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Application of Industry 4.0 in the Automotive Sector

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Purpose: *This paper aims to analyze the current state of Industry 4.0 in the automotive sector to show the associated expectations, opportunities, risks, and challenges. Requirements and concrete approaches for future research needs are derived within the framework of a research agenda.*

Methodology: *The methodology includes a systematic literature review, establishing a well-founded definition of the Industry 4.0 term for the automotive industry. Expectations, opportunities, risks, and challenges are answered in the context of a PESTEL analysis. In addition, elements of a research agenda based on the belief-action-outcome model are highlighted.*

Findings: *Our paper includes 180 identified publications and an industry-specific definition in the context of a concept matrix. The concept matrix comprises three main clusters and fifteen interdisciplinary technologies and concepts. Using a PESTEL analysis, publications are categorized into six defined perspectives. As part of a research agenda for future investigation, 32 open research questions are proposed, grouped into three themes and four subcategories.*

Originality: *In the current literature, to the best of our knowledge no approaches provide even deeper insights into the status quo of Industry 4.0 applications in the automotive sector. Thus, this paper is one of the first to provide a substantial approach to key Industry 4.0 technologies and concepts in this sector using a PESTEL analysis.*

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1 Introduction

The intensified competition in the global market and the rapid development of demand have prompted enterprises to adopt modern technologies to make production more intelligent (Lin et al., 2018, p. 589). Industry 4.0 is the current trend towards progressive automation and shared information exchange in the manufacturing and technology sectors such as the automotive industry (Lin et al., 2018, p. 589). In the context of the fourth industrial revolution, Industry 4.0 extends modern digital technologies to a more comprehensive scope, which primarily includes cyber-physical systems (CPS), the Internet of Things (IoT), and cloud computing (Lin et al., 2018, p. 589). From the perspective of companies, a major challenge to overcome is that constantly changing conditions for the adaptation of products and services should be taken into account, and value chains should be continuously analyzed and improved using modern technologies (Biahmou et al., 2016, pp. 672–673). Gao et al. (2016, p. 1) argue that disruptive changes are to be expected in the automotive and logistics industry. Based on these challenges, new Industry 4.0 technologies and concepts are constantly being researched to ensure smooth production in the automotive industry. Against this background, this paper aims to clarify the following research questions:

- Research question 1: What status quo is currently associated with Industry 4.0 technologies and concepts in the automotive sector?
- Research question 2: What expectations, opportunities, risks, and challenges are associated with the concept of Industry 4.0 in the automotive sector?

2 Industry 4.0 in the automotive sector: classification and conceptualization

2.1 Concept of Industry 4.0

The term Industry 4.0 is widely used concerning the variety of production concepts that are firmly established in the scientific literature (e.g., advanced manufacturing or lean production) (Oesterreich and Teuteberg, 2016, p. 122). From a technological perspective, Industry 4.0 is understood as the increasing digitalization and automation of the production environment and the design of a digital value chain between products and their respective working environment and business partners (Lasi et al., 2014, p. 240). Kagermann, Wahlster, and Helbig (2013, p. 6) posit the following elements as crucial prerequisites for the implementation of Industry 4.0:

- *horizontal integration across value networks* to enable cross-company networking of information technologies, processes, and data flows across business partners, and suppliers to promote intensive partnership-based cooperation within the value chain (Oesterreich and Teuteberg, 2016, p. 123);
- *continuous and digital integration of engineering within the complete value chain processes* to enable a high degree of customer-oriented design of the end products and thus considerable savings opportunities concerning a company's internal expenses (Oesterreich and Teuteberg, 2016, p. 123);
- *networked production systems and vertical integration* to ensure an integrated and intelligent manufacturing environment due to the integration and consistency of IT systems, processes, and data flows within an organization, starting from the development area through production to the logistics and sales process (Oesterreich and Teuteberg, 2016, p. 123).

2.2 Special features and economic impact on the automotive sector

The automotive industry is an important industrial sector in Germany and it has a significant impact on economic development. Specifically, in the production environment of companies, this sector promotes innovation, development, and employment (Barthel et al., 2010, p. 6). Schwarz-Kocher and Stieler (2019, p. 36) state that the German automotive industry is facing major changes due to the digitalization of products and manufacturing. Adapting all fields of activity to the framework of Industry 4.0 will likely place increased performance requirements on all employees in terms of complexity, generalization skills, and the ability to implement digital solutions. Furthermore, a much stronger level of independence, communication skills, and the willingness to take personal responsibility will be necessary (Butollo, Jürgens, and Krzywdzinski, 2018, p. 75). Ganschar et al. (2013, p. 20) state that the demands to innovate are growing exponentially due to the rapidly advancing technological development. Another significant challenge is the demand for flexibility, for which a highly short reaction time is required regarding the respective circumstances (e.g., fluctuating market or customer requirements). Specifically, the available data and information must be compiled and processed in a relatively short amount of time (Ganschar et al., 2013, p. 21).

3 Research methodology

3.1 Systematic literature review

A preliminary overview of the current state of science and practice is presented in this paper based on a systematic literature review that follows vom Brocke et al.'s (2009) and Webster and Watson's (2002) guidelines. This research process is divided into the *definition of the research scope*, *conceptualization*, *literature search and selection*, *literature analysis*, and *deduction of challenges*. The scope of the analysis is outlined in Section 2. Furthermore, in Section 2, the concept of Industry 4.0 is presented, and thus the conceptualization is considered. The literature search and selection led to a database that reviews the most relevant publications, ensuring analyzability. The databases ScienceDirect, IEEE Xplore Digital Library, EBSCOhost (Business Source Premier Database), and Scopus were searched to assess the existing literature and address the interdisciplinarity of Industry 4.0. In particular, EBSCOhost, and Scopus covered a wide range of scientific and practical journals, magazines, conferences proceedings, field notes, and any other kind of related works. To be considered for further investigation, the publications had to contain the term "Industrie 4.0" or "Industry 4.0" in the title. Since expressions referring to Industry 4.0 have become established outside of Germany (Oesterreich, Schuir, and Teuteberg, 2020, p. 5), terms such as "Industrial Internet," coined by the American Industrial Internet Consortium, the Chinese initiative "Internet Plus," the Japanese initiative "Industrial Value-Chain" or the French activities under the name "Industrie du futur" (Lu and Li, 2004; Müller and Voigt, 2018; Evans and Annunziata, 2021) were also searched. The literature search was conducted between January and February 2021.

3.2 Qualitative and quantitative content analysis

Content analysis comprises concentrating several text words into reduced content classes based on explicit coding guidelines and systematically condensing them in a repeatable manner (Stemler, 2000, p. 5), and it is useful to analyze developmental trends and behavioral patterns in different texts with large amounts of data. For this reason, qualitative content analysis is applied for category-based text interpretation (Mayring, 2000) and frequency analysis (Sidorova et al., 2008) is applied for statistics-based text interpretation (Berelson, 1952) to combine the potential of both methods. Regarding qualitative content analysis, the recommended actions derived from Mayring's (2000) stage model were followed. For the frequency analysis, Sidorova et al.'s (2008) approach was followed to examine the information obtained using the software QDA Miner (Provalis Research, 2011) and its extension WordStat (Provalis Research, 2014). The results of the software-based content analysis are presented in Section 4.

3.3 Related work

Overall, 10,054 hits were determined via a search in the title of the databases. All identified publications are extracted in a second step using the export function of ScienceDirect, IEEE Xplore Digital Library, EBSCOhost, and Scopus with the corresponding bibliographic data including their abstracts. Given the high number of publications to be reviewed, manual coding in the subsequent content analysis required extensive time (Oesterreich, Schuir, and Teuteberg, 2020, p. 6). We therefore adopted a systematic text analysis approach by employing the text analysis tool QDA Miner (Provalis Research, 2011) and its extension WordStat (Provalis Research, 2014) for the subsequent analysis steps. For this purpose, the abstracts were imported into QDA Miner, followed by an analysis of the word stems *automotive*, *automobiles,* and *car*, which filtered out 305 possible publications for our research topic. This was followed by a data cleaning step, a check for possible duplicates, and an analysis of the relevance and quality with respect to our research topic in the title, abstract, and articles' keywords. If a publication demonstrated insufficient thematic and substantiated relevance, it was sorted out. Specifically, a contribution was classified as not relevant if it did not fit into the focus of this scientific work, namely the application of Industry 4.0 in the automotive sector. Within the scope of this cleaning step in addition to the relevance and quality analysis step, a total of 132 contributions were identified and excluded from the entire sample. Hence, a backward and forward search was performed across the remaining 173 publications, the results of which were filtered according to the same pattern. Using the backward and forward search, seven additional publications were identified. The 180 papers deemed relevant served as the basis for the literature review presented in Section 4. The list of identified papers can be found at: https://tinyurl.com/3njhcad5.

The related works published between 2013–2021 were summarized and divided based on the topic area in the context of Industry 4.0 and the applied research methods. The papers can be found at: https://tinyurl.com/3njhcad5 (position 2), where “LA” stands for literature analysis, “ES” for empirical study, “CS” for case study, “Su” for survey, “In” for interview, “SA” for scenario analysis, and “Ex” for experiment.

Most of the publications focused on the effects and challenges of Industry 4.0 in the automotive industry, similar to our contribution (see https://tinyurl.com/3njhcad5 (position 2)). However, there is no deeper investigation available concerning the expectations, opportunities, risks, and challenges associated with the concept of Industry 4.0 in the automotive industry. Thus, this paper is the first to provide a substantial approach to crucial Industry 4.0 technologies and concepts in the automotive industry. Additional statistical results of this research and the results of the subsequent content analysis are provided in Section 4, which form the basis for the research agenda presented in Section 5.

4 Results

4.1 Literature analysis

Based on the quantitative analysis of previously-published papers on Industry 4.0 topics, the aim is to investigate the extent to which the development process follows the characteristic behavioral patterns (Oesterreich, Schuir, and Teuteberg, 2020, p. 7), including in the automotive industry. Our results indicate a similar progression to that outlined by Abrahamson and Fairchild (1999, p. 708), who proved in their study on management fashions that there is typically a long dormant phase before a short-lived increase, leading to a symmetrical, bell-shaped popularity curve (Abrahamson, 1996, p. 257). Following Abrahamson and Fairchild (1999), this research paper distinguishes between two types of publications:

- Academic publications, such as academic journals, conference proceedings, working papers, and book chapters;
- Practical publications, namely articles published in practical and hands-on journals, and other types of publications, such as magazines or reports.

The absolute and relative frequency distributions of each publication type between 2013 and 2021 is presented in Figure 1.

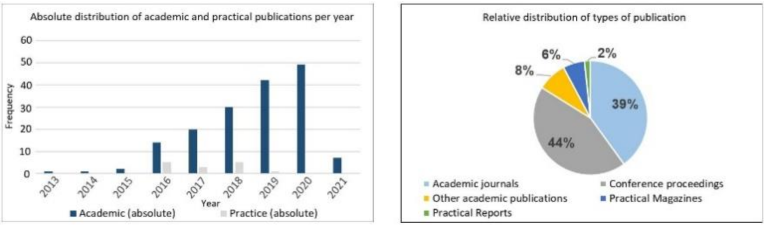

Figure 1: Absolute and relative distribution of academic and practical publications

The results of the literature analysis reveal that the scientific discourse began in 2013 and increased significantly from 2016. The relative frequency distribution shows that the preferred publication venues are scholarly publications, such as conference papers, journal articles, and other scientific papers, accounting for more than 90% of the total literature sample. This is followed by practical publication venues, such as magazines and reports. In sum, the results of the literature review show that Industry 4.0 for the automotive industry is at the peak of a discussion and development cycle (Oesterreich, Schuir, and Teuteberg, 2020, p. 8).

Subsequently, we examined which Industry 4.0 technologies and concepts pertaining to the automotive industry were mentioned in the identified publications (Figure 2). The qualitative content analysis revealed that 78 out of 180 articles examined mentioned simulation and modeling, implying that these technologies or concepts of Industry 4.0 are considered essential in the automotive industry, followed by IoT, or Internet of Services. Other typical technologies and concepts in the context of Industry 4.0 in the automotive industry include CPS or embedded systems, automation, big data and data analytics, and platforms. Meanwhile, classic basic technologies and concepts of Industry 4.0 are cloud computing, smart factory, 3D printing, or additive manufacturing (AM) (Oesterreich and Teuteberg, 2016, p. 126), virtual reality (VR), virtual validation, virtual engineering, augmented reality (AR), digitization, or digital twin.

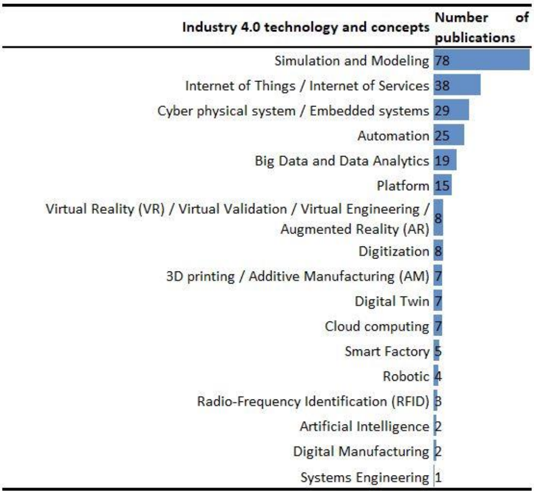

Figure 2: Industry 4.0 technologies and concepts in the identified publications

Additionally, robotic, radio-frequency identification (RFID), artificial intelligence, digital manufacturing, and systems engineering are essential components for enabling Industry 4.0 in the automotive industry.

In response to the first research question and based on the findings from the content analysis, it can be claimed that the industry-specific definition of Industry 4.0 in the automotive industry encompasses a broad spectrum of interdisciplinary technologies and concepts that enable digitization and automation in the automotive industry at individual stages of development. The term Industry 4.0 is sometimes used and understood as synonymous with the increasing provision of information and communication technologies and other technologies in the manufacturing industry, without further specification (Oesterreich and Teuteberg, 2016, p. 127).

The identified technologies, concepts, synonyms, and terminologies were grouped into three main clusters and fifteen concepts/technologies were then summarized in a concept matrix following Webster and Watson (2002) based on Oesterreich and Teuteberg (2016, p. 128). The defined groups occasionally overlapped, as several contributions were assigned to more than one group. Specifically, 105 publications were assigned to different concepts and groups. For example, if an article involved IoT and CPS, it was integrated into both concepts. The statistical results of the analyzed publications are illustrated in the concept matrix in Figure 3.

Cluster	**Significant Industry 4.0 technologies and concepts**	**Number of relevant publications**
Smart Factory (C1)	Internet of Things (IoT) / Internet of Services (IoS)	37
	Cyber physical systems (CPS) / Embedded systems	27
	Automation	25
	3D printing / Additive Manufacturing (AM)	7
	Robotic	4
	Digital Manufacturing	2
	Systems Engineering	1
	Radio-Frequency Identification	3
Simulation and Modeling (C2)	Simulation tools / Simulation models	13
	Digital Twin	7
	Virtual Reality (VR) / Virtual Validation / Virtual Engineering / Augmented Reality (AR)	7
Digitization and Virtualization (C3)	Big Data and Data Analytics	15
	Platform	14
	Cloud computing	7
	Digitization	8
	Total	**177**

Figure 3: Concept matrix following Webster and Watson (2002) based on Oesterreich and Teuteberg (2016, p. 128)

Qualitative results:

Cluster 1: Smart Factory

The first cluster (C1) in Figure 3 presents a comprehensive set of technologies and concepts that lie at the heart of Industry 4.0 for the automotive industry and aim at automating production and creating a *smart factory*. Essentially, some approaches to the creation of a smart factory in the automotive industry prevail (e.g., Häußler, 2020, p. 1). EOS (2020) explains that manufacturing companies are reaching their own performance limits regarding adaptability, the feasibility of complicated components, and product individualization. With 3D printing, the possibilities for integrated, smart, and, above all, digitally supported manufacturing (EOS, 2020) can be realized in the context of *digital manufacturing*. Digital manufacturing is featured by the use of technologies for digital model generation and replication in planning and production processes (Siemens PLS Software, 2008, p. 2). Additionally, *3D printing,* or *additive manufacturing,* has gained considerable importance in the automotive industry, and it is difficult to imagine production and improvement without this technology (Grohmann, 2019). The central technologies in Cluster 1 are *CPS* and *embedded systems*. The interaction of intelligent components and manufacturing machines to be produced in the manufacturing process with CPS can significantly change production, as these components and manufacturing machines can constantly communicate with each other, and thus independently recognize where and when a manufacturing process is carried out. Moreover, they can do so in a coordinated manner (Wolff and Schulze, 2013, p. 24), as in the automotive industry, for example. The *IoT,* or *Internet of Services,* is one of the most significant technologies in C1. From a technological perspective, the IoT is a combination of sensor technology such as RFID, further communication, cloud applications, ERP, and business intelligence technologies (Oesterreich and Teuteberg, 2016, p. 129). In this context, the corresponding sensors are integrated into the physical and technical components of vehicles, working machines, robotics, or equipment components to realize connections with the internet (Oesterreich and Teuteberg, 2016, p. 129). According to BMWI (2021, p. 1), RFID is one of the core technologies in the realization of Industry 4.0, but it has not yet consistently established itself in the automotive industry. Volkswagen AG illustrates the group-wide use of RFID technology with the exemplary transparent prototype in a first model test (BMWI, 2021, p. 1). An equally essential component of the smart factory vision in the context of Industry 4.0 is *automation*. Based on Nüßle (2018), the automotive industry among the sectors in the field of manufacturing and assembly technology has the highest levels of maturity in automation. An interdisciplinary approach to economical and effective product design involving diverse subject matter experts is ensured by *systems engineering* (Bretting, 2017) (e.g., as support for the production process of the automotive industry). *Robotics* is equally worth mentioning, as according to Einertshofer (2018) numerous companies in the automotive industry already use collaborative robots, also known as cobots, in their manufacturing environments.

Cluster 2: Simulation and Modeling

Cluster 2 (C2) concerns *simulation and modeling*, two further core topics in the context of Industry 4.0 in the automotive industry. *Simulations* allow representing plants and production processes as models and thus analyzing and optimizing the work sequences in the production environment in a targeted manner (Gora, 2003, p. 18). Through *modeling*, requirements are checked for correctness at an early stage, which makes error detection and correction much more cost-effective (Iqbal et al., 2020, p. 8698). *Simulation tools* and *simulation models* for virtual commissioning promise comprehensive interfaces for the implementation of existing partial models when modeling a digital twin of a machine or robot (Völker, 2020, p. 1). The *digital twin* is another core technology or concept of C2, and it offers significant opportunities for simulation-based planning and optimization in the industrial environments of the automotive industry (Kritzinger et al., 2018, p. 1016). Other critical technologies in C2 are *VR, virtual validation, virtual engineering, and AR*. Against the backdrop of increasing competitive pressure on automotive manufacturers to reduce production times and strive for ongoing quality improvement, VR has proven its advantages in numerous fields (e.g., development, production, assembly, and training) (Lawson, Salanitri, and Waterfield, 2016, p. 323). For the early phases of product development, especially before the actual product manufacturing and the start of production, virtual validation methods (Damrath et al., 2016, p. 307) can provide additional support. Damrath et al. (2016) propose a procedure for the energy-efficient design of an assembly system through virtual validation.

Moreover, AR technologies can be used for service and customer support training in the automotive industry (Lima et al., 2017, p. 100).

Cluster 3: Digitization and Virtualization

The third cluster (C3) in Figure 3 comprises *digitization and virtualization*. According to the BMBF (2020, p. 85), advancing digitization is crucial for the introduction of new types of products and services. Meanwhile, according to Brücker (2014), the provision of high-quality visual solutions (e.g., 3D visualizations) across the entire value chain causes a generalization process of workflows in product development and launch. *Big data and data analytics* represent a broad spectrum in the automotive industry whose applications are highly extensive (Rampelli, Vadlamani, and Nukala, 2014, p. 24) (e.g., in the area of production, in the context of quality control, or to increase productivity (Kampker et al., 2018, pp. 122–126)). Another significant component in C3 is *cloud computing*, whose importance in the automotive industry continues to grow relative to networking, electromobility, and PLM, among others, as Schäfer and Fricke (2013, p. 52) explain. Additionally, *digitization* is an essential approach in C3. Digital technologies optimize existing process flows based on improved customer approach, optimal planning of needs, or better interpretation of the customer's individual wishes (Sedan and Gissler, 2015, p. 1). C3 ends with the central technology *platform*. In terms of products, several companies currently rely on a platform and a design corresponding product groups on this basis (Simpson, Siddique, and Jiao, 2006, p. 3). Based on the results, it can be concluded that the articles analyzed in the systematic literature review primarily concern the technical aspects of Industry 4.0-related technologies. Economy-, society-related, and ethical or legal issues are only addressed to a limited degree. According to the first research question, the status quo of Industry 4.0 technologies and concepts in the automotive industry is at different levels of maturity. However, various solutions have been presented to digitize production and logistics processes in the automotive industry and significantly improve productivity.

4.2 Expectations, opportunities, risks, and challenges of Industry 4.0 in the automotive industry

Based on the definition of the term, a further objective is to address the expectations, opportunities, risks, and challenges associated with Industry 4.0 in the automotive industry. The publications derived from the 180 sources through literature research were categorized into six defined perspectives using a PESTEL analysis (Kaplan and Norton, 2008). Specifically, the expectations and opportunities were assigned to political (P), economic (E), sociocultural (S), technological (T), environmental (E*), and legal (L) perspectives (Table 1 and Table 2), which allowed us to reflect on changes and trends in our topic.

Table 1: Opportunities of Industry 4.0 in the automotive industry

	Opportunities
P	**Increased public relations:** By linking Industry 4.0 and science communication, an interface between industry and the public can be created, contributing to fluid and effective change and positive interaction for both partners (Becerir and Peschke, 2019, p. 288).
E	**Improved collaboration and communication:** Applying a digital platform in the automotive industry 4.0 context and involving the customer in various processes such as service configuration can ultimately enhance customer experience (Silva et al., 2018, p. 2; da Silva et al., 2018). **Increased productivity and quality:** Implementing Industry 4.0 from the perspective of costs and benefits and incorporating the process failure mode effects analysis (PFMEA) can improve productivity in the automotive industry (Bermúdez and Juárez, 2017, p. 737). Additionally, technologies such as the IoT or CPS can increase quality performance in the context of Industry 4.0 in the automotive industry (Tasmin et al., 2020, p. 160). **Reduced costs:** The analysis of critical factors (e.g., data management) prior to the implementation of Industry 4.0 technologies in the automotive industry can reduce costs in the long term (Bhatia and Kumar, 2020, p. 1). Similarly,

	Opportunities
	Maintenance 4.0 (Nissoul et al., 2020, p. 1) effects can have a cost-saving impact on the automotive sector.
S	**Improved decision-making processes:** A suitable framework for the introduction of Industry 4.0 technologies in manufacturing companies (e.g., in the automotive industry) can benefits for decision-makers (Yadav et al., 2020a, p. 1). In addition, the application of a web visualization platform in the context of Industry 4.0 can be used to support decision-making in organizations (Rebelo et al., 2019, p. 71). **Reduced complexity and dynamics in human-computer interaction systems:** Designing an efficient and user-friendly human-IoT interaction mechanism can reduce the complexity and dynamics in the Industry 4.0 context of the automotive industry (Yang et al., 2018, p. 463).
T	**Improved data evaluation:** Analyzing the performance of the Edge OBD-II device using Industry 4.0 technologies such as the IoT can provide independent vehicle data for customer feedback and tracking (Silva et al., 2020, p. 88). **Improved infrastructure:** The implementation of Industry 4.0 can increase facilities automation and adaptability during the production processes in the automotive industry (Ruggero et al., 2020, p. 131).
E*	**Improved resource usage:** Following the promotion of the understanding of sustainability as part of Industry 4.0, renewable energy can reduce manufacturing costs and increase revenues (Becerir and Peschke, 2019, p. 288) in the automotive sector. **Improved energy efficiency:** Energy efficiency can be increased as a result of reducing overarching structural difficulties within the automotive sector, identifying relevant viewpoints and influencing variables relative to accelerating the adoption of Industry 4.0 technologies (Hidayatno, Rahman, and Daniyasti, 2019, p. 334). **Reduced energy consumption:** Energy consumption can be reduced by efficient manufacturing facilities and by incorporating energy efficiency software (EES). Moreover, continuous optimization in the field of big data analytics can significantly reduce energy costs (Adenuga, Mpofu, and Boitumelo, 2019, p. 735).

	Opportunities
L	**Improved fulfillment of target agreements:** Globalization, digitalization (e.g., technologies such as Digital Master or 3D Master), and the digital transformation in the automotive industry can help to better meet changing customer behavior and demands (Biahmou et al., 2016, p. 672).

By contrast, automotive companies must consider a variety of challenges or difficulties before implementing digital transformation (cf. Table 2).

Table 2: Challenges of Industry 4.0 in the automotive industry

	Challenges
P	**Job market changes:** Major difficulties for foreign investors in investing in Industry 4.0 technologies or concepts within the automotive industry can be caused by local conditions, such as strongly increasing wage trends and declining employment (Olejniczak, Miszczynski, and Itohisa, 2020, p. 196). These prospects for the industry must be considered as part of Industry 4.0 implementation.
E	**Adhere to the highest quality standards at competitive prices:** Detecting defects is a major challenge in the production of electronic components in the automotive industry, because failures in this field can contribute to damage and fatal consequences (Schwebig and Tutsch, 2020, p. 167). Similarly, it is necessary to address the challenges regarding the quality assurance of the essential components in the context of future development trends in engine manufacturing (Obara and Guedes, 2017, p. 1). **Risk and uncertainty regarding strategic planning activities:** A challenge is posed to automotive industry in the context of Industry 4.0 by high-risk potential and the associated planning uncertainty of manufacturing companies (Riel and Flatscher, 2017, p. 323). **High resource requirements and loss of speed in data transmission due to large data volumes:** The collection, networking, securing, evaluation, and analysis of extensive data sets from various information sources, such as machine controllers, sensor systems, production systems (Santos et al., 2017, p. 750) is

	Challenges
	leading to a crucial challenge in the automotive industry in the course of Industry 4.0.
S	**Horizontal and vertical cooperation in the context of manufacturing and assembly optimization:** One of the main challenges facing automotive companies in the digital environment and Industry 4.0 is the lack of technical tools and methods, such as CPS (Silva et al., 2018, p. 6; da Silva et al., 2018). Similarly, a fundamental challenge is to design and support industrial automation applications with respect to the IoT so that they exhibit real-time mode performance at different stages (Gidlund et al., 2018, p. 2194). **Supplier paradigm:** A significant challenge to be solved is the just-in-sequence supply in the entire supply chain of manufacturing and service processes in the automotive industry (Juhász and Bányai, 2018, p. 226). **Organizational redesign and process changes:** The implementation of Industry 4.0 in the automotive industry should be deepened and sustained across all prevailing organizational processes to be positioned for new ways of working and organizational concepts in the factories of the future (Bader et al., 2019, p. 756). **Insufficient employee competence:** A fundamental challenge for many automotive companies will be the insufficient employee know-how regarding Industry 4.0 technologies, which can be overcome by applying new aspects in education and research (e.g., human and social sciences) (Bryon-Portet, Montastruc, and Le Lann, 2016, pp. 24).
T	**Adhere to technological standards and reference architectures:** Regardless of the current state of maturity and operational capabilities of most technologies, many of them do not meet satisfactory standards, such as security standards, in the context of Industry 4.0 (MacRae, 2016) or they require a uniform user interface regarding the flexible design of acquisition processes (Beckers et al., 2020, p. 1444). Furthermore, a reference architecture specifically geared to the industry to implement Industry 4.0 is missing (Lasi et al., 2014, p. 241). This reference architecture should be developed with the specific environment of the automotive sector in mind and with a particular focus on their organizational aspects (e.g., customer management). **Security and data protection issues:** A key requirement for Industry 4.0 in the automotive industry is to address security and data protection issues against, for

	Challenges
	example, autonomous vehicle cyberattacks associated with implementation issues (Gupta et al., 2020, p. 1).
E*	**Energy efficiency and sustainability:** To counter the reliability challenges related to the quality of services (QoS) within the network infrastructure in the manufacturing process, latency should be minimized (Muliawan, 2019, p. 1) and sustainably optimized.
L	**“Legal Framework” as a “brake”/enabler:** Legal issues impacted by the implementation of Industry 4.0 in the automotive industry are liability (product/contractual liability, risk distribution), labor law, regulations, intellectual property, data protection, IT security, EU legislation, standards and (smart) contracts, and autonomous systems.

Considering these diverse research challenges, it can be deduced that the automotive industry should include more than just technical adjustments. From a scientific perspective, the opportunities and challenges presented yield research topics that should be included in a research agenda.

5 Elements of a research agenda

The results show that current research streams focus on analyzing the technical aspects of Industry 4.0 in the automotive industry. In many cases, economic, social, ethical, or legal issues are not considered. For example, there is a need to apply reference modeling regarding Industry 4.0 in the automotive industry. Approaches to the design and implementation of Industry 4.0 in the automotive sector can be derived against this background (Ickerott, Teuteberg, and Süßmuth, 2018, p. 1631). Methodologically, the structure is based on the belief-action-outcome (BAO) model (Melville, 2010).

	Subject / Topic	Research question / Reference	Potential impacts
Humans	Functions	(1) What competencies does an Industry 4.0 leader need? (2) What is the mode of operation and the system sequence? (3) What is the I4.0 reconfiguration strategy? (4) Does the DMS work during I4.0 disruptions? (5) To whom is the info system designed? (6) How is work evolving under Industry 4.0? (7) How does the program work under Industry 4.0? (8) With whom does the I4.0 work developed resonate? Based on Łupicka and Grzybowska (2018); Milisavljevic-Syed et al. (2019); Pereira et al. (2019)	Process model
Organizations	Added value of IT investments	(1) What can improved production through Industry 4.0 look like? (2) What does the Industrial IoT mean for business models? (3) What are the differences between Industry 4.0 technologies? (4) How effective are Industry 4.0 technologies? (5) What characterizes the user and provider view of I4.0 in business models? (6) What are the specifics and strategies of Industry 4.0? (7) How can the maturity of Industry 4.0 be measured? (8) To what extent does an assessment help promote I4.0? (9) What are models trained to do in the cloud? (10) What do Industry 4.0 technologies bring and how can they contribute to sustainability? Based on Arnold et al. (2016); Müller and Voigt (2017); Moica et al. (2018); Lucato et al. (2019); Müller (2019); Elnagar and Thomas (2020)	Benefits of the innovation, cost-benefit analysis, Industry 4.0 decision criteria
	Risk Management	(1) How can digitization be integrated into IT risk management? (2) In which way is the I4.0 transformation of manufacturing systems realized? (3) What are the demands and competitiveness of I4.0? (4) What are companies' expectations regarding economic policy and Industry 4.0? Based on da Silva et al. (2018); Milisavljevic-Syed et al. (2019); Nick et al. (2019)	Risk management model, alignment
Technology	IT structures and applications	(1) What does the concept of I4.0 involve for networks? (2) What is the deficit between collaborative networks and I4.0? (3) How can I4.0 be realized with regard to networks? (4) Which functionalities/user requirements are relevant for I4.0? (5) What about the performance of the RFID system? (6) What are the benefits of using a collaborative robot? (7) What sensors do vehicles rely on? (8) What parameters influence costs and stability? (9) For which cars fit smart design customizations? (10) How important will big data, IoT, etc. be in the future? Based on Saldivar et al. (2016b); Velandia et al. (2016); Cisneros-Cabrera, Sampaio, and Mehandjie (2018); da Silva et al. (2018); Silva et al. (2018); Lima et al. (2019); Liu et al. (2019); Milisavljevic-Syed et al. (2019); Nick et al. (2019); Pereira et al. (2019); Perzyk, Dybowski, and Kozłowski (2019); Zakoldaev et al. (2019); Beke, Horvath, and Takacs-Gyorgy (2020); Elnagar and Thomas (2020); Roman and Bunsen (2021)	IT architecture model, IT security, model, software prototype

Figure 4: Research questions derived from the results

The focus here is on the dominant beliefs about human-technology interaction. It serves as a model for the development, realization, and evaluation of actions. Furthermore, the BAO framework is suitable for user-specific development and the use of methods to measure the results of initiated transformation processes. According to Webster and Watson (2002, pp. xv–xix), the starting point of any academic research project should be to review existing scientific knowledge through a systematic literature search and a subsequent content analysis to identify the status quo of the research area, further areas to explore, and research gaps. The currently open research questions that emerged from the analysis of the literature are presented in Figure 4.

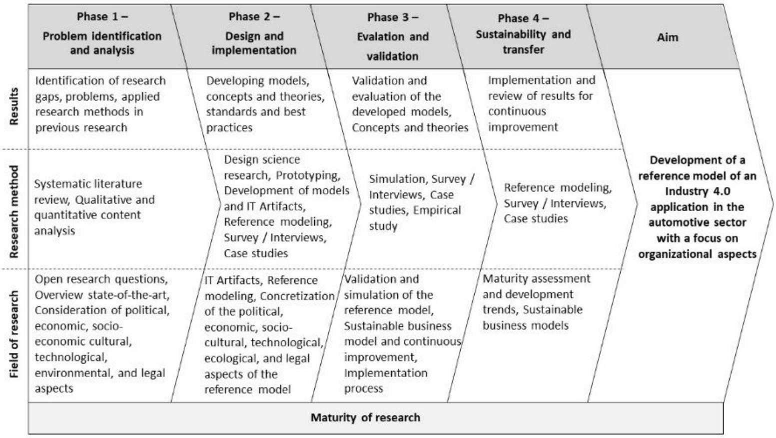

Figure 5: Proposed research agenda

We advise an iterative approach based on the design science approach to meet the rapid pace of the research within the available time (Hevner et al., 2004). Exemplary challenges and problem aspects are presented as part of the research agenda in Figure 5. Another element of the proposed research agenda includes activities to develop the concept and reference model. An empirical research approach and structured approach are suitable to explore the questions in this section in greater depth. To explore the economic and technical aspects of the questions (e.g., the construction of a technical system architecture), an expert-oriented approach based on interviews would be useful to develop reasoned responses based on a concentration and evaluation of expert knowledge. For the socio-cultural aspects of the questions, surveys would be useful since they enable simulating extensive evaluation and decision problems of a socio-scientific nature (Oesterreich and Teuteberg, 2016, p. 137). The validation of the constructed reference model should be carried out based on factors such as significance, transferability, and robustness (Burda and Teuteberg, 2013, p. 449). Validation can be realized through analytical and theoretical research methods, which are primarily based on deductive reasoning. On the other hand, empirical analysis is proposed to validate the model through experience (Fettke and Loos, 2003, p. 2945). Following its implementation, the developed reference model should be constantly reviewed and optimized in the direction of sustainability through using development trends and maturity models, among others.

6 Conclusion and outlook

6.1 Implications for research and practice

This research paper has analyzed the state of science and technology related to Industry 4.0 in the automotive sector and presented the main implications from a wide range of perspectives. The results are listed in Table 3.

Table 3: Main findings, implications, and propositions

Main finding (MF)	Implications and propositions
Research question 1: What status quo is currently associated with Industry 4.0 technologies and concepts in the automotive sector?	
MF1a: Industry 4.0 for the automotive sector refers to a variety of interdisciplinary technologies and concepts (e.g., the IoT, CPS, Big Data, and Data Analytics) that support the digitalization, automation, and integration of the production process at all levels of the value chain to ensure vehicle production. MF1b: The development statuses of these Industry 4.0 technologies and concepts in the automotive industry are at different levels of maturity.	• Companies should not only focus on the technical aspects of Industry 4.0-related technologies, but also discuss economic, social, ethical, and legal issues. • Companies should mobilize horizontal and vertical collaborations (e.g., with suppliers) to simultaneously foster communication and collaboration with these partners.

Main finding (MF)	Implications and propositions
MF1c: Some technologies (e.g., cloud computing or software for visualizations or 3D simulations) have reached a certain level of market maturity and are in use, whereas other technologies are in the development phase. Prototypes and application capabilities are being designed for mainstream use (e.g., digital twin, AR, VR).	• Companies should be guided by established practical examples, showing practicable approaches to the introduction of Industry 4.0 applications for digitization and automation in the automotive sector.
Research question 2: What expectations, opportunities, risks, and challenges are associated with the concept of Industry 4.0 in the automotive sector?	
MF2a: The use of Industry 4.0 technologies has a profound impact on the entire automotive sector, the industrial companies involved, suppliers, the environment, and employees. MF2b: The economic benefits of Industry 4.0 in the automotive sector are not only improved productivity, efficiency, quality, and collaboration, but also increased safety and sustainability.	• Companies should address a wide range of political, economic, social, technological, environmental, and legal challenges (e.g., organizational redesigns and process changes). • Companies should confront employees with increasing job requirements to allay anxiety about job loss and computers (e.g., artificial intelligence). • Companies should clarify unresolved issues, such as the lack of technical standards for many technologies.

6.2 Limitations

In addition to the knowledge gained as described above, this study has some limitations, which offer suggestions for approaches for future research. First, the results of the analysis of Industry 4.0 applications in the automotive sector are based on a sample of 180 scientific and practice-oriented publications that were considered significant for this study. The search was based on various interdisciplinary literature databases, although such an approach cannot ensure the completeness of the relevant publications. Furthermore, given that the sample only included English- and German-language publications, the results reflect only technologies and concepts of the automotive sector on Industry 4.0 in English- and German-speaking countries. As such, the discussion of other areas, including those that are economically distinctive in some cases, is not considered in this work. This analysis should be expanded to publications in other languages to obtain a comprehensive understanding of applications in the automotive industry. Although Industry 4.0 represents an interesting research subject due to its intensified consideration, other digitization initiatives also require analysis. Further research is thus needed to deepen the research results and validate them with the results from other areas of the automotive sector.

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