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***Abstract***

This paper examines the changes in the innovation ecosystem of the German automotive industry for the technology field of automotive software from the perspective of individual firms. The change of the innovation ecosystem of the German car industry through introduction of software-defined vehicles is being classified as a radical transformation. Focus of the analysis is the beginning formation of the software ecosystem in the German car industry. Based on qualitative data, three explorative company case studies on three leading German car manufacturers Volkswagen, BMW and Mercedes-Benz are presented. The exploratory case studies focus on company-centric innovation ecosystems of VW, BMW and Mercedes in the software sector which are integrated into an overall software innovation system of the German automotive industry. The case studies aim is to analyse the formation phase of the digital innovation ecosystem of German car manufacturers. It intends to contribute towards a further development of the innovation ecosystem concept and a better understanding of the formation phase of an innovation ecosystem

*Keywords*

Innovation Ecosystems, Digital Innovation, Software, Automotive Industry, Germany

## 1. Introduction: Change in the software-based innovation ecosystem of the automotive industry in Germany

The automotive industry and its ecosystem have changed profoundly under the influence of new technologies over the last 20 years (cf. Nischak, Handelt 2019). This paper examines the changes in the innovation ecosystem of the German automotive industry from the perspective of individual actors for the technology field of automotive software. Instead of collecting patent data, qualitative data and information on projects of individual actors and the collaborations between actors are collected. Based on these data, three explorative company case studies on VW, BMW and Mercedes-Benz are formed. These are then compared with each other and analyzed and interpreted against the theoretical background of the innovation ecosystem concept. This qualitative research design was chosen for several reasons: Firstly, a standardized operating system for the automobile is a relatively new topic that has not yet been thoroughly and comprehensively addressed either in business practice or in academia. On the other hand, case studies of individual companies are intended to contribute to the microfoundation of the concept of the innovation ecosystem, which has so far been analyzed primarily from the perspective of the industry as a whole and thus represents a macro concept. The article examines the structure of the innovation ecosystem based on the activities and cooperations of the individual companies (bottom-up approach), which interact to form an innovation ecosystem for the technology field of software in automotive engineering.

The paper focuses on company-centric innovation ecosystems of VW, BMW and Mercedes in the software sector. Considered together with the cooperation partners of these three companies (American technology companies, semiconductor manufacturers, cloud service providers, automotive suppliers, other players), these result in the formation of a multicentric software ecosystem of the German automotive industry. This ecosystem is designed to generate software innovations. The German automotive industry's software innovation ecosystem is both a collection and agglomeration of innovation ecosystems of individual companies.

The paper investigates the following research gap:

Very little research has been done in the scientific literature on the transformation of innovation ecosystems. In works that mainly pursue conceptual definitions and classifications of innovation ecosystems, the change of an ecosystem is not addressed at all (Oh et al. 2016, Granstrand, Holgersson 2020, De Vasconcelos Gomes et al. 2016). Dynamic changes of an ecosystem over time are only addressed by a few authors. Change in innovation ecosystems and the life cycle of such ecosystems are explored in Klimas and Czakon (2021, p. 267 f.), Dias Sant'Ana et al. (2020, p. 2736) and Dedehayir, Mäkinen, Ortt (2016). All three papers address the emergence and life cycle of an ecosystem but they do not present empirical evidence, instead they conduct literature reviews. This paper is focusing on the early stage of ecosystem formation, the ecosystem structure and it presents own empirical work. Static snapshots of the innovation ecosystem dominate the literature (cf. Gueler, Schneider 2021, Dahms, Cabrilo, Kingkaew 2019, Freiling, Baron 2017). Previous studies have not sufficiently taken into account the fact that an innovation ecosystem results from the actions of individual companies and is subject to constant change. The early phase of the development of an innovation ecosystem has also hardly been researched to date (Dedehayir, Mäkinnen, Ortt, 2016). This article therefore focuses more on the formation of a new innovation ecosystem from the perspective of individual companies.

Research on innovation ecosystems has grown significantly in scope and importance in recent years. The majority of publications do not focus on the development phase of an innovation ecosystem (e.g. Gomes et al. 2018, Autio/Thomas 2018, Adner/Kapoor 2009). The author of this article found a total of 6 research papers that focus on the early phase of the development of an innovation ecosystem. Each of these publications has found its own theoretical approach to the topic of the genesis of an ecosystem. The papers also differ in their thematic focus, their theoretical foundation and the empirical research conducted. Jacobides, Cennamo and Gawer (2018) examine the prerequisites for the emergence of an ecosystem and work out modularity and various forms of interdependencies as reasons for its emergence. However, they do not deal with the actual emergence and development of a young ecosystem; they stop at analyzing the prerequisites of an ecosystem. Adner (2017) deals with the structure and strategy of an ecosystem and distinguishes ecosystems from other collaborative arrangements such as value networks and open innovation. He describes the early phase of ecosystem genesis in his empirical case study of the Michelin PAX maturity system. In his conceptual-theoretical explanations, however, he does not go into the early phase of an ecosystem and does not distinguish between young and mature ecosystems. Autio (2022) distinguishes between a top-down and a bottom-up approach to the emergence of an ecosystem; he creates a frame of reference for analyzing the bottom-up orchestration of an ecosystem with the four levels of analysis, the technological layer, economic layer, institutional layer and behavioral layer. For each of these four levels, he distinguishes between the foundation, growth and maturity phases of an ecosystem, although he gives them different names: ignition phase, momentum phase and control phase. His explanations thus cover the entire life cycle of an ecosystem.

The article by Hannah and Eisenhardt (2015) examines also the development phase of an ecosystem and focuses primarily on strategy issues. The authors develop a specific strategy concept for ecosystems (bottleneck strategy, component strategy, system strategy) and apply the concept to their qualitative case study of 5 companies in the developing U.S. residential solar industry, whose ecosystem began to unfold in 2007. Their paper differs substantially from the paper at hand which focuses on the structure of ecosystems in the unfolding phase and not on strategy issus. In their article, Autio and Thomas (2018) apply the institutional perspective to the evolution of an ecosystem and focus on the early stages of ecosystem creation. Accordingly, they analyse the influence of legitimacy standards on the evolution of an ecosystem and examine 4 strategies of providers to legitimize and implement their ecosystem: cultural compatiblity, cognitve legitimacy, and value; social learning, technical instrumentality and value; economic externalities, pragmatic legitimacy and value; standardization, coalitions, regulatory legitimacy, and value. They apply their theoretical concepts to 2 practical examples, the companies Qualcomm and Salesforce.com. Their work differs from the paper at hand by the choice of a very different theoretical framework (neoinstituionalism). Dattee, Alexy and Autio (2017) investigate the emergence of an ecosystem and examine issues of strategy and control in this early phase. The early phase of the emergence of an ecosystem is characterized by a high degree of uncertainty for all actors involved. Dattee, Alexy and Autio provide qualitative case studies of two organizations that want to develop new ecosystems around a technical innovation with multiple, still uncertain applications. For both organizations, the high level of uncertainty creates problems in formulating a vision and a value proposition as well as in convincing and attracting participants to the ecosystem. The authors also apply the systems dynamics perspective on ecosystems as an empirical method for evaluating the case studies. Their paper differs from the paper at hand by the methodology choosen (system dynamics instead of economic classification)

This article differs from the 6 research papers mentioned above. It examines questions of the structure and structural change of an ecosystem and not primarily the strategy of an ecosystem (Hannah and Eisenhardt 2015) or the preconditions for the emergence of an ecosystem (Jacobides, Cennamo and Gawer 2018). This article examines the early formation phase of an ecosystem both empirically with a qualitative case study and conceptually and theoretically, while other articles analyze the early phase either only empirically (Adner 2017) or only theoretically (Autio and Thomas 2018). This article also differs from the research by Autio (2022) and Dattee, Alexy and Autio (2017): it focuses on the early phase and not on the entire life cycle of an ecosystem (Autio 2022) and presents its own, self-collected empirical study of a real ecosystem, while Autio (2022) draws on practical examples from other research articles. This article differs from the article by Dattee, Alexy and Autio (2017) in that it strives for a complete survey of the ecosystem of an entire industry and its change over time instead of the ecosystem of 2 companies. The evaluation methodology is also different: while Dattee, Alexy and Autio (2017) carry out a sophisticated evaluation of the case study results using System Dynamics models, this article is limited to the evaluation and interpretation using a classification and analysis scheme derived at the beginning of the article, which captures the key characteristics of ecosystems.

The innovation ecosystem of the German car industry has been studied only sporadically so far. Nischak and Hanelt (2019) examine the innovation ecosystem of the entire global auto industry using patent data. This paper, on the other hand, focuses on the innovation ecosystem of the German automotive industry, which is examined with qualitative data and the help of explorative case studies. Recent research presented on the topic of digitization in the auto industry also differs from the paper presented here. Weiß et al. (2018) examine the problems faced by OEM manufacturers in building digital vehicle platforms. In doing so, they focus on the automakers' internal company relationships and do not take the comprehensive, cross-company perspective of the whole innovation ecosystem. Kaiser, Stocker, and Fellmann (2019) focus on data-based service ecosystems in the auto industry, while the focus of this paper is on the software-based innovation ecosystem of the German auto industry. Schäfer, Jud, and Mikusz (2015) examine digital service platforms of German car manufacturers; they strongly relegate the topic of software (as the basis of the service platform) and a cross-company view of the entire ecosystem to the background. The paper by Kim, Paek and Lee (2022) comes closest to the present research paper, however, the authors examine the topic of change of an innovation ecosystem by comparing VW and Toyota. They also examine the entire innovation ecosystem of these two automakers (batteries, semiconductors, software, electric vehicle platform and mobility services, map services, etc.). In contrast, this paper focuses on software and secondarily semiconductors at the three leading German automakers.

The aim of this paper is twofold: first to develop a deeper understanding of ecosystem change and especially of the formation phase of an innovation ecosystem. The second aim is to generate more knowledge on an until now hardly researched developing innovation ecosystem in business practice: the actors and structures of the developing software ecosystem in the German car industry with focus on the formation stage of this ecosystem.

The research methodology is based on explorative qualitative case studies on three German carmakers, their external cooperation partners and their overall positions in the software ecosystem of the German car industry. This explorative, qualitative research methodology is choosen because the technology field of car software is still in its infancy, unfolding and strongly chainging, and not well researched until now. The results of the empirical inquiry are used to further develop the theoretical concept of innovation ecosystems.

The contribution of this paper can be seen in several points. First a deeper understanding of the actors, changing structures and processes in the early formation stage of an innovation ecosystem is the main result. Second the results of this qualitative research have several implications for the concept of innovation ecosystems. Third, an empirical analysis of the software ecosystem of the German automotive industry, which has been little researched so far, is presented.

The structure of the article is as follows: After the introduction, chapter 2 presents the concept of innovation ecosystem as a theoretical basis. Chapter 3 presents the data collection and research methodology of the paper. Chapter 4 is about the strategic importance of software in cars and in the car industry. Chapter 5 presents the three exploratory case studies on BMW, Mercedes-Benz, Volkswagen and their value creation partners in software and digital innovation. The interpretation of the three case studies takes place in chapter 6. The classification of the different changes in the software ecosystem of the German car industry and their interpretation in light of the theory of innovation ecosystems takes place in chapter 7. Chapter 8 concludes with a summary where also starting points for the advancement of the innovation ecosystem concept and limitations of this study pointed out.

## 2. Conceptual and theoretical foundations: ecosystem, innovation ecosystem and change

Few companies possess all the resources and competencies needed for radical innovation themselves. Therefore, the collaboration of different players in an ecosystem is necessary to be able to develop new products and services. (cf. Kim/Paek/Lee 2022, p. 1). An ecosystem describes "the complex interplay of diverse resources, actors, and their actions interconnected by the objective of developing new value propositions" (Nischak, Hanelt 2019, p. 1.). An ecosystem is typically a network of collaborating and/or competing firms that is grouped around a single firm, a few core firms, or a technology platform. In this ecosystem, material goods and services are produced (cf. Dias Sant'Ana et al. 2020, pp. 2725, 2737). The various actors compete for resources in the ecosystem by entering into partnerships with other actors (cf. Kim, Paek, Lee 2022, pp. 1, 2). It is often the central node (i. e. a focal firm) in the ecosystem that builds and manages the innovation platform to integrate and coordinate the peripheral value creation partners (cf. Dias Sant'Ana et al. 2020, p. 2739).

A special case of an ecosystem is a company's innovation ecosystem. A body of research on innovation ecosystems has developed over the past 30 years (see the literature review in Dedehayir, Mäkinen, Ortt 2016 and De Vasconcelos Gomes et al 2016, see also the critical assessment of the concept in Oh et al 2016). The term innovation ecosystem is used very differently in the scientific literature. Grandstand and Holgersson (2020) examine 120 publications and find 21 more or less different definitions for the term innovation ecosystem. (cf. Grandstand, Holgersson 2020, p. 2). They propose the following definition: "An *innovation ecosystem* is the evolving set of actors, activities and artifacts, and the institutions and relations, including complementary and substitute relations, that are important for the innovative performance of an actor or a population of actors.… An innovation ecosystem could in other words include an actor system with collaborative (complementary) and competitive (substitute) relations with or without a focal firm, and an artifact system with complementary and substitute relations." (Grandstand, Holgersson 2020, p. 3).

Klimas and Czakon's (2022, p. 275) literature review identifies 34 different types of innovation ecosystems. The demarcation of ecosystems from similar, partly overlapping concepts such as networks and clusters as well as communities of interest, user communities, regional and national innovation systems is not clear (cf. Klimas, Czakon 2022, p. 250 f. as well as Oh et al. 2016). Differences can be seen in the fact that innovation ecosystems emphasize the systemic character, i.e. the connections between actors, more and give greater space to market forces than initiatives by governments and NGOs (cf. Oh et al 2016, p. 2).

Depending on the dominant technology field or strategic asset or strategic product several types of innovation ecosystems can be differentiated: Data based innovation ecosystem, hardware-based innovation ecosystem, software-based innovation ecosystem, (digital) service-based innovation ecosystem and digital innovation ecosystem. "Digital innovation ecosystems are online platforms on which customers, users and developers can build synergistic relationships, generating network externalities which increase the values of both hardware and software innovations. Thus, a digital innovation ecosystem can mean the apps, platforms, and distributors that make the technology viable" (Oh et al. 2016, p. 3). In this paper the focus is on the software ecosystem of the German car industry. In order to successfully operate in an software ecosystem firms need access to and control of specialized resources and competencies, especially IT resources, IT competencies, software and software competencies.

The question is whether an innovation ecosystem is an evolutionary entity or one that is consciously and purposefully designed and managed? (cf. Oh et al. 2016, p. 2, who prefer the latter view). A mediating position is that "Innovation ecosystems, once designed, do evolve." (Oh et al. 2016, p. 4). The evoluatonary dynamics of an innovation econsystems are best described as follows: “Ecosystem actors, acting flexibly and loosely coupled, are co-evolving and continously adapting to the environment to survive and to sustain competitive advantages” (Kim/Paek/Lee 2022, p. 3, 4). The consequence is: “Relations in an innovation ecosystem evolve in unforeseen and unstable ways, moving from cooperation to competition and vice-versa." (Kim/Paek/Lee 2022, p. 4).

A discontinuous technology with a whole new knowledge base opens the ecosystem to new companies, complementors and competitors. Initially, there is a lot of turbulence and uncertainty in the ecosystem until a new Dominant Design emerges. A breakthrough innovation challenges the existing ecosystem. Established companies have great difficulty responding to technological discontinuity because they focus on previous technologies and their refinement. When an established company adopts a radical innovation, it also changes its involvement in its previous ecosystem. This can loosen or sever old ties with current suppliers. Newly established firms or firms entering the market may be better able to adapt to the radical innovation, e.g., because they do not have a stock of old resources and competencies (cf. Kim/Paek/Lee 2022, p. 4).

It is possible to conceive a life cycle for innovation ecosystems similarly to the life cycles of technologies and products. Innovation ecosystems have different development phases. At the beginning a formation phase, where new firms build up internal capacities for R&D and create new technologies, the collaboration with external partners is at the beginning, there are often changes of partners, the structure of the innovation ecosystem is very fluid. In the growth phase the innovation ecosystem enlarges R&D capacities and invested funds, cooperations with external partners are now institutionalized, change of partners occours sometimes, the structure of the innovation system becomes more stable. In the saturation phase the innovation system ist fully elaborated, firms are doing R&D in a routine manner, external partnerships are stable, the structure of the innovation ecosystem is consolidated and fixed. In the degeneration phase the meaning and significance of the innovation ecosystems starts to vanish due to technological change, R&D capacities are reduced as are invested funds, actors start leaving the innovation ecosystem. This paper is focusing on the first phase, the formation stage of an innovation ecosystem.

Innovation ecosystem change is a difficult research topic to study due to a coevolution of technology, innovation, new and established firms. A change in the innovation ecosystem is taking place, for example, through the entry of new players. This enables the ecosystem to produce a new type of innovation. At the same time, however, the innovation to be brought forth also defines and changes the structure of the ecosystem by growth opportunities for innovative firms and failure of other firms. On the one hand, technological change defines the requirements for the system partners and, on the other hand, successful or failed innovations determine the size and structure of the innovation ecosystem, which will have influence on the technologies and innovations generated by the ecosystem in the future.

The change of an innovation ecosystem manifests itself either in the change of its structure or in the innovations it produces. The change in ecosystem structure is evident in many ways. On the one hand, there is a shift in system boundaries. This is expressed in the merger and the greater or lesser overlap with other innovation ecosystems. In addition, there is growth or shrinkage of innovation ecosystems, measured by aggregate R&D expenditures or the number of members. Another indicator is the entry of new actors into the innovation ecosystem respectively the exit of established actors from the innovation ecosystem. Other aspects can be found in the change of relationships between actors (establishment of new relationships, abandonment or change of previous relationships), the change of the position of individual actors (e.g. from the edge to the center of the innovation ecosystem or vice versa) and the changed importance of individual actors for the functioning and innovation outcomes of the ecosystem (upgrading, devaluing of an individual actor).

The change of an innovation ecosystem is not only reflected in the structural change of the system, but also in the change of the product and process innovations produced by the innovation system. For example, this is expressed in a change in the innovation content (increase or decrease in material goods or service innovations, technology-based or organization-based innovations) or the degree of innovation (from incremental to radical innovations or vice versa).

The result is either incremental further development or radical transformation of the innovation ecosystem, which can be estimated by the extent to which the structural and innovation-related parameters of the innovation ecosystem change.

Changes in technology imply changes in the ecosystem, e.g. by changing the positions or relationships of individual actors to other actors or by new actors becoming relevant for the ecosystem (cf. Kim/Paek/Lee 2022, p. 11). Therefore "... ecosystem activities at the inter-organizational level play an essential part in the incumbents' strategies to efficiently respond to radical technological change" (Kim/Paek/Lee 2022, p. 11).

## 3. Research methodology and data collection

For the empirical part, an explorative, qualitative research case study (cf. Yin 2014, Eisenhardt 1989) is conducted in the form of 3 comparative firm case studies. The qualitative research approach of the case study is particularly suitable for research topics that have been little explored so far (cf. Burr, Schmidt 2014), as the topic of software in the automobile currently is. The case studies have an exploratory character, i.e. they aim to prepare a hitherto little researched empirical field (software ecosystem of the German automotive industry) for research. The case study results are also intended to contribute to the further development of the Resource- and Competence-Based View of the firm.

Instead of collecting patent data, this paper collects qualitative data and information on projects of individual actors and cooperations between actors. The collected data are condensed into two explorative firm case studies on the digitalisation of the automobile at BMW and Mercedes-Benz. These cases are then compared as well as analysed and interpreted against the theoretical background of the Resource- and Competence-Based View (cf. Barney 1991, Prahalad, Hamel 1990, Burr 2017).

The data collection took the form of a document and content analysis. For this purpose, current publications for the period from 2017 to 2023 in the German business press (business newspaper Handelsblatt), annual reports and firm websites of the two car manufacturers, as well as relevant scientific publications (period from 2015) and publications in practice-oriented trade journals (first publications as early as 2003) were reviewed. The study period from 2015 onwards was chosen deliberately: The first electric car from Tesla, the Model S, appeared in Germany in 2013. With a certain time lag, this triggered a public discussion about electric cars and a debate among experts about the advantages and disadvantages of a standardized automotive system in Germany. The evaluation of the daily newspaper Handelsblatt as the main, but not sole, data basis is justified as follows: This paper examines German car manufacturers, which are better and more comprehensively documented in German-language reporting than in foreign reporting. The reference to the current business press offers further significant advantages: The articles are written for a broader professional audience, managers, capital investors, thus not biased by a methodological approach and a particular theoretical perspective of a researcher. The data extracted from the Handelsblatt articles is therefore a good basis for further management research. The topic of vehicle operating systems is currently highly topical and still undergoing major changes. The strategic and operational decisions and possible changes of direction of car manufacturers can be followed very closely in a daily news source. As the Handelsblatt is purely a business newspaper, objective and competent reporting on business topics is more guaranteed than with the general press, which is aimed at a broad readership with a wide range of interests. The systematic content analysis for data evaluation (cf. Mayring 2015) made it possible to obtain relevant findings despite the very heterogeneous, sometimes difficult to delimit and also contradictory discussion of the topic of automotive software in the business press and the very small number of scientific publications on this topic to date.

For the explorative analysis, a so-called Purposive Sample was formed, comprising the firms BMW, Mercedes Benz and Volkswagen. The logic and strength of purposive sampling lies in the selection of information-rich cases for in-depth investigation. Cases from which much can be learned about something relevant to the purpose of the study are considered informative (Patton 2015). Volkswagen, BMW and Mercedes Benz represent the largest players in the German automotive market and are therefore of particular interest to the study in Patton's (2015) sense. However, the narrowing down of the study cases also reflects the fact that all three firms are pursuing ambitious goals with regard to the digitization of the automobile, while pursuing very contrasting strategies to achieve their goals.

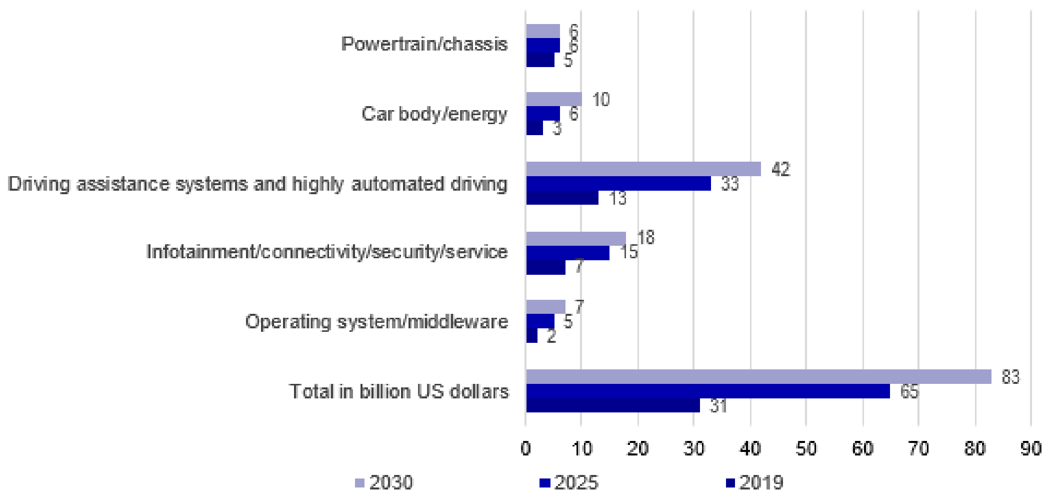
The purposive sample from the German business press contained 87 articles published from 2018 to 2023. The 14 categories for content analysis were derived from the theoretical concept of innovation ecosystem as depicted in chapter 2 and from the practical literature concerning car software: IT resources, IT competencies, software competencies, organizational change, collaborative arrangement, partner firm, number of partner firms, choosing a cooperation partner, change of cooperation partner, value networks, focal firm, value creation, technology platform, technological change, software.

**Table 1**: Categories for content analysis

| **Category for content analysis** | **Derived from** |
|---|---|
| IT resources | Burr/Fritz/Kianpour/Valentowitsch 2024, p. 3 |
| IT competencies | Burr/Fritz/Kianpour/Valentowitsch 2024, p. 3 |
| Software | Burr/Fritz/Kianpour/Valentowitsch 2024, p. 4 |
| Software competencies | Burr/Fritz/Kianpour/Valentowitsch 2024, p. 3 |
| Organizational change | Kim/Paek/Lee 2022, p. 4 |
| Collaborative arrangement | Kim/Paek/Lee 2022, p. 1 |
| Partner firm | Schäfer/Jud/Mikuscz 2015, p. 388 |
| Choosing a cooperation partner | Kim/Paek/Lee 2022, pp. 1,2 |
| Change of cooperation partner | Kim/Paek/Lee 2022, pp. 1,2 |
| Value network | Kim/Paek/Lee 2022, p. 3 |
| Focal firm | Grandstand/Holgersson 2020, p. 3 |
| Value creation | Kim/Paek/Lee 2022, p. 2 |
| Technology platform | Dias Sant ´Ana et al. 2020, pp 2725, 2737; Klimas/Czakon 2022, p. 276 |
| Technological change | Kim/Paek/Lee 2022, p. 4 |

The interpretation of all documents under study and the categorization was done by one rater (the author of this paper) to avoid problems of inter-rater-reliability. Because only one rater conducted the analysis, it was not possible to calculate numerically indexes of inter-rater-reliability like Krippenforff´s Alpha (cf. Marzin, Balzano, Mariori 2024). The quality and reliability of the analysis was improved by the following measures: Standardized and consistent procedures with 13 defined categories for content analysis were used during repeated assessements. The selection from the 87 articles and the order of analysis were randomized to prevent biases due to routinization. There were three time intervals for analyzing the 87 articles with a break of 2 weeks between every interval to avoid memory bias. The author took care to triangulate the data sources and also mirrored articles from the business press with academic publications and primary sources such as firm websites and annual reports of firms, he refrained from independently collecting new primary data. The main reason for this is, that the deveolopment of the software based vehicle and of software competencies is still in an early stage. Carmakers are at present very reluctant to cooperate with academic research to investigate software strategies in the car industry due to the strategic importance of car software.

**Figure 1**: Market potential of automotive software – Forecasted market volume in billion US$ (Source: McKinsey)




In the following, the results of three firm case studies are presented, which are based on a content analysis of current business literature (above all the German business newspaper Handelsblatt) and thematically relevant scientific articles and firm data.

## 4. Strategic importance of software in the automobile

"It is a misconception that a car is an iPhone on wheels - it is much more complex, more elaborate" (BMW CEO Zipse, quoted in Holtermann, Hubik 2023, p. 21).

The automotive software sector currently has considerable market volumes with strong growth expectations up to 2030. (cf. Holtermann, Hubik 2023, p. 20). Figure 1 illustrates the various subsectors of automotive software and their growth potential.

Automotive software is causing enormous change in the product architecture of the car, it´s product and process technologies: "The engine was the technological heart of the automobile; in the future, it will be the software." (Hartung, Huettel, Schü 2022, p. 64). Software and digitization are changing not only the car but also the organization of the car producer: "Digitization is defining the car and our organization. That is the real revolution" (Duesmann, CEO of carmaker Audi, quoted in Fasse 2020, p. 19). The increasing importance of software in the car has huge impact on the organization of R&D processes and business models of automotive companies: The development of a car operating system and the availability of a uniform software architecture that no longer has to be completely changed for each newly developed vehicle are prerequisites for significantly accelerating the development processes for new vehicles. (cf. Hubik, Menzel 2022, p. 18). The automotive OS does not only accelerate R&D processes, it totally changes the way new cars are developed: "Blume (CEO of Volkswagen, author´s note) also wants to re-anchor the topic of software in the strategy. The group should first define the software and then derive the models-not the other way around anymore." (Fasse, Menzel, Murphy, Tyborski 2022, p. 1) The operating system of an automobile has not only deep impact on the technology and organization of a car firm. It is also of strategic importance for a car manufacturer: Software will account for just under a third of the car's value added (see Buchenau 2020, p. 29). Only if a car manufacturer has its own operating system and data sovereignty can it learn which features and functions customers want and which they do not, how to improve operating systems, voice assistants and program apps. The precondition for this is access to driver´s usage data (see Hubik, Menzel, Tyborski 2022, p. 22 and Fasse, Hubik, Krolle, Menzel, Tyborski 2021, p. 6). From the perspective of many customers the stability and ergonomic look and feel of software is a decisive factor influencing buyer´s decisions: "In China, according to BMW, the digital equipment of cars is also the most important purchase criterion" (Fasse 2020, p. 1). "In the important Chinese market, two-thirds of customers are willing to switch brands if the car's digital connectivity isn't right, …. ." (Fasse 2020, p. 4). Not only Chinese customers but also American customers place a high priority on software functionality and quality. The latest quality study by the American analyst firm JD.Power attested to below-average product quality for German car manufacturers. The main reasons for the poor quality assessment of German cars by American customers were software errors such as outdated digital maps, problems with smartphone integration or with voice recognition (cf. Holtermann 2023, p. 28).

In their longitudinal study based on patent data, Nischak and Hanelt (2019) show how the auto industry ecosystem changed from 2002 to 2017. From 2002 to 2007, the core of the ecosystem consisted of the 7 technology fields of engine, body, auto parts, metals, steel processing, jewelry and watches, chemicals, and crude oil and gas. Only at the periphery of the ecosystem, i.e. at the periphery of the auto industry, were technologies such as semiconductors, software, communication devices and computer systems found in the period under review. This picture changed in the period 2007 to 2012: 12 technology fields are now found at the core of the ecosystem, with 6 technology fields now newly included in the core, i.e., having gained in importance: Software, Communication Devices, Audio and Video Equipment, Power Supply. These technologies have migrated from the periphery to the core of the ecosystem, here the increasing focus on connectivity and electrical systems in the vehicle is evident. (cf. Nischak, Hanelt 2019, p. 9). In the period from 2012 to 2017, the importance of the technology fields electrical services, communication devices, audio and video equipment, energy supply, and software in the core of the ecosystem increased once again, reaching the importance of the previous technology fields. In particular, vehicle connectivity technologies (semiconductors, electronic components, engineering services) and vehicle software have greatly increased in importance. (cf. Nischak, Hanelt 2019, p. 10 f.)

## 5. The innovation ecosystem of German car manufacturers in car software

### 5.1 OEM car manufacturers and their own resources / competencies in the field of car software

VW is working on its own operating system for the car, as are BMW and Mercedes-Benz (see Ludowig, Tyborski. 2020, p. 4). For this, the companies need software resources (software developers, financial resources) that they can develop into corporate competencies.

The situation of German OEM manufacturers in mid-2023 can be described as follows: "Because so far, despite investing billions in software development, they are lagging behind competitors such as Tesla or new Chinese electric car brands. They are dependent on tech corporations like Google and suppliers like Bosch, Continental and ZF. The software engagement of German automakers is predominantly characterized by problems and delays." (Hubik, Tyborski 2023, p. 20). Deficits in electromobility are evident not only at mass manufacturer VW but also at German premium manufacturers, especially in the Chinese market (cf. Tyborski 2023 d, p. 12)

Weiß et al. (2018), explain why OEM manufacturers are struggling with software. For established car manufacturers, the introduction and operation of a digital vehicle platform represent a major challenge for strategic, organizational, marketing and technology-related reasons. They therefore require profound changes and transformation of structures, processes and mindsets within the company. (cf. Weiß et al. 2018 for more detail).

**Table 2**: Comparison of the three firm case studies: building up software competencies with own resources

| **Firm** | **BMW** | **Mercedes-Benz** | **Volkswagen** |
|---|---|---|---|
| IT professionals | 4000 (May 2021) – 8500 | 5000, planned 8000 | 3000 (2021), 6000(end 2022), planned final expansion 10000 by 2025 |
| Anchoring the IT topic in the Executive Board | no | Chief Technology Officer | VW Group: Board of Management and Supervisory Board VW Cariad<br>VW AG: Board of Management department New Mobility<br>Porsche AG: Car-IT board department<br>Audi AG: Board of Management department for Finance, Legal Affairs and IT |
| Central organizational unit for IT in the vehicle | BMW Digital Car and BMW Car IT | Mercedes Benz Electric Hub | VW Cariad |
| Planned costs for the operating system | n. a. | 4.6 billion euros | Planned 2.5 billion euros per year<br>VW OS 1.2: 5 billion euros |
| Latest version of OS | BMW OS 9 (planned November 2023), self created | MB.OS (introduced in 2023 as part of the vehicle platform 2.0), partly self created | VW OS 1.2 (planned for the end of 2023, introduction in the car model Audi Q6 E-tron), partly self created |

Traditional car manufacturers have major knowledge deficits with regard to operating in a digital economy (see Felser/Wynn 2023, p. 180). The main cause of the knowledge deficit in the German automotive industry is the extensive outsourcing of IT operations and software creation in the past. This approach has led to deficits in software competencies on the part of OEMs. "Until now, the software for the car has come primarily from suppliers and service providers. OEM manufacturers write perhaps only 10% of the necessary code. But a "software-defined car" requires a central operating system instead of over a hundred small control elements. The carmakers must quickly build up the capabilities for this and program it themselves." (Felser/Wynn 2023, p. 183 f.). The knowledge deficit of German carmakers exists in six knowledge areas namely software development, data analysis and data management, capabilities to integrate existing software solutions for individual ECUs into an integral software architecture, cloud services and cloud sourcing, management of digital platforms and ecosystems, cybersecurity and IT organization, sourcing management, and cooperation skills with technology companies. (cf. Felser/Wynn 2023, pp. 184- 188). While almost all German automakers initially aimed for a large share of internally generated software in the car, this goal was reduced with increasing technical problems, time and budget overruns, and recognizable know-how and competence deficits among automakers in the area of software (cf. Backovic, Hubik, Tyborski 2023, p. 4). Car manufacturers have since been opening up more to cooperation with American technology groups such as Google and Apple. (cf. Backovic, Hubik, Tyborski 2023, p. 1), with chip manufacturers, cloud service providers and with their traditional cooperation partners, the automotive suppliers.

### 5.2 Cooperation of OEM manufacturers with external partners in the car software

The following depicts and analyzes the cooperations of German car companies with external partners in the software sector. These include American technology companies, chip manufacturers, cloud service providers and traditional automotive suppliers in Western markets, especially in the German market. In China German car companies have differing cooperative agreements with Chinese partners.

### 5.2.1 Cooperation with automotive suppliers in the software and hardware sector

Bosch has built up its expertise and competencies in software and semiconductors internally over a period of 40 to 60 years, because Bosch has held a leading position in the integration of electronics into the vehicle since the 1970s. The former tire manufacturer Continental has built up competence in electronics, software and hardware through acquisitions, e.g. the automotive electronics division of Siemens, over the past decades. (cf. Ludowig, Tyborski 2020, p. 4). ZF has likewise acquired expertise in electronics with the acquisitions of TRW and Wabco (cf. Buchenau 2023a, p. 31) and also cooperates with Microsoft. The big German automotive suppliers have traditionally occupied the topic of software in the car. The reasons for this are, on the one hand, that the large OEMs did not want to concern themselves with software for a long time and, on the other hand, that they purchased the software together with car parts and car systems from the suppliers. As a result, suppliers have been able to build up very significant software capacities in recent decades by establishing and expanding software departments and taking over other suppliers. "While suppliers have been able to gain experience in the area of software in cars for decades, it was at best a marginal topic for carmakers, but is now moving to center stage. As a result, suppliers not only have more knowledge of software development than carmakers. They also have more developers. Bosch, Conti and ZF employ more than 60,000 IT experts worldwide. The automakers have around 12,000. (Tyborski, Buchenau 2021, p. 10.)

**Table 3**: German 1 tier suppliers and their offerings in digital innovation

| Firm | Bosch | Continental | ZF |
|---|---|---|---|
| Number of software developers and IT specialists | 17000-44000 | 19000-20000 | 9000 |
| Software solutions for autonomous driving | Yes | Yes | yes |
| Solutions for the middleware of car operating systems | Yes | yes | yes |
| Production of vehicle computers (hardware) | | | |
| Own production of microprocessors | Yes | No | No |

These data are not fully reliable because the figures often include employees who develop software for other business areas or for the supplier's own needs. Furthermore, the software capacities are usually distributed worldwide and not concentrated at the location in Germany. It is also unclear which employee categories are counted by the companies as software employees and IT specialists and which are not. In particular, it must be clarified whether employees in supporting and administrative functions were also included here. The survey is further complicated by the fact that many companies have established several subsidiaries, some of them in different countries, for different software activities.

**Volkswagen** cooperates with Bosch to develop software for autonomous driving (cf. Murphy, Menzel 2022, p. 46 and Hubik, Menzel, Tyborski 2022, p. 23), but this cooperation is limited in time and not intended to be permanent. (cf. Holtermann, Backovic, Tyborski 2023, p. 23.) Volkswagen cooperates with Continental to develop the middleware for the VW operating system. (cf. Murphy, Menzel 2022, p. 46). VW Cariad is developing the app store together with the Samsung subsidiary Harman (cf. Backovic 2023c, p. 4). Volkswagen uses Continental's high-performance computers in the car model ID.3 (see Pertschy 2022).

**BMW** does not cooperate with a German automotive supplier in the field of autonomous driving (instead a cooperation with US firm Qualcomm was signed) and BMW developed the middleware for its car operating system itself. BMW integrates the app store of Faurecia, but develops the user interface itself because BMW wants to retain control over the customer interface. (cf. Holtermann, Scheuer 2023, p. 22) BMW uses Continental's vehicle computers in the car model BMW iX (see Pertschy 2022).

**Mercedes-Benz** does not cooperate with a German automotive supplier in the field of autonomous driving (instead a cooperation with US firm Nvidia was signed), part of the middleware is also developed by Nvidia. Mercedes is also working with the automotive supplier Faurecia Aptoide on app integration. (Cf. Hubik, Menzel, Tyborski 2022, p. 22). Mercedes-Benz buys the central vehicle computers for some car models from Bosch.

German car suppliers increasingly deliver hardware and software components to **Chinese electric car manufacturers** producing in China. By doing business with newly established Chinese car manufacturers, German suppliers compensate for the low sales figures of German electric cars in China. (cf. Buchenau, Gusbeth, Tyborski 2023, p. 18 and Buchenau, Tyborski 2023, p. 20). In some cases, new technology from German suppliers is first used by the innovative Chinese automakers in China (cf. Buchenau, Tyborski 2023, p. 1). By turning to Chinese automakers, German suppliers can also reduce their great dependence on German OEMs. This represents a partial decoupling of German automotive suppliers and German OEM manufacturers (cf. Buchenau, Tyborski 2023, p. 21).

In essence, all three German automotive suppliers are pursuing a very similar strategy. Continental wants to invest more in future business areas such as autonomous driving, software and hardware computers for the car. (cf. Ludowig, Tyborski. 2020, p. 1). Bosch and ZF also see their future in these business areas.

The situation of German automotive suppliers is further complicated by their low profits compared to carmakers and the need to make substantial upfront investments in R&D and digitization. (cf. Buchenau 2023c, p. 29 as well as Buchenau, Tyborski 2023, p. 20): "Due to the high upfront costs and the still low unit numbers, no automotive supplier is making money from electromobility so far." (Buchenau 2023c, p. 29).

### 5.2.2 Cooperation with the chip industry (hardware and software)

The traditional suppliers of German automakers for chips and control units are the semiconductor groups STMicroelectronics, Infineon, NXP and Renesas. In the case of high-performance processors for autonomous driving, chip manufacturers from the USA in particular are trying to establish themselves as cooperation partners for German automakers in the software ecosystem. (cf. Holtermann, Hofer, Scheuer 2023, p. 28).

For both **Nvidia** and **Qualcomm**, the business with the automotive industry is a small business segment next to their dominant business with the smartphone and computer industry, but one that is growing very strongly. Nvidia achieved sales of USD 566 million in the automotive industry in 2022. Meanwhile, Qualcomm achieved sales of USD 945 million in the automotive industry in the first three quarters of 2022 (see Sharma 2022).

The Israeli company **Mobileye** (in which the semiconductor manufacturer Intel holds a significant stake) offers sensor systems for autonomous driving. As of 2022, Mobileye employs 3100 people and has 50 customers. (cf. Hofer 2022b, p. 25). Mobileye's solutions are used in 800 vehicle models. (cf. Hofer, Holtermann 2022, p. 20).

**Volkswagen** has entered into a comprehensive collaboration with MobilEye. Previously, Volkswagen dissolved the Argo AI joint venture for autonomous driving Robottaxis operated with Ford in October 2022 (See Buchenau, Hofer 2023, p. 26 as well as Holtermann 2022, p. 28.). There is a lot of technical know-how from Mobileye in the VW software platform E1.2. (cf. Menzel, Schütze 2022, p. 20). Volkswagen is working with STMicrolectronics to develop chips for its E2.0 operating system (in this case for the vehicle's connectivity and energy management and over-the-air updates), which are manufactured by contract manufacturer TSMC (see Tyborski 2022a, p. 19). VW is thus getting deeper into the chip business. With this chip cooperation, VW will in the future bypass the major automotive suppliers Bosch, Continental and ZF, which are to use only the chips jointly developed by STM and Cariad in the future. VW is thus relying on direct cooperation with chip manufacturers to expand its competencies in chip development. (cf. Tyborski 2022a, p. 19). This relieves Tier 1 automotive suppliers of the responsibility for semiconductor supply, but also means declining sales for Tier 1 suppliers with their own chip production, such as Bosch. (cf. Tyborski 2022a, p. 19). For VW, the cooperation with STMicroelectronics is another chip partnership in addition to the cooperation with Qualcomm on chips for autonomous driving, which are installed in the vehicle's central computers (cf. Tyborski 2022a, p. 19 and Hofer, Holtermann 2022, p. 20). Together with Bosch, VW Cariad is developing the software for automated driving, which is to run on Qualcomm chips from 2026. (Cf. Hubik, Menzel, Tyborski 2022, p. 23). It is still unclear which processor manufacturer will cooperate with VW on infotainment. A cooperation with Qualcomm is considered unlikely, as VW wants to avoid too much dependence on a single manufacturer. (Cf. Hubik, Menzel, Tyborski 2022, p. 22). In addition, there is no uniform supplier for the chips for autonomous driving at VW for all group companies. Chips are supplied by Nvidia, Qualcomm and Samsung. (cf. Jahn, Menzel, Tyborski 2022, p. 22).

**BMW** initially worked with Mobileye on automated driving (cf. Hofer 2022b, p. 25), but has decided to switch to Qualcomm for the development of future vehicle generations (cf. Hofer, Holtermann 2022, p. 20). BMW is now cooperating with Qualcomm on autonomous driving (cf. Hubik, Menzel, Tyborski 2022, p. 22). "The two companies are jointly developing a software kit for autonomous driving. What is special about the agreement is that not only the Munich-based automaker will use this technology in its models. The U.S. semiconductor supplier is also to sell the know-how to other brands and auto parts suppliers worldwide." (Holtermann, Hofer, Scheuer 2023, p. 28) Qualcomm will be responsible for the distribution of the jointly developed software packages. The revenue split between Qualcomm and BMW is confidential (cf. Hubik, Menzel, Tyborski 2022, p. 22).

**Mercedes-Benz** also cooperates with other companies on chip design (see Hubik 2022a, p. 20). Mercedes-Benz has entered into a cooperation with Nvidia for autonomous driving. (see Buchenau, Hofer 2023, p. 26 and Hubik, Menzel, Tyborski 2022, p. 22), which represents a close development partnership. Nvidia develops the software for autonomous driving with Mercedes and designs chips because Mercedes has no expertise of its own in this area. (cf. Holtermann 2022a, p. 46). In return, NVIDIA receives more than 40% of Mercedes' sales of software for automated driving. (cf. Hubik, Menzel, Tyborski 2022, p. 22). In June 2020, Mercedes entered into a cooperation with NVIDIA to develop fully updateable on-board networks. This technology is to be introduced across all model series from 2024 onwards (see Fasse 2020, p. 19). Mercedes is also cooperating with Qualcomm and installing Qualcomm Snapdragon chips in its MBUX infotainment platform. The Qualcomm chips thus replace the NVIDIA chips previously used in the MBUX system. (cf. Bellmer 2022). It can be assumed that Mercedes wants to avoid dependence on one chip manufacturer.

The strategy of Mercedes, BMW and Volkswagen in the chip sector and their alliances with American chip manufacturers have serious consequences: “German carmakers are becoming increasingly dependent." (Holtermann, Hofer, Scheuer 2023, p. 28)

### 5.2.3 Cooperation and competition with Google (Android Auto) and Apple (Carplay) on software for entertainment and the vehicle operating system

"The goal is to take control of the screens in the car." (Holtermann, Scheuer 2023, p. 23)

An important motive for automakers to cooperate with American software companies is that customers are used to the digital software environments of Google and Apple and also want to use them in their cars (see Backovic 2023, p. 21). "More and more drivers are demanding the same user experience in the car that they know from their smartphones. They want to be navigated by Google Maps, access their Spotify music playlist, or talk to Apple's Siri voice assistant."(Fasse, Hubik, Krolle, Menzel, Tyborski 2021, p. 6) In addition, the media content contributed by Google and Apple (YouTube videos, Apple Music) is also very attractive for many customers, they want to enjoy it also in the car. Google's advantage, which makes Android Auto additionally attractive for many car users, is the Google Maps service (see Holtermann, Scheuer 2023, p. 22). The voice assistant is also a strength and operating advantage of Google. (see Fasse 2020, p. 19).

With Carplay, **Apple** offers a solution package similar in functionality to Android Automotive. (see Scheuer, Backovic 2023, p. 27). The latest version of Carplay also monitors data from the car, such as speed, air conditioning, and fuel level. (cf. Holtermann, Hubik Scheuer 2023, p. 31). Apple has efforts to expand the functionality of Carplay beyond displaying the iPhone screen on the car's screens. Apple's goal is to deeply integrate Carplay with the car's hardware, and development is moving in the direction of an operating system for the car. (see Scheuer 2022, p. 18).

**Google** is simultaneously pursuing several approaches or business models with its software for the automobile. These are characterized by a step-by-step approach. "In the beginning, there was the simple mirroring of the smartphone display in the car, called "Projected Mode" by Google (often also referred to as Android Auto, author's note). In a second step, Google offers its Android system, also in an open-source version. While carmakers can change this as they wish, the dependency increases, for example, when Google releases an update." (Holtermann, Hubik, Scheuer 2023, p. 30) "A vehicle manufacturer has the choice, when using AOSP (Android Open Source Project, author's note), to develop important functions such as map service, voice assistant, and app store themselves or to license these from Google as Google Automotive Services (GAS)." (Weber, Raisch 2023, p. 33). The "Google Automotive Services" (GAS) system goes even further, incorporating a range of Google services and offering increasingly important functions in the vehicle such as the air conditioning or the rearview camera (cf. Holtermann, Hubik, Scheuer 2023, p. 30 and Weber, Raisch 2023, p. 33 f.).

Android Automotive, offered by Google, is a permanently installed operating system for cars that can be used independently of Android phones. (see Scheuer, Backovic 2023, p. 27). Google Automotive has so far been used by Volvo, Renault, PSA and GM. (cf. Ludowig, Tyborski. 2020, p. 4).

"AAOS (Android Automotive OS, author's note) is well on its way to becoming the operating system of choice for all future infotainment systems." (Holtermann, Hubik, Scheuer 2023, p. 30). "With AAOS, the company is providing an operating system that can be used to control more than just the entertainment program in the car. The software has the potential to become the operating system for the entire vehicle, even if important areas are still missing. For example, Google has nothing to show in the area of driver assistance systems so far." (Holtermann, Hubik, Scheuer 2023, p. 30). "So far, it is not clear if and when Google also wants to take control of safety-relevant areas in cars." (Holtermann, Hubik, Scheuer 2023, p. 30).

Google has accommodated the German carmakers by offering "Google built-in" as a reduced solution instead of Android Automotive Service. This means that Google does not take over the complete entertainment in the car (AAS), but the car manufacturers can integrate individual Google apps into their own operating system while retaining data sovereignty. (see Backovic, Hubik, Tyborski 2023, p. 1).

"Among the big losers in this development are classic map providers such as TomTom or Here Technologies, which are likely to lose a large part of their business with German automotive prestige customers in the foreseeable future." (Holtermann, Hubik 2023a, p. 22). In this context, the German automakers Audi, BMW and Daimler jointly acquired the digital map service **Here** from Nokia in 2015 (cf. Holtermann, Schauer 2023, p. 22 as well as Kaiser/Stocker/Fellmann 2019, p. 5).

There have recently been signs that **Volkswagen** is increasingly opening up to Google Apps (e.g. Google Maps, YouTube). This can be seen from corresponding considerations in the VW Group (see Backovic

2023). The fact that VW Cariad has opened up more to external software solutions is shown, for example, by the fact that the software for the infotainment system is based on Google's open-source code. This step is intended to improve the speed and running behavior of the software. (cf. Holtermann, Backovic, Tyborski 2023, p. 22.). Until now, Porsche has refused to cooperate closely with Google in order to continue to have exclusive access to data on its cars and to avoid the need to share this data with Google (see Scheuer/Backovic 2023, p. 27 and Holtermann, Backovic, Tyborski 2023, p. 22.). However, VW and Porsche are currently working on or considering integrating Google AAOS into the car. (cf. Holtermann, Hubik Scheuer 2023, p. 30).

As of 2023, **BMW** was one of the first users of Android in automobiles. BMW is careful to limit the use of Android to infotainment and not to use GAS in order to maintain its autonomy and independence. (cf. Holtermann, Hubik, Scheuer 2023, p. 31). BMW integrates Android Auto as a smartphone mirror into its infotainment software and also uses open Android source code. In contrast, the transfer of data to Google and, as a consequence, the Android Automotive Services operating system is rejected (cf. Holtermann, Hubik 2023, p. 21). BMW works with Amazon on voice control and adopts its Alexa voice control system. (cf. Holtermann, Backovic, Tyborski 2023, p. 23, Holtermann, Hubik 2023, p. 21). However, data sovereignty is retained in this area as well. (cf. Holtermann, Hubik, Scheuer 2023, p. 31).

**Mercedes-Benz** also does not want to adopt Google's GAS infotainment system. (cf. Holtermann, Hubik, Scheuer 2023, p. 31). As of 2023, Mercedes has integrated Google Maps and YouTube into its own MB.OS operating system, but retains data sovereignty in this cooperation model.  In return, Mercedes pays license fees to Google. (cf. Holtermann, Hubik 2023, p. 1, Backovic 2023, p. 21, Holtermann, Hubik 2023a, p. 22).

Both Mercedes-Benz and BMW are considering and examining the integration of elements of Google's Google Automotive Services software, aiming to retain data sovereignty and control over the interface with the customer. (cf. Hubik 2022, p. 23).

Apple's partners in Carplay are **Mercedes, Audi and Porsche** (see Scheuer 2022, p. 18). However, Mercedes expressed surprise at this statement from Apple because no agreement had been concluded with Apple, but only options were being evaluated. (Hubik, Menzel, Tyborski 2022, p. 22). Mercedes does not want to integrate complete infotainment systems such as Google Android Automotive or Apple Carplay under any circumstances, because otherwise there is a risk of losing data sovereignty. (see Hubik, Menzel, Tyborski 2022, p. 22).

The increasing openness of car manufacturers to Internet and software groups cannot be interpreted as a capitulation on the part of the automotive industry if car manufacturers succeed in creating key parts of the car operating system themselves, integrating Google and Apple apps into their own operating system, and asserting data sovereignty over Apple and Google. Such an objective can be achieved by agreeing on license payments instead of data transfer (see Micijevic 2023, p. 46).

### 5.2.4 Collaboration with cloud service providers

In 2021 the world market for cloud services had a volume of 178 bill. USD, the dominating American cloud service providers are **Amazon** Web Services, **Microsoft** Azure and **Google** Cloud. Cloud services for the automobile industry accounted for a market volume of 16,5 bill. USD. (cf. Straits Research 2022)

**Volkswagen** has a close cooperation with Microsoft to build its own cloud based on Azure. The aim is to develop new mobility services around the vehicle. (cf. Menzel 2020, p. 19) The automotive cloud built with Microsoft on the basis of Azure is intended to develop new mobility services around the car and approach customers. (cf. Kerkmann, Menzel, Murphy 2019, p. 16). The first car model to be connected to the Automotive Cloud was the VW ID.3 (cf. Menzel 2019a, p. 18).

"Amazon was not offered the "automotive cloud" - because of the too close connection to trade and customer data." (Kerkmann, Menzel, Murphy 2019, p. 16) But Volkswagen is building an industrial cloud for global vehicle production with Amazon. VW plans to network all 122 vehicle plants worldwide with the Amazon Cloud (see Kerkmann, Menzel, Murphy 2019, p. 16). This should help to increase efficiency in vehicle production by 30% by 2025. (see Kerkmann, Menzel, Murphy 2019, p. 16). The cooperation is intended to achieve end-to-end digitization of production, whereas up to now IT has still differed from location to location. (cf. Kerkmann, Menzel, Murphy 2019, p. 16). "Volkswagen wants to digitally network its 122 factories and, in perspective, also include suppliers. VW is building an industrial cloud with the help of the U.S. online retailer Amazon, and the networking of machines is to take place via Siemens' Mindsphere platform." (Höpner, Menzel 2019, p. 1) Also planned for the realization of the VW Industrial Cloud is a cooperation with Siemens, which will use the Mindsphere software solution to integrate the plants, machines and factory systems of different manufacturers in the 122 VW plants and network them in the cloud built with Amazon AWS. (cf. VW 2019). VW is designing its planned Industrial Cloud as an open platform. The aim is to integrate companies from the entire value chain of the automotive industry and to build up a partner network. According to VW, the aim is also to include 1500 suppliers and partner companies in the network. It is also conceivable that other car manufacturers will be added to the cloud. (cf. Kerkmann, Menzel, Murphy 2019, p. 16).

For cloud services, VW also cooperates with Deutsche Telekom. (cf. Kerkmann, Menzel, Murphy 2019, p. 16).

Overall, VW is pursuing a multicloud strategy to reduce dependencies on one cloud provider.

Catena-X is a consortium around **BMW** and SAP to digitally map the value chain. The aim is to facilitate the exchange of data between companies, with the data remaining with the companies themselves. The consortium comprises 104 members, including car manufacturers, suppliers and IT providers. The goal is to create an open cloud platform. Currently, 800-1000 developers are working on the project and the budget is 230 million euros. (cf. Kerkmann 2022, p. 20). Catena-X is part of Gaia-X, the European project for the development of a cloud data infrastructure. An open source component developed by the Fraunhofer-Gesellschaft is used for data exchange (cf. Kerkmann 2022, p. 20).

BMW is also working with Microsoft on a cloud solution to digitize production at BMW plants in order to increase efficiency. Suppliers are also to be integrated into this open manufacturing platform. (cf. Knitterscheidt, Kerkmann, Fasse, 2019). The large car manufacturers also cooperate with small software specialists on cloud solutions. One example of this is BMW's cooperation with QAware in the development of a cloud-based mainframe application that transfers vehicle production bills of materials to the Azure Cloud (see Christ 2023).

Together with Amazon Web Services, BMW is implementing a cloud solution for vehicle data, whereby BMW retains complete control over the vehicle data. The cooperation between BMW and AWS has existed since 2015 (cf. Donath 2022, p. 1).

It is clear that BMW does not obtain all cloud services from a single cloud provider either, presumably to avoid dependencies.

**Mercedes-Benz** is implementing a new data platform in all its car plants as a cloud solution based on Azure from Microsoft. (cf. Hubik 2022a, p. 21). Among other things, this is intended to help "banish all paper from the production plants" (Hubik 2022a, p. 21) and achieve efficiency gains of 20% in Mercedes car production by 2025. (cf. Hubik 2022a, p. 21). Furthermore, Mercedes-Benz has agreed to cooperate with Google on cloud services in 2023 (cf. Zwick 2023).

Nevertheless, it remains to be stated that the European economy (and thus also the German car manufacturers) is increasingly dependent on the cloud offerings of the three American providers Microsoft, Google and Amazon, because there is no globally active cloud provider from Europe and the European cloud offerings Gaia-X and the infrastructure offerings of SAP and Telekom have so far only served niche markets. New cloud providers such as Ionos (Germany), OVH (France) and the Schwarz Group (Germany) have so far been too small for the scale-intensive cloud business and are also only active in Europe. (cf. Scheuer 2023, p. 14). "Europe's gap to Amazon, Microsoft and Google can hardly be closed. ... The long-term consequences of the dependence of the European economy can hardly be overestimated." (Scheuer 2023, p. 14)

### 5.2.5 Collaboration with Chinese partners

The previous explanations showed the cooperation strategies of German car manufacturers for Western markets. This would have to be detached from a consideration of the Chinese market, in which many western cooperation partners (e.g. Google) of the German car manufacturers do not have market access. German automakers must therefore cooperate with other partners in the Chinese market.

For example, **VW** is cooperating in China with the Chinese software company Thundersoft in testing software, and in the field of autonomous driving with the Chinese AI specialist Horizon Robotics. In the infotainment sector, possible cooperation partners for German automakers in China are Huawei, Tencent and Alibaba, not Google. (cf. Backovic 2023a, p. 7). VW is investing up to 2 billion euros in a partnership with the Chinese software developer Horizon Robotics to develop solutions for autonomous driving. VW thus intends to use Chinese software development expertise locally. (Brandstätter 2022, p. 20). Outside China, Bosch is VW's cooperation partner for autonomous driving. (cf. Backovic, Murphy 2023, p. 23). In China, VW has to integrate the super app Wechat into its vehicles (Brandstätter 2022, p. 21). Together with Horizon Robotics, VW also wants to get into chip development, the semiconductors are to be used in autonomous driving (cf. Menzel, Tyborski 2022 a, p. 25). "In total, VW plans to invest 2.4 billion euros in its additional digitization efforts in China." (Menzel, Tyborski 2022a, p. 25), of which 1.3 billion euros will flow into the new joint venture. The cooperation with Horizon Robotics will be handled by Cariad (see Menzel, Tyborski 2022a, p. 25.). In addition, Cariad had also established its own Chinese subsidiary to better meet the software needs of Chinese customers. Recently VW is establishing a platform partnership in China with Xpeng, a Chinese electric car manufacturer founded in 2014. Together, the partners plan to develop two new mid-range electric models, with Xpeng contributing software solutions for driver assistance and autonomous driving, a voice assistant, and an electric car platform. The cooperation is consolidated by VW taking a 5% stake in Xpeng's capital (see Backovic, Murphy, Tybroski 2023, p. 18 f. and Tyborski 2023c, p. 1). Critics see this cooperation as an expression of VW's weakness in the development of electric cars and digital solutions. This is particularly evident in the Chinese market (see Tyborski 2023 b, p. 18). Audi has established close cooperation with SAIC in China (see Tyborski 2023 c, p. 1). Audi wants to use an electric car platform from SAIC and develop a new electric platform together with SAIC by 2026, to be launched on the market in 2027/28. In the process, Audi will upload its own car software to SAIC's platform. The purchase of SAIC's electric platform is interpreted as a lack of confidence by Audi in the modular electric kit (MEB) available in the VW Group. (cf. Fasse, Murphy, Tyborski 2023, pp. 1, 18, 19).

**BMW** plans to produce the next-generation electric Mini on Great Wall's platform in China and export it from there (cf. Fasse, Murphy, Tyborski 2023, p. 19). BMW has established a joint venture with the Chinese technology company ArcherMind Technology (software for cars, cloud applications). Cooperation with the China Automotive Technology & Research Center (CATARC), e.g. on intelligent connected vehicles, is currently being initiated. (cf. unknown 2023) BMW also cooperates in China with companies such as Alibaba Group Holding, China Unicom, Huawei Technologies, Navinfo and Tencent Holdings, as well as with Chinese universities such as Tongji University and Tsinghua University. (cf. BMW 2023). China is already home to BMW's largest research and development capacities outside Germany. Sites in Beijing, Shanghai, Shenyang and Nanjing employ a total of more than 3200 research and development staff, including many software specialists. (cf. unknown 2023).

**Mercedes-Benz** has categorically ruled out adopting platforms from other manufacturers. (cf. Hubik 2023, p. 29). Daimler-Benz has agreed several collaborations in the Chinese market. For example, Mercedes is cooperating with the Chinese technology company Baidu in the field of autonomous driving and connectivity (see Conrad 2018). In the areas of cloud computing, cyber security and autonomous driving, Mercedes cooperates with Tencent. (see Weber 2022). In China, Mercedes does not work with Google, but with Amap for navigation and Tencent (Wechat App) for entertainment (cf. Holtermann, Hubik 2023a, pp. 1, 23 and Backovic, Hubik, Tyborski 2023, p. 4).

### 5.2.6 Other cooperation partners in the software sector

The aforementioned list of players in the software ecosystem of the automotive industry is not complete and can never be complete because new players will appear in the software ecosystem as technical progress in the digitization and electrification of the vehicle increases. For example, BMW AG has entered into a cooperation with Deutsche Telekom AG to network BMW's vehicles using 5G mobile communications (cf. Geelen 2021, p. 1). The cooperation enables Deutsche Telekom customers to extend their 5 G mobile communications contract to the networked vehicle. Here, the MobilityConnect option for EUR 9.95 per month was created. For customers, the benefits of 5 G networking include being able to take their personal vehicle settings with them to other vehicles, such as rental cars. In addition, the networking of vehicles with 5 G mobile communications will enable a wide range of innovative service offerings relating to the automobile (see Geelen 2021, p. 1,2).

Other sources of knowledge for automotive manufacturers to build up the necessary software expertise could be cooperation with start-up companies, venture capital firms, software specialists, management consultancies, universities and business-related research institutes. (cf. Felser/Wynn 2023, p. 181 and (cf. Kim/Paek/Lee 2022, p. 12). These collaborations were not the focus of this paper.

Newly founded software start-ups with a focus on the automotive industry could also become cooperation partners of German OEM manufacturers in the future. According to the Crunchbase database, a large number of software companies with a focus on automotive software have been founded in Germany or by German entrepreneurs abroad in recent years. Among them are Veecle (autonomous driving) from Saarbrücken, Innoventis (cybersecurity in automobiles) from Würzburg, understand.ai (simulation and test for autonomous driving functions) from Karlsruhe, SiaSearch (autonomous driving) from Berlin, Sigra (autonomous driving) from Herfelde, Fernride (autonomous transport vehicles), Blickfeld (software for 3D environmental information) from Munich, Double Slash (software for over the air updates) from Stuttgart, Vector Informatik (software for the automotive industry) from Stuttgart and Apex.AI (vehicle operating system) from Palo Alto (USA). The Fraunhofer Institute concludes, "Germany currently has many small and highly specialized software companies, for example in the environment of corporations in the automotive industry." (Fraunhofer ICT Alliance 2021, p. 12). The Fraunhofer Institute counts the large automotive manufacturers and suppliers as "companies in the software secondary industry, in which software is not an independent product, but an important, indispensable product component." (Fraunhofer ICT Alliance 2021, p. 5).

In addition to the traditional automotive suppliers, engineering service providers that have always provided development services for OEM manufacturers could also become partners of OEM manufacturers in the area of software. For example, P3 Systems tests the software in entertainment systems for car manufacturers, while Tracetronik from Dresden carries out automated software tests for car manufacturers. As a development service provider, Bosch subsidiary EDAG focuses on IT systems in cars, among other things.

## 6. Results – competition, cooperation and ongoing change in the formation phase of the software ecosystem of the German automotive industry

The following three figures show the firm specifc software ecosystems of the free car firms under study.

**Figure 2**: Volkswagen's software ecosystem

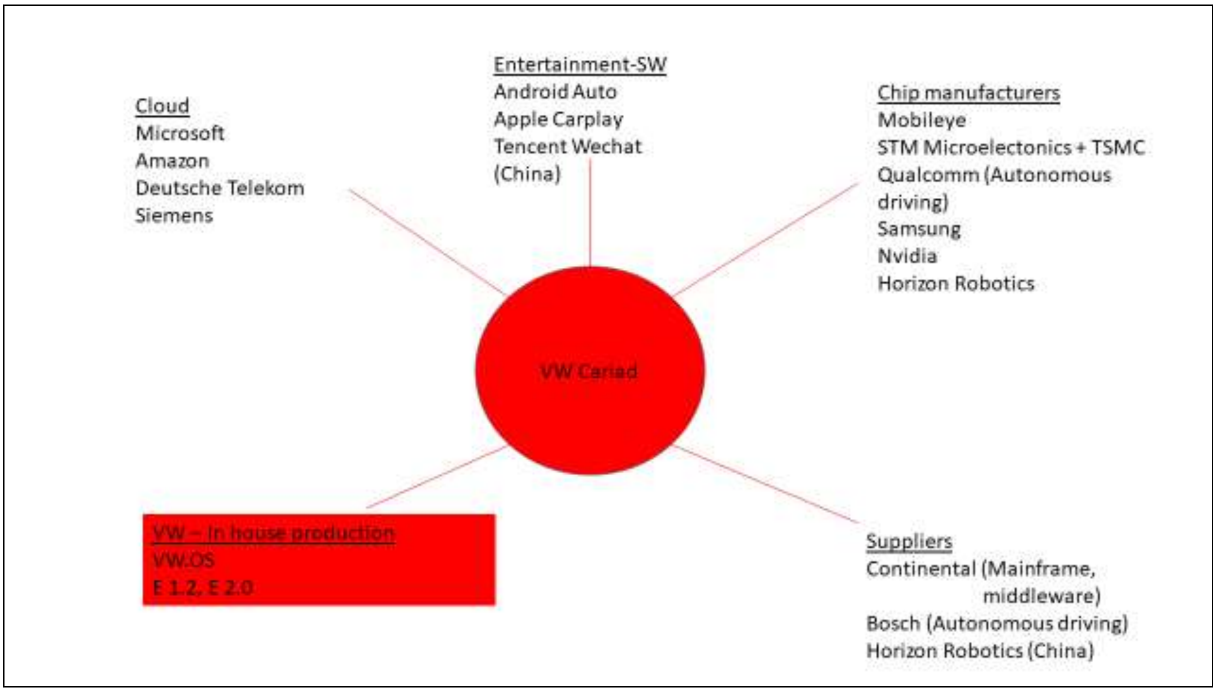



**Figure 3**: BMW's software ecosystem

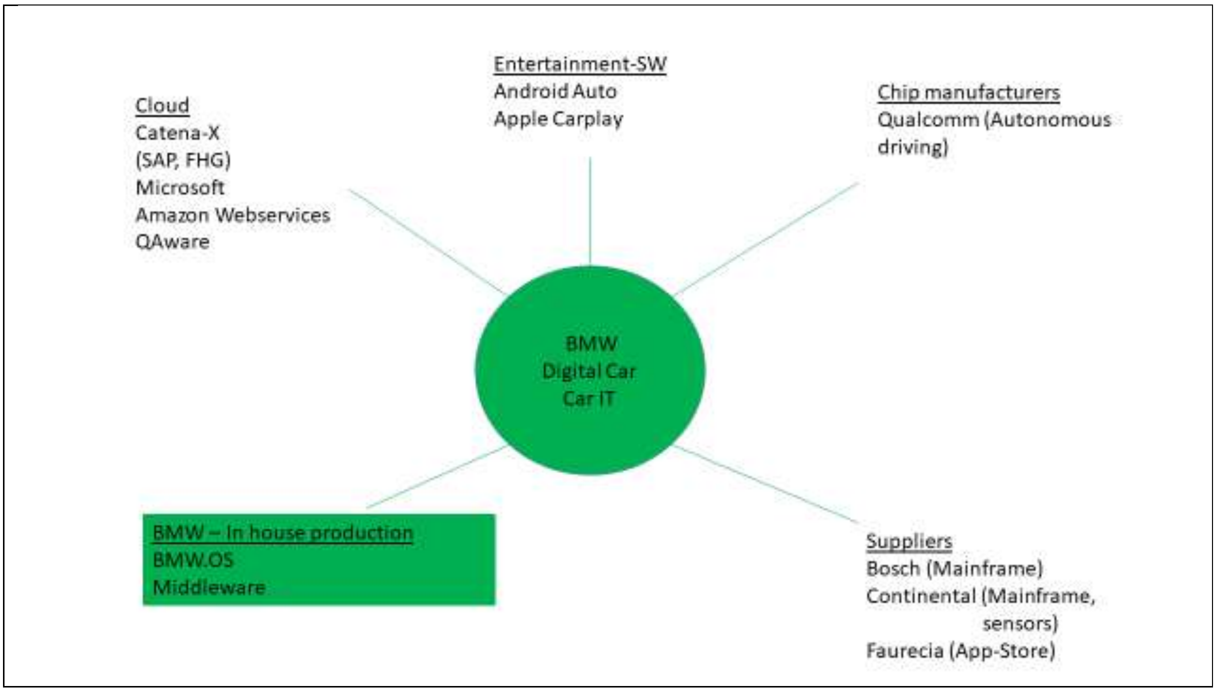
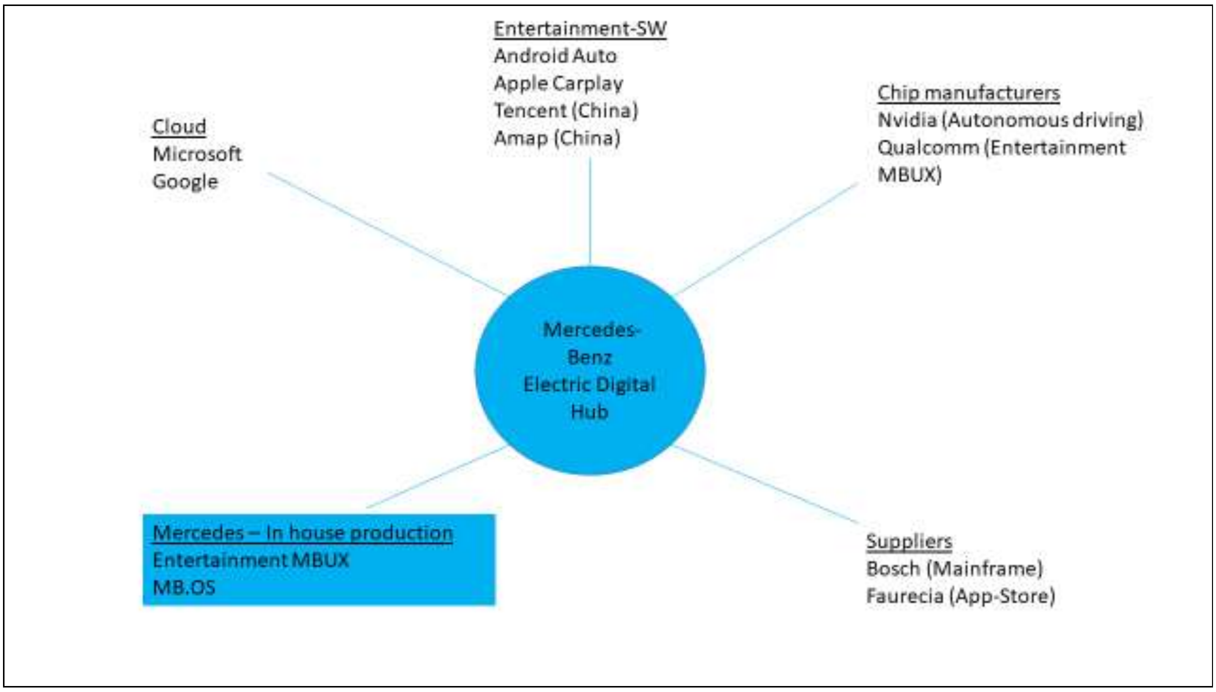
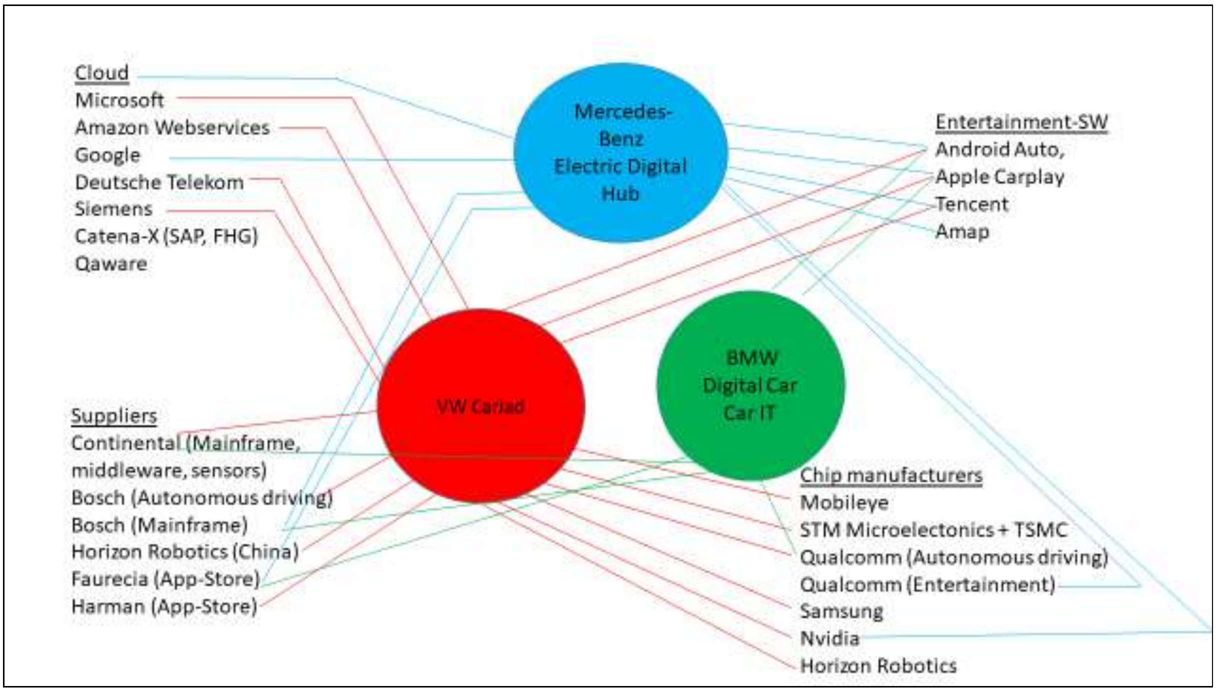


**Figure 4**: The Mercedes-Benz software ecosystem




The following figure provides an overview of the whole software ecosystem in the German automotive industry.

**Figure 5**: The overall software ecosystem of the German automotive industry




The transformation of the German auto industry's innovation ecosystem through transition to the software-defined vehicle can be assessed and characterized by the following aspects and trends.

## 7. Discussion

The innovation ecosystem of the German automotive industry currently consists of 3 company-specific innovation ecosystems, each of which is controlled by the three manufacturers VW Group, Mercedes-Benz and BMW as focal companies. From an overarching perspective, the innovation ecosystem of the German automotive industry is multi-centric, with the VW Group being a prominent player with its large production volume and sales volume.

Collaboration in the ecosystem is focused on several emerging and stabilizing platforms which are not technologically compatible to each other. These central innovation platforms are the car operating system of the respective vehicle manufacturer and the OEM manufacturers' new service business models based on car software and user data, e.g. in the form of connected car services. The OEM manufacturers currently control access to these innovation platforms and select the value creation partners.

There is currently no industry-wide accepted technology platform in the German automotive industry. One reason for this is that the three German OEM manufacturers each develop their own vehicle operating system and also develop their own connected car service platforms. Consequently, the specific platforms of 3 OEM manufacturers are predominant.

Currently, a hybrid innovation ecosystem prevails in the German automotive industry, one subsystem is focused on the classic automobile and is highly developed, efficient and mature, the other subsystem is focused on the software-based automobile and is currently in the formation phase. It is obvious to speak of a hybrid innovation ecosystem instead of 2 separate innovation ecosystems because there are still synergies between both types of automobiles and all players are also actively involved in both parts of the car eco system.

The software ecosystem of the German automotive industry is still in its formation phase. In such an early stage of ecosystem development, companies are still looking for the ideal procedures, ways and organizational solutions to generate value creation and appropriate the profits from it. (cf. Dias Sant'Ana et al. 2020), p. 2736)

Typically for the formation phase is also intensive cross-company collaboration in value creation with several and changing partners. OEM manufacturers continue to cooperate with traditional automotive suppliers, but are increasingly integrating semiconductor groups, cloud service providers and American technology groups into the value creation process for software-based vehicles.

Collaboration is predominantly organized vertically (OEM and automotive suppliers, cloud service providers, semiconductor manufacturers), although horizontal collaboration between companies at the same level of the value chain (e.g., VW with Chinese carmakers) has slowly been gaining in importance. Cross-industry collaboration (e.g., OEM with U.S. technology groups Google and Apple) is particularly important for the software-based automobile. Cooperative relationships prevail between the players, but also competitive relationships (e.g., between Google and Apple among themselves and potentially competitive relationships in the future between these two companies and OEM carmakers).

Typical of an emerging innovation ecosystem is that there are still numerous duplications, changing partnerships, isolated sub-ecosystems, missing or competing standards, and actors are still searching for the most beneficial solutions for all stakeholders (cf. Dias Sant'Ana et al. 2020), p. 2736).

One important result is the "opening up of ecosystems that were previously strictly closed in the automotive industry, which are increasingly coming into contact with other industries: Internet, telecommunications, hardware, multimedia, plus navigation providers and other industry newcomers such as Apple and Google entering the market." (Gennen 2018, p. 25). The German automotive industry's software innovation ecosystem is changing in two ways: players from other industries are entering (mobile, semiconductors) and players from other countries (U.S. and China)

The structure of the innovation ecosystem has also changed due to the entry of new players into the innovation ecosystem (Apple, Google, Samsung, cloud service providers) or the exit of established players from the innovation ecosystem (2nd tier and 3rd tier automotive suppliers specializing in combustion engine technology).

The innovation ecosystem that is just forming will integrate foreign companies (USA, China) and companies from other industries (e.g. IT, software, content) as new elements. German system suppliers could increasingly decouple themselves from the German OEM manufacturers and expand cooperation with Chinese automakers. A formerly in Germany based innovation ecosystem has become a global innovation ecosystem.

The players in the now forming software-based innovation ecosystem of the automotive industry are very heterogeneous in terms of their industry origins (start-up companies, cloud service providers, semiconductor manufacturers, software groups), their company size, their expertise in car manufacturing or their expertise in the software field. The specialization and heterogeneity of the players results in the need for collaboration in the innovation ecosystem.

The innovation ecosystem is in a constant state of flux. This can be seen from the fact that players in the value network are changing their position. Typically for the formation phase are greater changes in the positions of single actors in the overall system. The automakers try to increase the performance and innovative power of their value network by selectively choosing (or deselecting) value creation partners, while at the same time reducing dependencies on individual players. As individual automakers shape their company-specific innovation ecosystem, the innovation ecosystem of the entire auto industry evolves at the same time. For example, BMW and VW have reduced their collaboration with Mobileye, thereby moving Mobileye more to the periphery of the overall German car innovation ecosystem. BMW, Mercedes, and VW increasingly seeking collaboration with Apple and Google, these two U.S. tech companies moved from the edge of the overall ecosystem increasingly to a near central position in the digital ecosystem. Conversely, the company Nvidia is attempting to move from the periphery of the ecosystem more to the center of the ecosystem with the help of collaborations (e.g., with Mercedes-Benz) and to become a central value creation actor and node in the value creation network.As a further example, Nvidia and Qualcomm have moved from the periphery to the center of the innovation ecosystem of the automotive industry through their collaborations with OEM manufacturers, while automotive suppliers such as Mahle or Eberspächer begin to move to the periphery of the innovation ecosystem because of their high value-added contributions to the traditional automobile based on combustion technology.

The relationships between the players in the unfolding innovation ecosystem are very change-intensive. While OEMs initially saw Google and Apple as potential competitors, they have recently increasingly sought cooperation with these companies in view of their own deficits in software competencies and content. In the long term, the relationship could become more competitive again, especially if the technology groups develop their own car operating systems with comprehensive functionality and mapping of all vehicle functions.

Many relationships in the software ecosystem were changed, generating increasingly complex networks in the software ecosystem. "In the end, however, the most important goal is to be able to develop software independently of the hardware..... This independence is only possible with appropriate middleware. In such a partnership, however, the need for coordination is great. Developers from Continental and Bosch have to exchange information regularly to ensure that their respective software packages can communicate with each other. For example, the autonomous driving software that Cariad is developing jointly with Bosch must also be able to communicate with the middleware. In the digital car world, Volkswagen is thus not the only company moving closer to its suppliers. The two largest supplier competitors must also move closer to each other" (Tyborski 2022b, p. 4).

The relationsships in the software ecosystem are becoming ever more complex as some of the car suppliers work with the same technology companies with which the OEMs also cooperate. “For central computing, suppliers rely on chip companies like Nvidia and Qualcomm. For AI development, they need the computing power of clouds from Amazon or Microsoft. Bosch, for example, had recently announced a cloud partnership with Microsoft, and Continental one with Amazon." (Tyborski, Buchenau 2021, p. 10). For example, the automotive supplier ZF is Mobileye's largest customer, Mobileye generates 43% of its revenue with ZF (see Hofer, Holtermann 2022, p. 20). The OEM manufacturers BMW and Tesla cooperated with Mobileye in the past and currently VW has a cooperation with Mobileye.

The transition from the classic automobile (combustion technology, vehicle electronics) to the software-based automobile has led to a profound change in the innovation ecosystem of the German automotive industry: The previous innovation ecosystem was primarily characterized by the cooperation of German OEM manufacturers with German system suppliers as well as Tier2 and Tier3 automotive suppliers. "The old structure of automakers on one side and suppliers on the other is being broken up as a result. Both sides have to open up to the tech groups in certain areas." (Tyborski, Buchenau 2021, p. 10). OEM manufacturers today try to establish alternative sources of supply and cooperation partners for car software and to play off the car suppliers against American technology groups. (Tyborski, Buchenau 2021, p. 10). "Mercedes and BMW are relying on the U.S. giants Nvidia or Qualcomm with close collaborations for autonomous driving functions. If the combination of German premium manufacturers and U.S. tech groups is faster and better in software and hardware development, the chances of the major automotive suppliers Bosch, Continental and ZF retaining their ancestral strong position in the industry will dwindle in the digital future of the car." (Buchenau 2022, p. 31). Volkswagen is choosing a different path and, in addition to working with the major German automotive suppliers, with the involvement of American technology groups, is also focusing on cooperative ventures with Chinese automakers (to whom the major German automotive suppliers also supply important components for electromobility) in the Chinese market.

Not only new firms appeared and new relationsships were institutionalized, but single firms also had to cope with significant change of their role and strategy in the value network. The German OEM manufacturers are trying to adapt their value chains to the software-based automobile. However, since the value chains of BMW, VW and Mercedes-Benz partly comprise the same companies, there are points of contact between the value chains, which from an overarching perspective looks like a single complex value network. In this innovation ecosystem, the OEMs seek collaboration with the particularly innovative partners and compete with each other for the most significant partners. That strategic thinking is slowly changing among OEM manufacturers can be seen in the new collaboration and revenue sharing models that BMW and Mercedes have agreed with NVIDIA and Qualcomm. Here, the OEM manufacturer no longer controls a value chain that it has built and managed, but must compete in the ecosystem to collaborate with high-competence partners and implement new collaboration and revenue-sharing models with them. OEM manufacturers are forced to adapt their innovation strategies to innovation ecosystem-based co-innovation with equal partners. The value chain controlled by one company is increasingly being replaced in the automotive industry by complex value networks in which diverse players, including those from other industries, work together in changing configurations. (cf. Schäfer, Jud, Mikusz 2015, p. 387).

The efforts of OEMs to catch up in software and establish and change partnerships with system suppliers, U.S. technology groups and Chinese technology groups and Chinese automakers have created turbulence and a profound change in the innovation ecosystem of the German auto industry. OEMs have loosened old ties with previous system suppliers and established new ties with new value creation partners. New players entered the innovation ecosystem, established players such as Tier 2 and 3 suppliers had to take new positions in the innovation ecosystem. The elevation of software technology in the innovation ecosystem profoundly changed the structure of the innovation ecosystem.

Changes in the structure of the innovation ecosystem are also reflected in the growth or contraction of the entire innovation ecosystem. For example, it can be assumed that in the transition period to the software-defined electric car, the previous innovation ecosystem of the combustion vehicle will lose importance, but will still continue to exist in parallel with the new innovation ecosystem. Since some new suppliers are assigned to the high-tech sector (software, semiconductor suppliers), the innovation ecosystem will initially still grow (e.g., measured by aggregated R&D expenditures of all players or the number of players), but will shrink again in the medium to long term. The main causes for this can be found in the beginning departure of suppliers of combustion technology.

The change of an innovation ecosystem is not only reflected in the structural change of the system, but also in the change of the innovations produced by the innovation system. It is becoming apparent that the resulting product innovations are significantly different from product innovations of traditional cars. There is an upgrading of service innovations (connected car services) and software-based innovations (separate sale of software-based assistance systems) and a loss of importance of innovations in the vehicle's powertrain (transmission, electric motor). Likewise, change in the innovation ecosystem is reflected in a changing degree of innovation of the new solutions. The software-defined vehicle appears to be a radical innovation from the point of view of the car manufacturers, who can only achieve minor competitive advantages with incremental improvements to combustion vehicles.

The result is a radical transformation (rather than incremental change) of the innovation ecosystem of the German automotive industry by the software-based vehicle. This radical transformation of the overall ecosystem is reflected in the extent to which the structural and innovation-related parameters (boundary of the ecosystem, new players, new relationships, change in innovation content and degree of innovation) of the innovation ecosystem of the German automotive industry change.

The innovation ecosystem of the German automotive industry is deliberately and purposefully designed by the leading three German car manufacturers and at the same time subjected to evolutionary change generated by the complex interaction network comprising all actors in the ecosystem. Individual, goal-oriented corporate decisions in context and interaction with other individual corporate decisions lead to an evolutionary further development of the overall innovation ecosystem.

These findings have several implications for the theoretical concept of the innovation ecosystem: The case studies have made it clear that, especially in the emergence phase of a new ecosystem, many elements of the ecosystem and their relationships are not yet fixed, but rather in a state of flux: The structure of the ecosystem is still changing as new actors enter and leave, the relationships between actors change, the positions of individual actors in the ecosystem change and the value creation roles of individual actors in the ecosystem change. The case studies have also shown that hybrid ecosystems emerge in the start-up phase during the transition period, in which the old ecosystem still exists but the new ecosystem has not yet fully established itself. The competition and coexistence between sub-ecosystems within a larger ecosystem has, to the author's knowledge, been little researched to date. Convergence with or a split-off from other ecosystems from other sectors can occur, particularly in the development phase of an ecosystem. The fact that an innovation ecosystem globalizes already in the development phase can be explained by comparative advantages of individual countries in the newly established technology or by the attractiveness and diversity of the sales markets in these countries, which makes local value creation attractive. The case studies have also shown that the start-up phase of an innovation ecosystem is not only about questions of innovation generation, but also about the management of dependencies between partners and the development of negotiating power vis-à-vis other companies. Dependencies, power and negotiating positions have so far received little attention in research on innovation ecosystems. A microfoundation of innovation ecosystems with the activities and decisions of individual companies in a specific, time-limited period can make the emergence of an innovation ecosystem comprehensible and explain it. There has been little research to date into the processes by which company-specific innovation ecosystems grow together to form an integrated innovation ecosystem for an entire industry. They can be triggered either by competition or cooperation between players or by government policy (e.g. funding policy). However, it is also conceivable that central actors in the ecosystem, to which several other actors have connections and which in turn connect the other actors, contribute to the consolidation of company-specific ecosystems.

## 8. Conclusion

The above company case studies have illustrated the transformation dynamics in the innovation ecosystem of the German automotive industry. It was triggered by the increasing importance of automotive software, where OEM manufacturers had and still have competence deficits. The new technology forced OEM manufacturers to cooperate with external value creation partners and thus promoted the entry and further expansion of players from other industries (semiconductors, cloud service providers, American technology groups) in the German automotive ecosystem which has been subjected to drastical change.

For future work, however, there are good points of connection to the present study at this point. For example, further studies can attempt to shed more detailed light on formation phase of the software car ecosystem through expert interviews or company surveys, for example, and thus gain an even more comprehensive understanding of the underlying causes and processes. More research is also needed in the field of hybrid ecosystems with coexisting spheres of analogue and digital technology, and on the lifecycle of ecosystems. As concerns the German car industry the decision process between developing proprietary firm specific software solutions or a standardized software platform for the whole industry or relying on open source software for the digitized car could be a fruitful research effort. How could it happen that the formerly very successsful partnership between German OEMs and German tier 1 suppliers was weakened in the case of car software. Car software speeded up this process of alienation but was not the initital cause for it.

The results of the case study must be understood in light of the limitations. For example, in the cases outlined, the representations refer to interpretative document analysis, which may have subjective character. In addition, the data are predominantly based on secondary sources. The author took care to triangulate the data sources and also mirrored articles from the business press and research with primary sources such as company websites and annual reports. He refrained from independently collecting new primary data because this relative young field of automotive technology is still strongly changing. Another limitation is the need to combine the three company case studies in order to achieve an integrated view of key parts of the innovation ecosystem of the German automotive industry, which can never be complete and conclusive due to the complexity of the German car ecosystem. Many other factors influencing change in the innovation ecosystem of the German car industry were not encompassed by this study: A change in the innovation ecosystem is generated by changes in government regulation (emission limits for combustion vehicles, ban on combustion technology) or other government-established framework conditions (e.g. liability rules for autonomous vehicles, government subsidies for buyers or car manufacturers of electric cars). Also contributing to change in the innovation ecosystem is the influence of the capital market, which signals, for example, a much higher stock market valuation of electric car manufacturers compared to traditional car manufacturers. Change in the innovation ecosystem is also caused by improved or worsened financing options for innovations, e.g., the provision of venture capital for start-up automotive companies. Finally, societal change - e.g., a changed understanding of mobility or a reduced (home office) or increased (e-commerce) need for mobility, changes in attitudes toward environmental protection and sustainability in mobility - also influences the development of the innovation ecosystem of the German automotive industry. The focus of this paper was on the change in product technology. For this reason, other drivers of change have been disregarded in the analysis.

In the medium to long term, the following development could result for the innovation ecosystem of the automotive industry: "Car manufacturers can make their ecosystems digital throughout in the medium and long term. The transition period requires a coexistence of conventional, analog system architecture and the new, digital ecosystem. This maps the previous system pillar completely digitally and runs redundantly alongside it until the complete changeover can take place. Later, there are viable concepts and experience to communicate digitally and efficiently with modern customers as well as digital partners." (Gennen 2018, p. 26). The development of the innovation ecosystem in the German automotive industry will therefore continue and is not over with the changeover to software-defined vehicles.

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