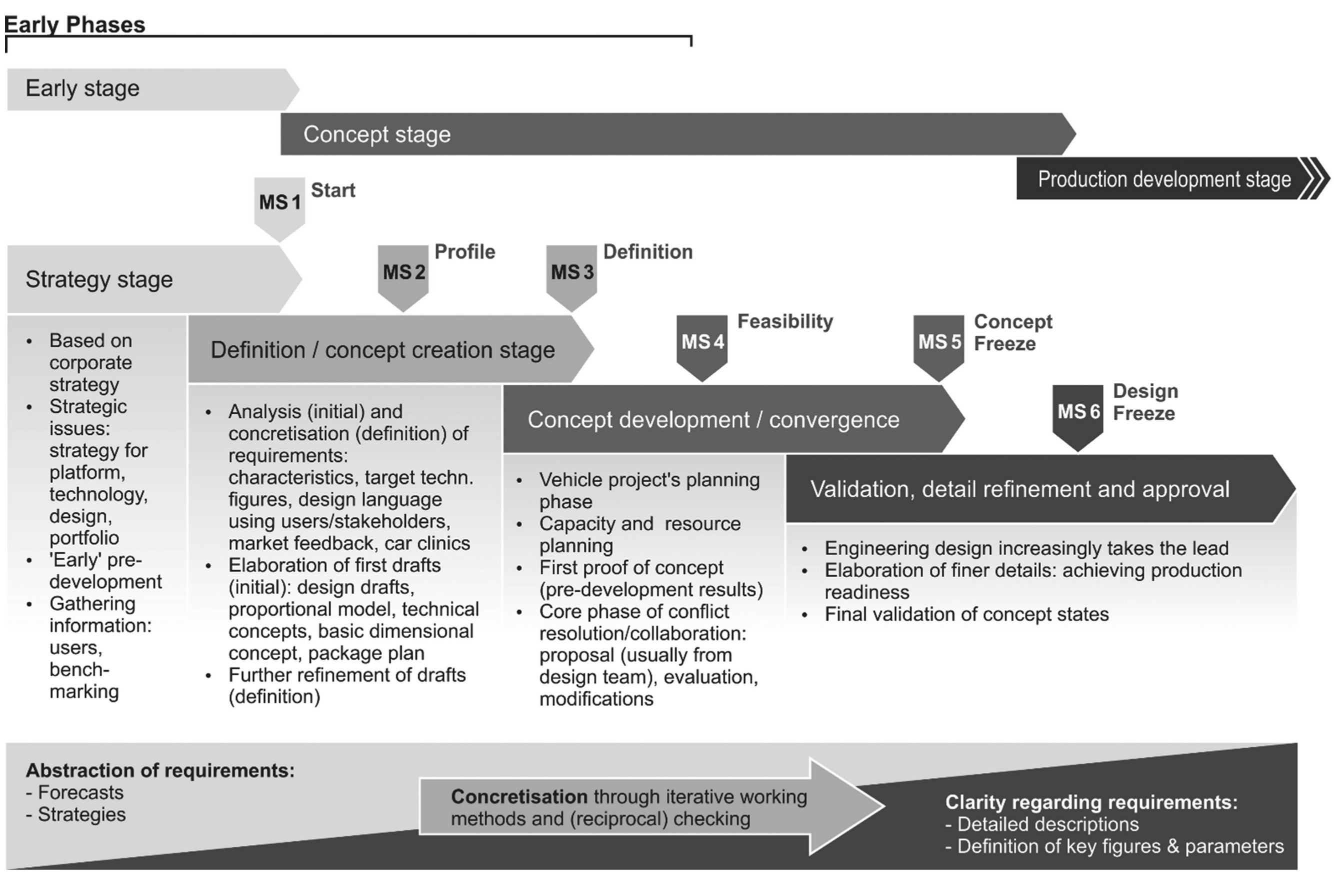

Figure 3. General stages and milestones in the early phases of automotive development.

surveys are carried out along with benchmarking of competitor models.

The key endpoint of this stage comes at milestone 1, "Start," at which point a "project profile" will be ready. Besides detailing a rough financial framework and timeframe, this overview describes a target vision for the vehicle from a corporate strategy perspective. This broadly defined set of targets marks the project's starting point for most of the technical specialist departments.

The *definition*/*concept creation stage* begins in the run-up to the official project start (MS 1) and comprises the two milestones "Profile" (MS2) and "Definition"' (MS3). Up to MS 2, the activities of the specialist departments mainly revolve around an initial analysis of the fundamental requirements. The aim is to analyze the characteristics, target technical figures, and design language with the help of user/stakeholder surveys, market feedback, and car clinics.

To this end, initial design drafts, proportional models, technical concepts, the basic dimensional concept, and the package plan are already elaborated. This analysis produces a "product profile," which is ready by MS 2. This contains a qualitative catalog of product characteristics and describes the framework specifications for continued development from the development departments' point of view.

Once this qualitative catalog of characteristics has been signed off by top management, the departments begin to specify further characteristics of the vehicle being developed based on the results of the analyses. This process of "concretisation" involves defining the vehicle by MS 3 by setting out concrete dimensions, data, and requirements. At the same time, the first concept drafts (design, ergonomics, and technology) are further refined in accordance with the set targets. Lastly, all quantitative target values for the vehicle have been stipulated at MS 3 and specific sets of requirements defined for continuing with the vehicle's design.

Over the course of MS 3, the *concept development*/*convergence* stage gets underway. This stage features the milestones "Feasibility" (MS 4) and "Concept Freeze" (MS 5). The already final concept idea usually continues to be developed up to MS 4. The specific planning of the vehicle development and production processes can be considered the fundamental element of this stage. This is when the central resources and capacities are planned for the remainder of development until SOP. Further to this, the first proof of concept is carried out by this milestone too, meaning that the various statuses of the vehicle technology, design, ergonomics, and concept are thoroughly checked for feasibility. Finally, an initial version of the specification book is ready at MS 4, along with a detailed evaluation of the concepts, meaning that a decision on a final concept has already been made by all departments or can definitely be taken.

Following MS 4, the concepts continue to be elaborated and work begins on the first details. Final decisions on the technological concepts have been made by MS 5. The vehicle's final design (styling) has been confirmed and approved by all development units, so the main surfaces are already frozen. Overall, vehicle manufacturability has been ensured and the specification book finalized to a point where the first procurement orders can start.

In general, the concept development/convergence stage can be viewed as the core phase of the liaison process between all units when designing a new vehicle, as it is now that most conflicting objectives need to be resolved in order to ensure that DTC has been validated by MS 5.

The final stage in the early phases of automotive development typically starts shortly after "Feasibility" (MS 4) and runs in parallel to concept development until MS 5. All work during this stage focuses primarily on *validation, detail refinement, and approval* of the final vehicle. As already indicated, the various concepts are checked and validated regarding technical, statutory, and production-related requirements. Whereas it is mainly the design departments that inject the concept with new impetus in the preceding phases and play an instrumental role in driving the concept's development forward, the production design team now takes the lead in this stage. This is primarily because both the technologies and the design will be readied for production during this stage and either the concepts or the end overall concept will undergo final validation.

The early phases conclude with the "Design Freeze" (MS 6). Once this milestone has been reached, the more detailed surfaces and, therefore, the whole vehicle are frozen. From this point in the process, if not before, the design department only plays an advisory role regarding the vehicle's geometry. The specification book has also been completely formulated, allowing production development to get underway so that production design, procurement, production planning, and homologation can be carried out. Ideally, the vehicle will be finalized in its entirety by this point. In reality, though, modifications and recursive processes still need to be carried out far into the subsequent production development stage. These can become necessary while finalizing the technical design or carrying out the type-approval process or as a result of external influencing factors, such as laws or market developments.

Two shifts in project responsibility can be observed over the course of the early phases. At the project's start, responsibility lies mainly with top management, who lays down requirements for the vehicle based on strategies and forecasts. As the project progresses, these requirements are first put into more specific terms by the departments and finally described in detail and defined using key figures and parameters. This is carried out primarily by the development departments. Top management, therefore, decides the specified requirements, while the actual task of elaborating, finalizing, and ultimately implementing them falls to the developers.

The second transition takes place during concept development, when responsibility shifts from the design departments to the engineering departments. These interrelationships will be examined more closely below.

4.2. Subprocesses of the Early Phases Taking the overall procedure in the early phases of vehicle development as described in Section 4.1 as a basis, the following takes a closer look at the core subprocesses of design, ergonomics, and DTC.

The focus here is the design process. This is described first in terms of the activities and processes carried out by the design departments. Second, we also provide a general overview of the models and tools used over the course of design development. We then move on to the tasks performed by the vehicle ergonomists. This section concludes with an in-depth description of the DTC.

Like the description of the general procedure in Section 4.1, the results obtained from the processes modeled in the workshops were synthesized. The design and ergonomics processes were both modeled by experts from the corresponding specialist departments. The procedures depend on the particular project and have been deliberately presented in a higher level of abstraction, making it impossible to draw any conclusions regarding OEM-specific processes. The activities involved are basically the same in terms of content; all that differs from manufacturer to manufacturer are the chronological and terminological descriptions.

All activities in the subprocesses are illustrated in Figure 4. The subprocesses start and finish at asynchronous points of the development project. The superordinate milestones serve as central synchronization points.

4.2.1. Design Process The design process described below depicts the general sequence of steps carried out for a new design. This type of project presents the design unit with the most tasks, and development of designs for new models has become a core competency of the OEMs. It should further be noted that exterior and interior design are described jointly here. The two areas are often developed separately from one another in practice, but their basic characteristics are nearly the same on a procedural level and they are very dependent on each other (Holder et al. 2018).

As already discussed in Section 4.1, a transition in responsibilities takes place during the design process: When the development process first starts, the design departments are actively involved, meaning that the design team submits proposals for the vehicle and is, therefore, instrumental in driving development forward. In some instances, responsibility for overall project management remains with the design-related studio engineering units. In addition to this, the design department has control over the design of the vehicle's shape in these early phases. Over the course of the process, the responsibility shifts from the design department to the engineering department. The design department then plays an increasingly passive, advisory role.

The design tasks begin in the strategy stage. A fundamental element of the design work is to detail/define the *design strategy* for the upcoming model. For this, various points for the new model's design language are derived from the corporate design philosophy. Initial visualizations play a vital role here, as does the question of the brand design's strategic orientation. According to Andersson & Warell (2015) and Fischer et al. (2019), two different forms of brand design can be distinguished here: Historical associations, also known as design-DNA, are used to highlight a model's similarity to its predecessor and thereby strengthen brand image. And the product portfolio comprising different models from the same brand and generation can serve to build and reinforce brand image. These strategic design considerations are also factored in to produce target and key themes at the project's official start to act as a guide for the designers in the subsequent design competition.

When the project starts, the *design context* is clarified among the design departments. This involves analyzing both design trends and competitors regarding any potential for the model's own design, based on the strategic information known about the vehicle so far. External design studios are commissioned here in some cases or findings from specific target markets (advanced studios) are incorporated.

Following the official start, the process of *design selection* commences in the design departments' studios. In order to generate as many different design proposals as possible, an internal design competition is held: Several

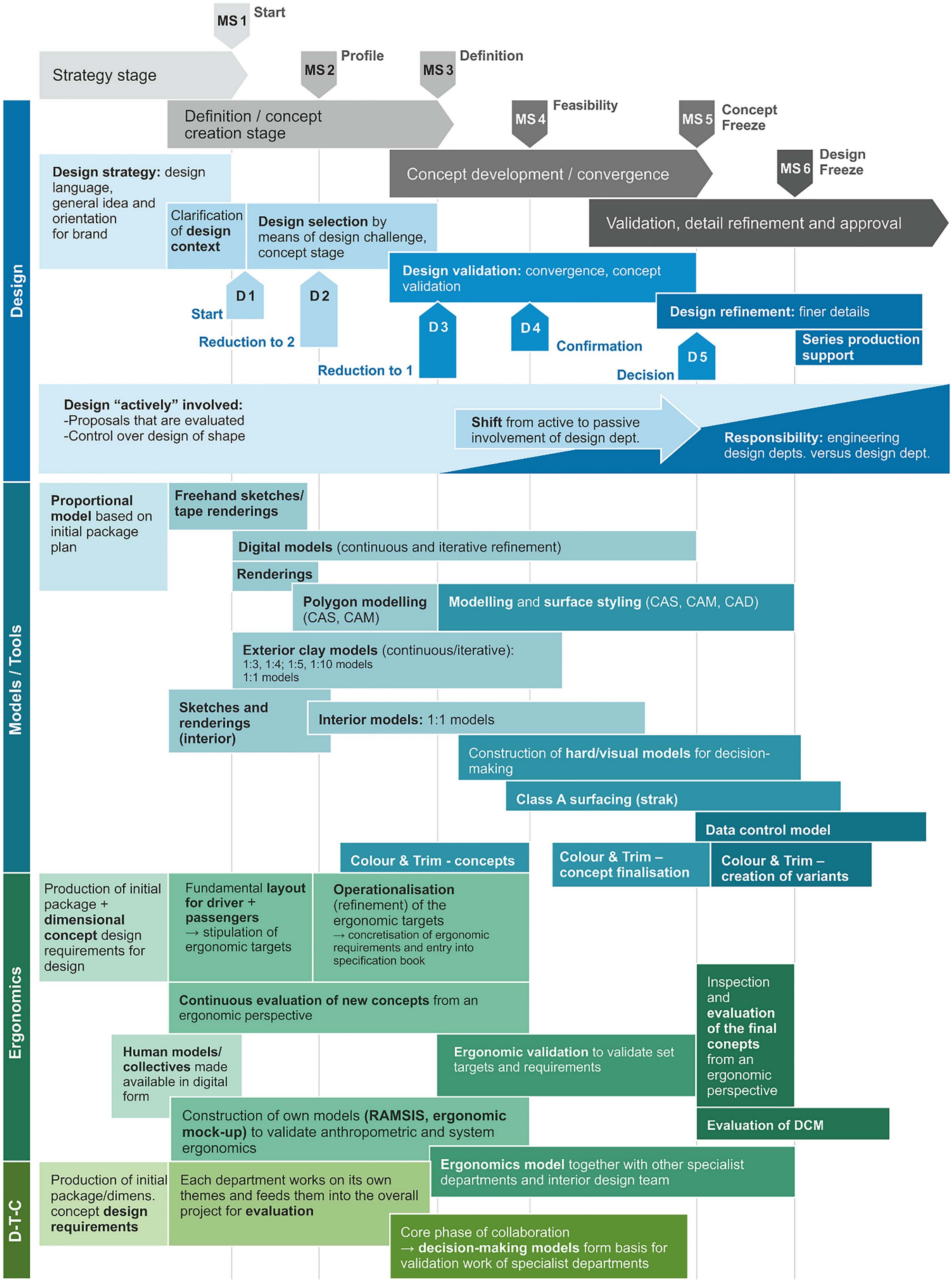

Figure 4. Illustration of the steps in the design (incl. models/tools), ergonomics, and DTC subprocesses.

designers each create their own design concept based on the key themes and basic information about the vehicle. These are evaluated, reduced, and refined on a continuous basis. Evaluation is primarily carried out internally in the design studio when the concept is at a very early stage. The designs are narrowed down to just a few concepts, usually two, at MS 2. By this point at the latest, the decision in favor of the two most promising and most contrasting designs is already taken based on evaluations from the technical departments. These two design concepts continue to be elaborated until MS 3 before being reduced to the final design at MS 3. As the design is of fundamental importance to the product, the decisions at D2 and D3 are taken by the board of management. There is a live presentation of the models, and the decision also takes into account the results from the technical evaluation of the designs.

Design validation begins in the run-up to MS 3. The activities carried out in this stage aim to converge all the concepts created to date (design, technology, ergonomics, aerodynamics, etc.) into a complete vehicle. Concept validation is another objective here, which involves undertaking a critical examination of the overall vehicle concept to check it complies with both internal targets (e.g., quality requirements) and external ones (e.g., legislation and customer benefits) and improving it as necessary. This stage is the core phase of the DTC process that is described in detail later. MS 4 (Feasibility) is, therefore, a key milestone as it is at this point that the selected design is confirmed: Ideally, the previously selected design will be confirmed as the design for a fully functioning, manufacturable vehicle by all departments. Based on the result at D4, the vehicle concept continues to be developed so that at MS 5 (Concept Freeze) the shaping of the vehicle's main surfaces has been defined, i.e., frozen. This means that, from this point onward, no further dimensional changes are made to these surfaces and the engineering departments can start work on finalizing the design.

MS 5/D5 represents the most crucial milestone in the design process, as the majority of the design work has been completed by this point. Overall responsibility for the vehicle project typically switches from the design departments to the engineering design departments as part of this milestone. During the subsequent *design refinement* phase, the design department concentrates on the vehicle's finer details, such as color and trim or designing the equipment variants. The design department's resources involved in the project are also normally scaled back significantly at this point.

Once MS 6 (Design Freeze) is reached, all of the vehicle's surfaces will ideally be classified as frozen. So, from this point, the design departments assist the production design team in an advisory capacity to help, e.g., adapt the design as a result of production-related changes. This *series production support* role usually comes to an end with the "Production Freeze" (not shown).

4.2.2. Design Models and Tools

Various models and tools are used over the course of the design process. The different models and tools are presented separately in this section to give a more precise overall picture. The use of models and tools is directly linked to the corresponding stage of the design process as described in Section 4.2.1. One of the principal functions fulfilled by the models and tools is helping with the shaping process. Digital, virtual, and physical models are deployed for this purpose. Second, the models serve to evaluate and validate the design and by that serving as decision-aid.

Proportional models are created as part of the design strategy. These are based on the dimensional concept and the initial basic package plans derived from the strategic requirements for the new model. They are used to determine significant measurements and, first and foremost, proportions, such as the wheelbase, front and rear overhang, ratio of glasshouse to body, etc., and incorporate them into the key design themes and objectives.

Freehand sketches and renderings are used for the early stages of design selection as well as for clarification of the design context. According to Bao et al. (2018), sketching is the most used method for generating ideas in the early stages. Tape renderings are mostly used for the exterior design, whereas digital renderings are already employed for the interior. Several digital renderings of the exterior and interior are usually available by MS 2. These serve primarily as decision aids for D2 ("Reduction to 2").

Digital models are produced when the design competition gets underway at the official project start (D1). These models undergo continuous and iterative refinement. They mostly consist of digital drawings at first. From D2 at the latest, however, *polygon models* are constructed in CAS and CAM tools. This data makes it possible to create virtual representations from various perspectives and with different surroundings and lighting conditions. These virtual representations assist the design and evaluation process using actual clay models, which are discussed below. The process of *modeling and surface styling* (CAS, CAM, and CAD) begins at D3 at the latest once the final design theme has been selected.

Physical models are made in addition to the digital models. Work also starts on *clay models* when the design competition begins. These are typically built to a small scale in the early contest and act as a communication medium both in the important steps of the shaping process and during design evaluation and selection. 1:1 models are constructed by D3 at the latest and are already built at D2 in some instances. These mainly serve as real-life decision-making aids for choosing the final design theme. The models then continue to be refined until D4 and are again used to help make decisions at this milestone. In contrast to the exterior design, usually only *1:1 models* are created for the interior as a basis for decision-making. The construction of these models does not begin until D2 has been reached.

Hard models or *visual models* are also built from D3. These are usually milled from plastic, making them difficult to modify. Consequently, these models are primarily used for the final round of decision-making or design validation.

Generally, the *class A surfacing (strak)* process begins before milestone D4. The aim of the work carried out here is to create manufacturable surfaces in CAD (Class A, B, and C surfaces) based on digital design models. Potentially critical design surfaces of the fully assembled vehicle are additionally visualized and evaluated as part of the strak process and solutions are proposed.

In parallel to the exterior and interior shaping work, the *color & trim* studios work on the design of the color scheme as well as the design of surface finishes and materials. These studios begin to prepare concepts after D2. After selecting suitable concepts as part of D4, these concepts are finalized. Following MS 6 (Design Freeze), the process of creating variants for selection in the configurator takes place.

The *data control model (DCM)* is classified as the final design model. It combines all the vehicle's dimensions in a single model and provides the data basis for production development. Work on creating the DCM usually starts over the course of D5 and the model is continuously refined.

4.2.3. Ergonomics Process

The following describes the ergonomics process in the early phases. When considering the ergonomics work during vehicle development, a distinction must be made between system ergonomics and anthropometric ergonomics (Bubb, 2021).

1) *System ergonomists* concentrate primarily on the control and operation of HMI systems. Schmid & Maier (2017) refer to this as microergonomics.
2) *Anthropometric workplace designer* work on all matters relating to the dimensional concept during automotive development. These can be termed macroergonomic tasks according to Schmid & Maier (2017). There is a standardized procedure for dimensional concept design according to Müller (2010).

The process described below refers to the anthropometric design of the vehicle concept, i.e., the creation and analysis of the dimensional concept's macroergonomics.

At the start of the strategy stage, the technical departments produce the initial package and *dimensional concepts*. These are based on both the details of the model's strategic orientation and the dimensions of the predecessor model, assuming one existed. This approach ensures explicit consideration is given to any feedback from the market in terms of ergonomics-related observations or customer complaints.

Producing the initial description of the new model's dimensional concept generally involves specifying and, if applicable, revising the *human models and collectives* that are to be considered on an anthropometric level. The families of digital models used (Bubb, 2021) are compiled based on the defined target markets and customers and made available in the form of digital manikins, usually with the aid of the RAMSIS software or similar software tools.

The core task of the ergonomics department gets underway following the official project start. Taking the strategic information and initial thoughts on the concept as a basis, a fundamental *layout* of the *driver's cockpit* and *passenger areas* is created. For this, all relevant dimensions and dimensional chains are derived from the digital human models while placing them ergonomically in the vehicle in the anthropometric positions in accordance with their role (driver or passenger). Based on this positioning, key dimensions are stipulated that are necessary in order to meet ergonomic targets. These targets are communicated to the other departments as requirements.

From MS 2 onward, the previously defined targets are *operationalised* (quantified and regularly checked for feasibility) and refined. By conducting various analyses and evaluations, the requirements in terms of ergonomic design are gradually concretized until they are finally entered into the specification book as fixed targets (MS 4).

In parallel to its own development of the dimensional concept and the ergonomic requirements and targets, the ergonomics department also evaluates the concept proposals regarding their fulfillment of ergonomic specifications. This *ergonomic evaluation* is factored into the decision-making process, e.g., when selecting design themes.

The department begins to construct its *own models and mock-ups* as soon as the project starts. The aim of these models is to validate the ergonomic specifications and targets by MS 4. At first, the models are primarily created in digital and virtual form (RAMSIS, VR environments). An ergonomic mock-up with all relevant anthropometric dimensions depicted on a 1:1 scale is usually constructed for feasibility approvals (MS 4).

The task of *ergonomic validation* commences when the concept development/convergence stage starts. The focus here is on validating the concepts from the other departments as well as the ergonomic department's own concepts with regard to the set ergonomic targets and requirements.

Following "Concept Freeze" (MS 5), the ergonomics department performs a *concluding evaluation of the final concepts* from an ergonomics perspective. At the same time, iterative *evaluation of the data control model* with regard to its ergonomic aspects begins.

For this purpose, it constructs its own, physical *ergonomics model* in collaboration with other relevant departments and the interior design team. This 1:1 model of the vehicle interior will represent the final state of the concept by "Design Freeze" (MS 6). The aim of this model is to help the decision and validation process by making it possible to experience the interior and its ergonomics.

4.2.4. Design-Technology Convergence As outlined in Section 2, the term DTC refers to the collaboration in general between the engineering and the design departments.

The technical departments pass on the requirements defined during the strategy stage to the design team in the form of, e.g., dimensional target points. Using these *design requirements* as a basis, the design departments set about their work as described in Section 4.2.1.

Following the official "Project Start" (MS 1), the individual departments prepare their *own themes and concepts* that serve primarily to either specify or fulfill their own requirements. In the technical departments, this work is mostly carried out on a component or module level, whereas on the design side, it is split up into the areas of exterior and interior. The concepts that are created are fed into the overall project for evaluation, enabling the other departments to assess the concepts in terms of their own requirements or specify their own requirements to align them with the other concepts.

The various individual concepts are already combined into joint overall concepts during the run-up to "Definition" (MS 3). This amalgamation of the different concepts forms the *core phase of the convergence process*. This is when conflicting objectives are resolved, and decision-making models are created. These models form the basis for the validation work performed by all departments until the vehicle concept is finalized at "Concept Freeze" (MS 5).

The procedure for converging the various concepts and finally the conflicting objectives to form a complete vehicle is described in more detail below. This convergence process begins in the strategy stage and ends by SOP at the latest. It happens at varying levels of intensity, however, particularly during the early phases. The following description, therefore, focuses on the core convergence phase that takes place toward the end of the concept stage.

Because of the tradeoff that traditionally takes place between aesthetic appearance and functional implementation, the process of amalgamating the respective concepts is usually described as a convergence *"funnel"* in literature (Kurz, 2008; Gusig & Kruse, 2010; Engeln, 2020; Widmann et al., 2021). This description is used with the aim of visualizing the gradual (iterative) convergence of the concepts from the different departments (see Figure 5).

Kurz (2008) describes this procedure as seen from the design perspective as an iterative loops, in which the proposals from the design department are evaluated by the other departments on the basis of models. Design then uses this evaluation to make the corresponding modifications and the more specific design draft is submitted for evaluation again. This process is reiterated until all conflicting objectives have been resolved or an acceptable compromise is found.

In practice, the tasks of shaping the vehicle and technological development are not carried out by individuals working alone. Instead, the concepts are usually the work of several developers and designers. Even when creating ideas and concepts, they are generally discussed in detail in interdisciplinary teams. Various disciplines are represented within the developer teams on a component level, ensuring that the fundamental framework conditions of the areas involved are normally already taken into account when creating the initial concepts. Design is the only discipline that deviates from this approach, with the proposals for the vehicle's styling primarily created in the design department by designers and modelers. Once they reach a certain status or have been reviewed internally, they are passed on to the other departments for evaluation. The reasoning behind this is that the very first ideas should take shape within a deliberately protected area to ensure that new and creative approaches are also given the necessary room to develop. Sooner or later though, there will come the first points of contact, after which there are usually smaller groups of sparring partners from design and engineering.

The procedure identified by Kurz (2008) can basically be applied to the entire DTC process. Concept ideas (I) are elaborated in the corresponding teams and already take fundamental aspects from other departments into consideration. The concepts that are developed are checked by further departments regarding their own requirements for the purpose of validation and evaluation (E). The concept team uses the feedback from this review as a basis for deciding what modifications (M) need to be made to the concept.

Figure 5 provides an illustration of the synchronization between the different units. This shows how the loops comprising *concept idea*, *evaluation,* and *modification* become tighter, meaning that the divergence in content is gradually reduced and there is a greater likelihood of resolving any conflicting objectives. A successful convergence process brings with it a growing mutual understanding of the problems experienced by the individual departments.

At the key milestones in particular, concept evaluations are performed by the departments that devised and laid down the technical requirements for the concepts. These reviews of the fulfillment of requirements are submitted to top management as the basis for making or confirming major concept decisions.

5. Discussion

During our literature research, it became clear that a research gap exists in the early phases of vehicle development, in particular regarding industrial design, ergonomics, and the DTC. There is little scientific knowledge available in the literature, especially about the individual activities and the interaction between these areas, or the topic is only considered at an abstract level (see Section 3).

We invited experts from the German automotive industry to describe actual applications in vehicle development. Deliberately selecting a wide variety of experts in terms

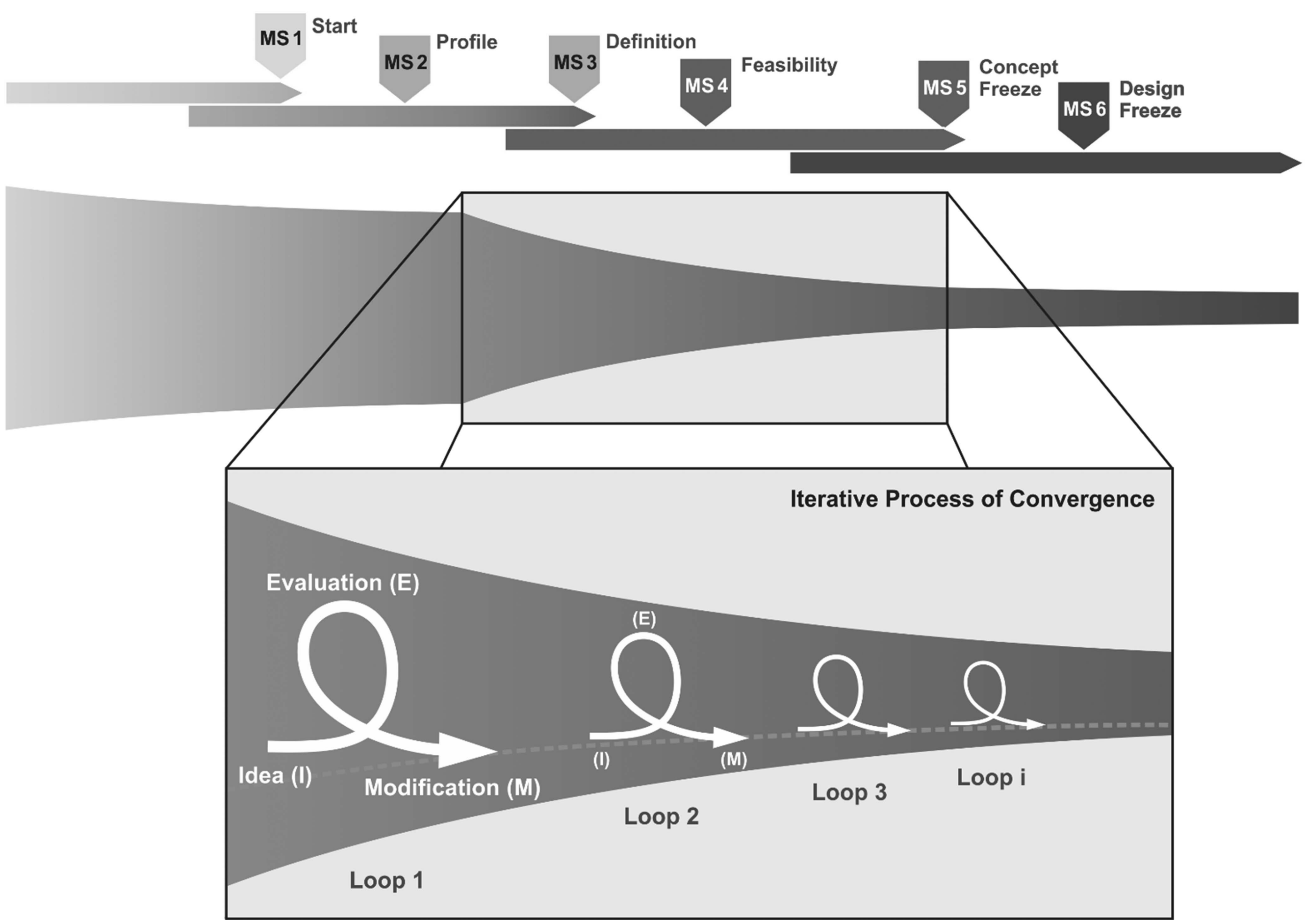

Figure 5. Visualization of the process of iterative convergence between the units involved in DTC, as per: Kurz, 2008; Gusig & Kruse, 2010; Engeln, 2020; Widmann et al., 2021.

of fields of application in the early phases of the PDP made it possible to register the various activities and interrelationships from real-world practice. It was possible to confirm known assessments from the literature on the vehicle development process and project management. Asking open-ended questions provided room to gather more practical knowledge and record characteristics of the processes, which have not been presented in theoretical-abstract considerations to date. All in all, the chosen format of the investigation provided a comprehensive picture of individual perceptions of the vehicle development process from the perspectives of the various development areas. The reference process presented is a combination of deriving central elements from scientifically proven general process elements and the specific insights of the experts interviewed on lived practice, including consideration of the collaboration between design and technology. This combination and the qualifications of the numerous experts result in the high validity of the process presented.

The vehicle development process differs only slightly from OEM to OEM, yet there is a high level of secrecy in the processes. For this reason, the reference process synthesised by us had to be standardized and abstracted so that no conclusions can be drawn about individual companies and their processes, specifically in terms of wordings. The general processes and milestones fit the phases and milestones found in literature and primarily serve the purpose of quality assurance. The intervals between milestones are likewise company-specific, so we deliberately avoided the $t = SOP - X\ months$ data typically used.

In order to enable an undistorted and universally valid reference process, simplifications were made and the process for new designs was deliberately modeled by the experts. This is the most complex type of vehicle development process (Weber, 2009; Gusig & Kruse, 2010; Raabe, 2013). In principle, our reference process describes the logical sequence of development activities at an overall process level as well as for the selected subprocesses. For the application of the reference process, it must be considered that the scope of the necessary activities and the scope of the relevant decisions primarily depend on the type of development project involved (Engeln, 2020). Furthermore, the process shown here can only be used as a reference, as every development project is unique, and all the people involved in the project have a significant impact on how the process is conducted. The fact that orientation within the overall process is generally helpful in the management of the project has been confirmed several times by the experts. However, practice shows that the statically depicted process is highly dynamic, which means a context-based adjustment of the timelines can be observed. In addition, processes are often depicted in the literature with hard phase transitions (e.g., Ruder & Trumpfheller, 2015). In practice, there is always an overlap between the phases, as work from later phases is sometimes started before central milestones, or further adjustments from the completed phase must be carried out after decisions have been made.

With regard to the industrial design process, with the help of the experts we mapped a dedicated sequence of design activities in order to ultimately present a consistent sequence of logical tasks and activities—from the initial product vision and the design strategy to the final selection of the design theme and the conclusion of the process with the design freeze. The characteristics of the working method, which the experts described to us as primarily incremental and iterative, match the basic descriptions from the literature (see Kurz, 2008; Feldinger et al., 2017; Meadows, 2017). The basic principle of DTC reflects the iterative sequence of the development of a design solution, evaluation, or validation of the solution by the technical departments and further development of the solution based on the results of the validation (Tovey, 1997; Cross, 2007; Kurz, 2008; Feldinger et al., 2017; Meadows 2017; Engeln, 2020; VDI 2424). In the interviews, the delay between design and technical validation was criticized by the technical departments. The design concept handed over for review is already outdated by the time the results are available, as the concept is constantly being developed during the validation phase. These descriptions also match the observations from Feldinger et al. (2017). The key design decisions are made synchronously with the superordinate product decisions, which reflects the observations of Kurz (2008). The concept phase was described by the experts as the core phase of DTC, which is consistent with descriptions of the importance and significance of design decisions gradually increasing in this phase and ultimately culminating in the primary key decision point—the concept freeze.

In summary, all the RQs (see Section 3) were answered, and as a result, the research gap identified (see Section 2) could be closed.

6. Conclusion and Outlook

In the literature, it is increasingly apparent that the existing process models are reaching their limits, as requirements in terms of new challenges facing both the car and development projects have changed significantly in the past few years. In our initial literature-based studies, we were able to demonstrate that the vehicle development process is much-discussed but only sparsely documented. The development process is usually presented as static in the literature, but the dynamic changes have not yet been researched (Clarkson & Eckert, 2005; Meboldt, 2008).

Alongside an established understanding of the current vehicle development process, the role of design in the vehicle development process was highlighted, as was the extent to which design is intertwined with technology. Fundamental requirements placed on design make methodological support necessary (Kraus et al., 2021; Widmann et al., 2021). This is shown in the use of new technologies. Due to the increased development complexity and the required development flexibility, a more methodical approach must be taken in the design process, as previous best practice approaches have reached their limits (Krzywinski, 2011). The design process takes place predominantly in the early phases of the PDP. As a result, the methods used are also different from those used in series production development (Tovey, 1997). It was found that there is a scientific gap in this area and that a detailed, methodically derived description of the vehicle development process in its subprocesses—design, tools, ergonomics, and DTC—is urgently needed in order to clarify the interrelationships, identify potential for optimization, and, therefore, lay the basis for further steps in a support methodology.

In order to establish a validated, universally applicable reference process derived from actual situations, we interviewed experts from the German automotive industry and modeled their understanding of the processes. This time-consuming and detailed procedure enabled us to determine the current situation. Based on these findings, it was possible to develop a detailed reference process for vehicle development with the following subprocesses: design, tools, ergonomics, and DTC. Based on this description, a general basis for a better understanding of the necessary activities and important interrelations between the different key areas in the early phases is set.

As further steps, it was detected that the key product decisions are made during the early phases of vehicle development. For the complex and often contradictory requirements in the DTC process, systematic project management support is, therefore, needed. Examples of this are methods such as user studies, etc. In further steps, it has to be clarified in which phase or in which work step which type of method is best suited. At the same time, from a purely psychological point of view, engineering and designing have always been an iterative process, which are characterized by constant target specification. The *"shortcomings"* identified by Hacker (2002) show that best practice is applied widely. This has become established to such an extent that the origins of iterative, goal-oriented development have ultimately become blurred. This, therefore, also requires comprehensive, methodological adaptability for future support methodologies at the interface of design and technology.

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