weizenbaum
institut

Weizenbaum Series #10
Working Paper

Automation, Digitalization, and Changes in Occupational Structures in the Automobile Industry in Germany, the United States, and Japan

A Brief History from the Early 1990s Until 2018

Martin Krzywdzinski
July 2020

Weizenbaum Series

Editors:
The Executive Board of the "Weizenbaum Institute for the Networked Society – The German Internet Institute"

Project Coordination:
Wissenschaftszentrum Berlin für Sozialforschung
Reichpietschufer 50
10785 Berlin

Visiting Address:
Hardenbergstraße 32
10623 Berlin
Email: info@weizenbaum-institut.de
Web: www.weizenbaum-institut.de

Editorial Assistant:
Roland Toth, M.A.

Persistent long-term archiving of this series is ensured by the Social Science Open Access Repository and the DOI registration service in Germany for social science and economic data da|ra.

DOI 10.34669/wi.ws/10

This work has been funded by the Federal Ministry of Education and Research of Germany (BMBF) (grant no.: 16DII111, 16DII112, 16DII113, 16DII114, 16DII115, 16DII116, 16DII117 – "Deutsches Internet-Institut").

Weizenbaum Series #10
Working Paper

Automation, Digitalization, and Changes in Occupational Structures in the Automobile Industry in Germany, the United States, and Japan

A Brief History from the Early 1990s Until 2018[1]

Martin Krzywdzinski[2]
July 2020

---

[1] This paper was presented at the GERPISA 2020 Conference “Going Digital. Transforming the Automotive Industry”. A German version is available at https://bibliothek.wzb.eu/pdf/2020/iii20-302.pdf

[2] Martin Krzywdzinski is Director at the Weizenbaum Institute for the Networked Society, head of the research group “Globalization, Work and Production” at the WZB Berlin Social Science Center and professor of international labor relations at the Helmut-Schmidt University Hamburg.

Abstract

In the current public discussion, it is considered certain that we are living in a time of rapidly advancing automation, which is driven in particular by the use of robots. Accordingly, many academic publications use robot density as the central indicator of automation. The present study challenges this perspective. It examines two central questions: First, what approaches to automation and digitalization have been pursued in the automotive industry in Germany, Japan and the USA? Second, how have employment and its occupational composition in the automotive industry developed in the three countries? The first part of the study focuses on the development of automation and digitalization approaches in the automotive industry from the early 1990s until today. It combines a qualitative analysis of press articles and a quantitative evaluation of the development of the stock of industrial robots from 1993 to 2018 based on the statistics of the International Federation of Robotics. The second part of the study focuses on the change in employment structures using occupational statistics from the Bureau of Labor Statistics (USA), the Federal Employment Agency (Germany) and the Statistics Bureau of Japan. The study questions the perception of an automation-related threat to employment and especially to production employment. At the same time, it discusses developments in Germany, Japan and the USA in comparison and highlights differences in automation and digitalization approaches as well as different paths of change in employment structures.

1. Introduction

Current analyses of technological change take it for granted that we are living in a time of rapidly increasing automation, which will particularly affect employees working in routine jobs. In such debates, production has been invoked as an example of a sector dominated by routine work. An influential study by Frey and Osborne (2013) predicted a probability of automation of 98% for assembly workers, 94% for welders, and over 90% for different types of machine operators - all typical occupations in the automotive industry. However, the current discussion has been dominated by abstract arguments about automation potential (Frey/Osborne 2013; Dengler/Matthes 2018), while detailed analyses of technological development and its effects on work have been rare (see as an exception Jürgens 2020).

The present study attempts to provide a realistic assessment of the development of process technologies and the changes in employment structures in the automotive sector. It builds on a research tradition at the WZB that emphasizes the interdependencies between technologies, production systems, employment structures, and personnel strategies (Jürgens et al. 1993; Jürgens 1997; Jürgens & Krzywdzinski 2016). It aims at a historical reconstruction of the development of automation and digitalization approaches in the automotive industry in order to arrive at an empirically based understanding of their motivations, forms and results. An international comparative approach will be followed in order to determine the spectrum of developments. The focus is on three central automobile manufacturing countries: Germany, Japan and the United States. The two main questions are[1]:

- What approaches to automation and digitalization are being pursued in the automotive industry in Germany, the United States, and Japan?
- How have employment and its occupational composition in the automotive industry developed in these three countries?

The study aims to correct three perceptions that are dominating the current public and academic discussions but are at least partially false. Firstly, it questions the perception that we are living in a phase of rapidly increasing automation, understood as the substitution of human labor by machines or computers. It uses qualitative and quantitative data to analyze the development of automation and digitalization approaches in the automotive industry from the early 1990s until today. The qualitative analysis is based on a total of 439 articles from automotive industry print outlets. The study also uses

---

[1] I would like to thank Ulrich Jürgens, Martin Kuhlmann and Florian Butollo, who read, commented and discussed with me the first version of this paper.

the figures provided by the International Federation of Robotics on the development of robot installations from 1993 to the present as a quantitative indicator.

Second, the study challenges the current focus in academic and public discussions on robots as the primary form of automation. Robot density (meaning the number of robots in relation to the number of employees) has become a tremendously popular indicator in research and is now used to explain phenomena as diverse as employment, pay inequalities between groups of employees, or international trade flows (e.g. Acemoglu/Restrepo 2017; Graetz/Michaels 2018; Aksoy et al. 2019; Carbonero et al. 2020). The assumption of these studies is that the number of robots is a useful indicator of automation or even of technological change in general – an assumption which to the author's knowledge has not been adequately tested and deserve to be questioned.

Third, the study questions perceptions of an automation-related decline in employment and in particular in production employment. These perceptions have so far been based on abstract calculations of substitution potential and not on empirical analyses. This study focuses on the structure of employment by occupations. The analysis of employment structures in the present study is based on occupational statistics provided by the Federal Employment Agency (Germany), the Bureau of Labor Statistics (United States), and the Statistics Bureau of Japan.

2. Back to the Future: Automation and Digitalization

Automation, which has become a central social issue in the current discussion about Industry 4.0 and digitalization, refers to a specific form of technology. Schulz-Schaeffer (2008: 1) has argued that we can understand technology as "artificially generated causal relationships" that produce "sufficiently reliably [...] certain desired effects." Technology can materialize in particular forms, for instance as a machine, but it can also manifest as a procedure or an algorithm. The term automation refers to a technology that can perform certain tasks without human intervention (Nof 2009). Automation thus applies to mechanical devices, electronically controlled machines and robots, and software systems that automatically process data. Advances in automation represent only one form of technological change—technological change also involves the development of entirely new techniques, materials, products, and product architectures, which in human history have often been more disruptive to business, work, and employment than automation (Christensen 1997).

The current public and academic debates on the development of automation and its effects on employment have been strongly influenced by econometric studies that, in essence, adopted a technological-deterministic perspective (see Hirsch-Kreinsen 2018). Two key assumptions are worth noting. First, these econometric studies assumed a linear progression of automation, from "less automation" to "more automation." Second, they assumed a clear correlation between automation and employment structures. In contrast, sociological research has pointed out that, with regard to automation approaches, it is important to account for (a) the material and technical conditions, (b) the companies' motives, and (c) the companies' organizational and work models.

The *material-technical conditions* primarily relate to the complexity of the product and its production, that is to the variety of parts and machining processes, the variability of the production environment, the production volumes, and the production speed (Baethge-Kinsky et al. 2018). The greater the complexity, the more difficult it is to automate the production process. For this reason, there are fundamental differences in automation levels in the automotive industry depending on the process in question. Mechanical processing, pressing, welding, and painting processes are highly automated (see Jürgens 2020; Kern/Schumann 1984). Automobile assembly, on the other hand, is a complex process with a large number of distinct work steps and many different variants; this area is consequently much less automated (Fujimoto 2017). The following empirical analysis will consider the material-technical conditions by comparing developments in assembly and car body construction.

With regard to the *motives for automation*, the economic literature emphasizes the role of costs (for example, by comparing the relative costs of equipment to those of labor) (cf. Acemoglu/Restrepo 2018, which is just one example of many). Cost considerations certainly play an important role, but they are by no means the only motive for automation. Empirical analyses show that automation is often introduced either because certain processing steps cannot be performed by humans at all, or because humans cannot do so with the required precision and quality (Krzywdzinski 2016). Desired improvements in ergonomics may also be a motive for automation, for example, when certain jobs cause great stress and damage to employees' health. One key point highlighted in analyses of the motives for automation is that there is no clear one best way; different approaches and strategies are possible (see e.g. Jürgens et al. 1993; Adler 1988; Fujimoto 1992 and 1997; Freyssenet 1999).

Decisions about the use of technology are made against the backdrop of specific products, production systems, and corporate strategies, but also specific education systems and industrial relations (Noble 1979; MacKenzie/Wajcman 1985; Wajcman 2006). Research on automation approaches in the 1980s and 1990s showed that Japanese automobile manufacturers' production systems were strongly guided by the goal of flexibility in the sense of being able to rapidly adapt the product mix and production volumes to market demand. Japanese companies only saw cost-reduction potential in automation technologies if the desired flexibility could be guaranteed (Jürgens et al. 1993; Adler 1988; Fujimoto 1992; MacDuffie/Pil 1997; Daito 2015). This implied a preference for simpler and more robust solutions and, in borderline cases, the abandonment of automation. In contrast to the Japanese companies, European companies—especially VW and Fiat—saw "high-tech" automation as a prerequisite for high quality and productivity; flexible adaptation of production was considered less important (at least in the 1980s). Until the 1980s, American companies (especially General Motors) had also focused on high-tech automation, but had experienced a fiasco (Ingrassia/White 1994). Since the end of the 1980s there has been a growing perception in the USA that high-tech automation was too rigid and error-prone (Adler 1988; Jürgens et al. 1988).

The 1990s saw two major developments. The first was the "Japan shock," triggered by the success of Japanese companies in the USA and later in Europe and by a series of studies that demonstrated the superiority of Japanese production concepts; the best-known study is Womack et al. (1991) on lean production (see also Krafcik 1988). Lean production integrated essential elements of Japanese production concepts and reduced European automobile companies' focus on high-tech automation (see Liker 2004 on the automation-skeptic perspective of lean production). The second development was the emergence of labor shortages and conflicts in Japan and Europe, which led to greater consideration of ergonomics and also prompted an improvement in the quality of work (see Fujimoto 1997; Niimi/Matsudaira 1997; Sandberg 1994; Jürgens 1995; Berggren 1997; Krzywdzinski 2020). Unfortunately, there have been no analyses of this kind comparing Germany, the United States, and Japan since the end of the 1990s, especially no longitudinal studies of companies.

Finally, with regard to the effects of the various automation approaches on work, we have to consider *labor and organizational models* (cf. Schumann et al. 1994; Baethge-Kinsky et al. 2018), which can vary greatly between companies (Jürgens et al. 1993; Liker et al. 1999; Krzywdzinski 2017). In the German automotive industry, the focus on high-tech automation in the 1980s and 1990s was accompanied by a labor model focused on professionalization and skilled work (Kern/Schumann 1984; Jürgens et al. 1993; Kuhlmann 2004; Krzywdzinski 2020). This was especially evident in highly automated areas such as car body construction; by contrast, manual areas such as assembly continued to be characterized by high proportions of semi-skilled workers (although at least car manufacturers were recruiting more and more workers with skilled-worker training in assembly as well; cf. Jürgens 2012). This situation has persisted to this day (Baethge-Kinsky et al. 2018). In Japan, companies' automation approaches, which emphasized flexibility, were also accompanied by labor models that strongly emphasized skill and personnel development, including for production workers. However, this involved offering internal company development paths rather than formal vocational training (Krzywdzinski/Jürgens 2019; Jürgens/Krzywdzinski 2016; Jürgens 2012). In the American case, by contrast, studies from the 1980s and 1990s reported a continued preoccupation with Taylorist forms of work organization, tight job demarcations, and very limited investment in training (Jürgens et al. 1993; Adler/Cole 1993). This development has continued into the 2000s (Rothstein 2016).

It should be noted here that the hoped-for effects of automation (or of technological change in general) often do not materialize until they are accompanied by changes in organizational structures (see the contributions in Jürgens 1997). It is therefore difficult to disentangle the effects of technology and organization. One important result of the discussion on lean production was that process organization came to have a central influence on productivity (Womack et al. 1990). Although the introduction of lean production was also accompanied by technical innovations, these innovations were of greatest importance as a form of support for organizational changes, the prerequisite for meaningful automation was the lean design of processes (Butollo et al. 2018; Adler/Cole 1993). The classic study by Womack et al (1990) even emphasized that the most efficient plants were characterized by the lowest levels of automation.

Analyzing automation approaches is just as complex as analyzing the digitalization of work processes. The term digitalization generally refers to the conversion of analog information into a digital format. When applied to the world of work, it can be understood as the establishment of networks between machines as well as the use of software systems and digital databases for monitoring, controlling, and optimizing work processes (Hirsch-Kreinsen/ten Hompel 2015). In this sense, digitalization only partially overlaps with automation. In some cases, it may well mean automation when certain calculations that were previously done by humans are now automatically done by the software. The virtual prototypes created by CAD systems are one example of this; these can be used to automatically run simulations regarding noise or the strength of physical structures—simulations which would previously have required real tests on physical prototypes. In other cases, however, digitalization also means the creation of entirely new possibilities that were not available in the past—in other words, digitalization cannot be equated with automation. In the case of the virtual prototypes mentioned above, for example, design options can be tried out and inspected extremely quickly.

The complexity of the relationship between digitalization and automation is due to the complexity of the knowledge work that digitalization concerns itself with. This is evident in the discussion on Industry 4.0 (Acatech/Forschungsunion 2013; Spath 2013). As Butollo et al (2018) has pointed out, Industry 4.0 does not describe a coherent production model but rather a bundle of very different technical developments. The networking of production equipment and the intensification of the collection, analysis, and use of process data to monitor and optimize work and production processes play a central role here. Even though the public discussion has largely focused on the topic of “robots” and thus on the potential automation of manual work, even a brief look at Industry 4.0 reveals that it has more to do with monitoring and maintenance activities in production processes and with planning, optimization, and development activities—in other words, knowledge work.

Knowledge work combines processes of knowledge acquisition, knowledge objectification, and knowledge re-transmission (Malsch 1987). In knowledge acquisition, both standardized—i.e. algorithmically representable—procedures and experience are used; knowledge objectification means the systematization of knowledge by defining rules, concepts, etc. Knowledge retransfer means the translation of objectified knowledge into application knowledge. Knowledge work implies a constant back and forth between, on the one hand, objectified procedures and, on the other hand, experience-led and creative activities. A number of studies have argued that it is precisely those knowledge components that cannot be objectified and that are based on experience and interaction that are becoming increasingly important (cf. Rammert 1999; Wilkesmann 2005). Digitalization can refer to the automation of the algorithmically representable elements of knowledge work; yet, with regard to creative activities, it is primarily a form of technical support.

In research on Industry 4.0, there is now a heated debate on the extent to which a push towards the objectification of knowledge and, accordingly, a change in skill requirements and work contents is taking place (see Acatech 2015; Günther et al. 2015; Boes/Kämpf 2016; Butollo et al. 2018). Most studies see little danger of automation: Even the aforementioned Frey-and-Osborne study (2013) estimates a probability of automation of jobs for engineers, computer scientists and software developers in low single-digit percentages. These arguments are part of a long-standing discussion that also goes back at least to the 1980s and 1990s. Even then, although individual studies identified a danger of automating engineering work (Shaiken 1984), most analyses questioned these dangers (Giordano 1992; McLoughlin 1989 and 1990; Salzmann 1989). So far, however, we have lacked long-term and comparative in-depth analyses of companies that could tie in with the discussions of the 1980s and 1990s.

In view of the lack of empirical material, the present study takes a new approach and seeks to build a bridge between the discussions of the 1980s and 1990s and today's debate on digitalization and automation. In the absence of company-related data and analyses, the study draws on industry-level sources and attempts to examine country-specific developments in the automotive sector as a whole. However, due to the focus on the sector as a whole and the limited data available, the sociological argument about the close connection between technical and organizational innovations can only be addressed indirectly. In particular, the data sources used here lack information on the changes in organizational structures and work organization. The study therefore only indirectly addresses changes in the area of work organization by analyzing occupational structures.

3. Data

The study combines data from four statistical sources and supplements these with an analysis of the automobile and automation industry press.

3.1. Automation and Digitalization Approaches

This analysis of the automation and digitalization approaches combines a qualitative and a quantitative approach. In a first step, a qualitative analysis of press articles was used to reconstruct developments. The focus was on three overarching areas: assembly, car body construction, and the indirect areas (product development, planning, and production control). One of the key sources for this study was the German-language industry journal *Automobil Produktion*, which reports monthly on developments in the automotive industry. A particular advantage of *Automobil Produktion* is that it not only covers news about market and product developments, but also about technical and organizational developments in production as well as in product development, planning, quality assurance, and other areas. *Automobil Produktion* reports on the global automotive industry but focuses on Germany and Europe. The study analyzed a total of 393 articles from *Automobil Produktion*. To capture the development of the American and Japanese automotive industries, 46 articles from *Automation World*, *Automotive*

Manufacturing Solutions, and other publications were also included. The procedure is described in more detail in the Appendix. The sources are cited in the analysis with the following abbreviations: AP (*Automobil Produktion*), AW (*Automation World*), and AMS (*Automotive Manufacturing Solutions*).

Note that a press article analysis does not allow for a systematic longitudinal analysis of a company (or group of companies) and cannot replace case-study-based approaches (see Jürgens 2020). Rather, the articles in the press are used to characterize the development of automation approaches for the entire automotive industry in the countries studied—of course, this does not capture the many differences between the companies.

In the second step, the automation approaches were examined using a quantitative indicator, namely the stock of industrial robots in the automotive industry. The statistical source is the database of the International Federation of Robotics (IFR), which contains information on Germany, the United States, and Japan. More detailed information is also provided in the Appendix.

3.2. Employment Structures

In this study, an analysis of automation and digitalization approaches is combined with an analysis of changes in employment structures. The analysis reconstructs the trends in different occupations in the blue-collar and white-collar areas (e.g., engineers and computer scientists). The aim is to obtain a precise picture of the development patterns. The absolute employment figures are based on data collected by the German Association of the Automobile Industry (VDA) in its yearly publications on international auto statistics. In addition, the study draws on occupational statistics for the automotive industry from the USA, Germany, and Japan.

For the USA, the study uses data from the Occupational Employment Statistics (OES) program of the Bureau of Labor Statistics (BLS). The OES program collects data on employment, occupations, and wage levels for employees in the U.S. economy every six months. About 180,000 to 200,000 companies are surveyed on each occasion. The BLS extrapolates the data to calculate total employment. Since the surveyed companies change (it is not a panel study), changes between years should be treated with a certain amount of caution. No annual occupational statistics are available for Japan. The best source is the Population Census, which is conducted every five years by the Statistics Bureau of Japan (SBJ) and covers the entire population. The data for the German automotive industry are from the Federal Employment Agency (*Bundesagentur für Arbeit, BA*). The Federal Employment Agency compiles annual employment statistics based on employers' social insurance reports. These notifications are submitted to the Federal Employment Agency via the health and pension insurance agencies and cover all employees.

During the period studied, there were a number of changes in the classification systems underlying the statistics used here. These are highlighted in the following analysis, as they limit the comparability of the data over time. A detailed explanation of the classification systems (and also of the abbreviations used for them in the presentation) and their changes over time can be found in the Appendix.

4. Historical Development of Automation and Digitalization Approaches

At the end of the 1980s, a kind of automation euphoria still prevailed in the automotive industry. It was well-founded, as the industry had achieved considerable successes in automation in its long history. The mechanical processing of metal parts had been automated by the introduction of single-purpose machines at Ford in the 1920s, the development of NC machines in the 1940s, and CNC machines in the 1970s (Jürgens 2020; Hsieh et al. 1997; Noble 1979). In the 1970s and 1980s, the introduction of welding jigs and welding robots largely automated car body construction, at least in the pioneering plants of the automotive industry (cf. Milkman/Pullman 1991; Kern/Schumann 1984; Jürgens et al. 1993). In the 1980s, large presses and press lines became more widespread in the press shops, and these also greatly reduced the proportion of manual work there. Assembly processes were the last bastions of manual work, but in the 1980s, there were also attempts to increase automation here (Heßler 2014; Fraunhofer IPA 1988).

In Germany, Daimler and Volkswagen—in particular Hall 54 of the Wolfsburg plant—were regarded as pioneers (Heßler 2014; Fraunhofer IPA 1988). But Japanese companies were also advancing automation (cf. Coffey/Thornley 2006). In 1993, the journal *Automobil Produktion* reported on three automobile plants in a series of articles: Toyota Tahara, Mazda Hofu, and Nissan Kyushu.[2] All three plants had almost completely automated body shops, i.e., both welding and material handling were largely done by robots. A particular source of pride for the Japanese plants was the flexibility of the

---

[2] AP April/June/August 1993

automation: Rotating clamping devices enabled the companies to produce several models on one body line. The transport of subassemblies in the body shop was handled by automated guided vehicles (AGVs). Even in assembly process automation levels ranged between 15% (Toyota[3]) and 20% (Nissan[4]).

At the beginning of the 1990s, however, strategies were reoriented. The cooling of the economy revealed the weakness of the highly automated plants: overcapacity and an inability to depress fixed costs. Lean production emerged as a new management concept that focused on organizational restructuring rather than automation.

4.1. Changing Approaches to Automation and Digitalization – Analysis of the Industry Press

The reorientation of the companies' automation approaches began in 1993 and 1994, but they took different paths depending on the production process. In the following, three areas are analyzed: the assembly shop, the body shop (an area that was already highly automated in the 1980s), and selected indirect areas (product development, process planning, production control).

Automation Approaches in Assembly

In the assembly areas, the move away from earlier automation strategies was most pronounced. In the 1990s, a reorganization of the assembly areas was undertaken to implement a clear flow orientation[5] and the just-in-time principle. This was supplemented by the modularization of processes and the outsourcing of modules (e.g., engine, doors, cockpit, etc.) to closed pre-assembly areas (for more on modularization, see Salerno 2001; Ro et al. 2007; MacDuffie 2013).

However, differences between German, Japanese, and American companies became apparent. In Japanese companies, assembly automation was reduced, and the new Toyota plant in Kyushu was designed with very limited automation in mind.[6] Even if not all Japanese companies turned away from the idea of assembly automation as strongly as

---

[3] AP June 1993

[4] AP August 1993. Robots were used at Nissan to install the rear lights, front and rear windows, seats, batteries, wheels and spare wheels, rubber seals on the doors, bumpers, and engines.

[5] According to the flow principle, production is divided into interlinked and synchronized sequences of work steps. The products move evenly in this chain, so that all work stations are used to capacity.

[6] AP September 1994

Toyota did (see Cusumano 1985 for more on Nissan), the 1990s were characterized by a skeptical attitude towards assembly automation in the Japanese automotive industry. Just like the Japanese companies, American companies also turned away from assembly automation in the 1990s. The new vehicle ramp-ups at the Ford and GM plants from the mid-1990s onwards were accompanied by a reduction in automation in the assembly areas. Companies still used automated processes for the "marriage" (the merging of the car body with the drive train) and gluing of windows, but further automation steps were mostly omitted.[7] The Production Director of Ford Europe formulated the strategy as follows:

> "One of our special features is that we use very little automation in final assembly. This will not change in the future. The experience of Far Eastern manufacturers who dismantled existing automation a few years ago served as a model, because automation in final assembly not only hinders a continuous and maximum increase in productivity, but sometimes even makes it completely impossible." (AP December 2000, p. 32)

However, German companies, especially Volkswagen, did not fully move away from automation in assembly. The modernization of the Daimler plant in Rastatt for the launch of the new A-Class in 1997 was accompanied by an expansion of assembly automation, which was also motivated by ergonomic objectives.[8] Assembly automation rates also increased from 30% to 33% in the ramp-up of the new Golf A4 at the VW plant in Wolfsburg in 1997.[9]

In the 2000s, there was hardly any change with regard to the automation of assembly in German automotive plants[10], but in other areas—such as the engine plants—more automation was also introduced.[11] Daimler, in particular, sought to introduce further automation in assembly. In 2009, the "Assembly 21" concept, which promised increased automation, was presented. An example of this was its rear axle assembly, which Daimler converted from a manual process supported by two robots to a highly auto-

---

[7] AP February 1995 and August 1995

[8] AP Special Edition A Class 1997; see also AP Special Edition S Class 1998. The rear door, the seats, the pedal module, the wheels, the slatted roof, the door seals, the windows, the canopy, the battery, and spare wheel well were mounted automatically; the "marriage" was automated, too.

[9] AP Special Edition Golf A4 1997. The entire chassis assembly (subframe, steering gear, wishbone, stabilizer, engine, front axle), the "marriage", and the installation of the battery, wheels, buffer rod and front end were automated. In addition, many bolting processes were partially automated. However, the influence of the move away from assembly automation, led by Japanese and American companies, was making itself felt in German companies' oversea plants. The new Daimler plant in Tuscaloosa largely dispensed with assembly automation (AP October 1997); in the case of Volkswagen the modernized Seat plant in Martorell, Spain was considered a model of a new strategy that made hardly any use of automation in assembly; the plants in Bratislava and Pamplona followed this pattern (AP June 2001; AP February 2002).

[10] AP December 2005

[11] AP July 2010

mated concept with 45 robots; in the process, the number of assembly workers was halved.[12] In this case, automation was based on a separation of the automatable and manual work steps and the optimization of the material feed. Short-cycle route trains supplied the station from central storage to create space for the robots.

The discussion about assembly automation received new impetus in the 2010s, when the first lightweight robots came onto the market. Lightweight robots resemble human arms and can be used relatively flexibly in assembly work. Nevertheless, there are major limitations, because lightweight robots are still very slow and can only work in a very standardized and rigid environment.[13] Nevertheless, in the 2010s, German automotive companies began trying out lightweight robots at simple assembly workstations, for example, when assembling transmission components (Daimler[14]) or gluing sound insulation to doors (BMW).[15] In the mid-2010s, AGVs also made a comeback in the intralogistics of production sites in the automotive industry.[16]

The development of the Volkswagen plant in Zwickau, where production of the new ID.3 electric car started in 2019, shows that assembly automation remains on German automotive companies' agenda. Volkswagen has presented Zwickau as the model plant for the production of its electric vehicles and is explicitly emphasizing the automation of assembly (Volkswagen 2020): The degree of assembly automation in Zwickau has been increased from 12% to 30%.[17] The increasing automation is also linked to changes in product architecture: The drivetrain of electric vehicles is much simpler than that of cars with combustion engines, which significantly reduces the number and complexity of assembly steps in the engine compartment and drivetrain. Although Volkswagen itself has emphasized the goal of increasing assembly automation,[18] note that the automation level reached in Zwickau is comparable to the one achieved in the VW plant in Wolfsburg in the 1990s.

The differences between developments in Germany and Japan can be exemplified using the contrast between current developments at Volkswagen and Toyota. The central aim underlying the organization of assembly processes at Toyota is cost reduction

---

[12] AP January 2009; vgl. AP June 2013

[13] AP June 2019

[14] AP November 2015

[15] AP October 2015

[16] AP April 2014, September 2015, April 2017; AMS April 2016

[17] In addition to the "marriage," the automated assembly process includes attaching the door seal, placing the glass roof, installing the rear and front axles, fitting the cockpit, bolting the chassis, adjusting the headlights, fine-tuning the chassis, and undertaking quality control of the gap and flush of the doors (Volkswagen 2020).

[18] AP September 2018

and flexibility. This means a limitation of or sometimes even a reduction in automation. The above-described dismantling of assembly automation in the 1990s continued in the 2000s. In the 2010s, Toyota's assembly areas reported automation levels of less than 10% (Rothfelder 2017). The Takaoka plant represents the most recent development in this area (see Schmitt 2019).[19] The plant has two assembly shops. Takaoka 1 is probably not very different from the assembly lines in Germany, yet it certainly is less automated. Takaoka 2 is not automated at all. The vehicles move through the assembly area on AGVs; there is no assembly line. Since the stations do not require any automation, they can be converted within a very short time. Takaoka 1 has an optimum cost level at 200,000 vehicles per year. If production increases beyond this level, Takaoka 2 takes over, as the capacities can be flexibly increased and decreased.[20]

The American "Big Three" (General Motors, Ford, and Chrysler) also remain skeptical about automating assembly processes, although, like the German manufacturers, they are experimenting with the use of lightweight robots and other automation techniques.[21] At its Orion plant, for example, GM uses six lightweight robots to glue the headliner, insert spare tires, adjust lights, and test sensors. However, the level of automation in assembly remains very low for most of the new product ramp-ups in the company's plants.[22]

In principle, it can therefore be said that German companies in the automotive industry did not turn away from the idea of assembly automation to the same extent as occurred in Japan and the USA. At the same time, the progress made in assembly automation over the last 30 years has been relatively small, meaning that today's automotive plants only differ from their predecessors in terms of assembly automation at individual stations.[23] Incidentally, Tesla recently attempted a major advance in assembly automa-

---

[19] See also AMS August 2017 on the Motomachi plant

[20] A certain similarity to the Takaoka concept is evident in projects by German car manufacturers that aim at making assembly processes more flexible. However, technology plays a greater role in Germany. Audi, for instance, is working on modular assembly concepts that deviate from the strict principle of the assembly line. As in Takaoka, these systems are based on AGVs. At Audi, however, the evidence is not in the ease with which the assembly areas can be converted but in the "smart" control of the AGVs and thus the flow of materials. Audi has been using AGVs to transport the bodies of the R8 in Neckersulm since 2015. In the process, certain derivatives automatically stop at special stations (e.g., fabric roof assembly) that most car bodies in production do not stop at. In this way, automatic flexibility is built into the assembly system. At present, this flexibility is limited to a few optional extras, but Audi sees "modular assembly" in Neckersulm as a model project for the future (AP September 2017). However, this approach does not mean a decentralized system. Rather, a central algorithm based on incoming orders calculates the most efficient utilization of the assembly stations and logistics chains and precisely determines the order sequence six days in advance (AP April 2018).

[21] AW April 2018; AMS May 2019

[22] AMS September 2015

[23] AP July 2018.

tion—the grandiose failure of this experiment was described in an article in the New York Times (Boudette 2018).

Finally, it should be noted that since the 1990s, automated support and control systems have become widespread in automotive plants, regardless of the company's country of origin. The ergonomics of the assembly processes have been improved by the introduction of more and more lifting aids, parts trolleys that move along the assembly line and other aids. Additionally, assistance systems have been introduced to support the work processes. This began in the mid-1990s, with the increasing use of screwdrivers with automatic control of torque and angle of rotation, which minimized faulty screw connections.[24] From the mid-1990s onwards, Audi, BMW, and other companies started installing information boards at assembly workstations that display information about the parts and special features required in each case based on an identification number read from the vehicle; this assists the workers.[25] In the 2000s, companies such as Audi and Daimler began installing laser sensors that control the size of the joints and the positioning of the module in lifting aids for installing heavy modules such as the cockpit.[26] Since the 2010s, companies have experimented with the use of data glasses, smart watches, and other devices to provide information to workers completing assembly and logistics processes (Evers et al. 2019).

Automation Approaches in the Body Shop

In contrast to the assembly areas, the body shops were already highly automated at the beginning of the 1990s and there was no turning back from automation here. Even in the Toyota plant in Kyushu—which largely abandoned assembly-shop automation—body-shop automation levels differed little from those in highly automated plants such as Toyota Tahara.[27] In the 1990s, automation levels of 90% to 100% were achieved in the body shops at most European, American, and Japanese factories.

As Figure 1 shows, the trends until the 2010s cannot be characterized as moving towards "more" automation—automation levels have remained largely constant. The figure shows the levels of body shop automation reported in German automotive plants in the journal *Automobil Produktion*. Automation levels of 90–100% have been achieved since the 1990s. Incidentally, these levels have become so commonplace in indus-

---

[24] AP February 1993, February 1994

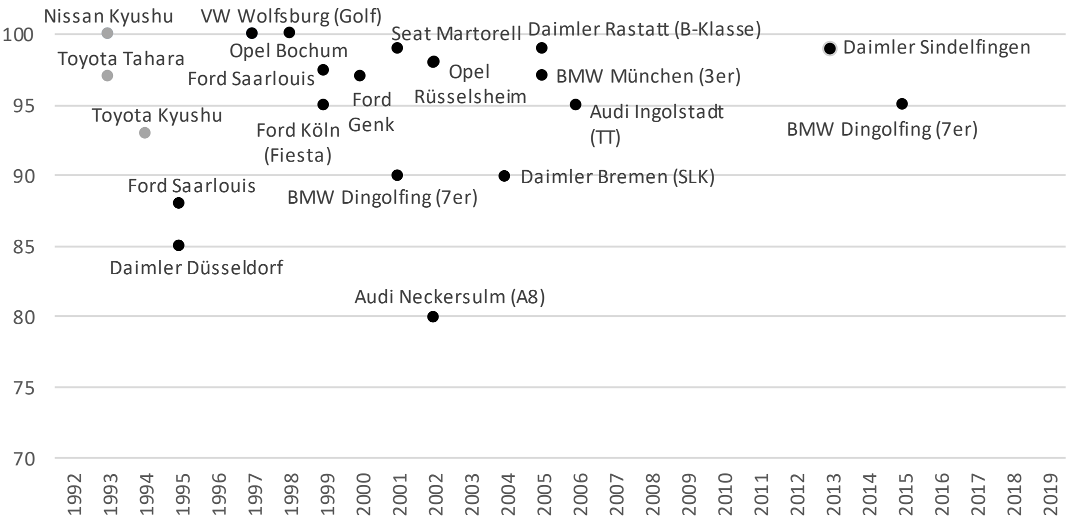
[25] AP April 1993

[26] AP Special Edition Audi A4 2001, AP February 2005

[27] AP September 1994

trialized high-wage countries that the magazine's factory portraits stopped quantifying the level of automation from around 2010 onwards.

Figure 1: Body shop automation levels of selected automobile plants



Source: Automobil Produktion, volumes 1992–2019. The figure shows all plants for which information about automation levels was available.

It should be noted here that although body-shop automation has reduced direct manual work on the product, humans still carry out the monitoring and maintenance work. This work has even gained in importance (Kuhlmann 2004). Manual welding has thus disappeared from the factories but human labor has not.

Since the 1990s, the change in technology in the body shops has been driven by several factors. First, the focus on lean production led to a reorganization of processes and an optimization of material flows. A dominant approach here was the organization of the body shop according to the herringbone layout[28]: the main line on which the bodies are welded is in the center; the welding lines for the subassemblies (side panels, roof, doors, etc.) are arranged like herringbones so that they lead to the main line and the subassembly task in question is completed at the right place next to the main line. The side lines are connected to the main line by roller conveyors, from which the robots can grip directly. In this way, transport distances and the need for manual insertion activities have been minimized. This has also made it possible to phase out the expensive and failure-prone AGVs, most of which disappeared again from the automobile factories from the mid-1990s onwards.[29]

---

[28] AP Special Edition A Class 1997, Special Edition Golf A4 1997, AP Special Edition Opel Bochum 1998, AP June 1998, AP January 2000

[29] AP February 2002

Second, since the 1990s, the variety of joining techniques in car body construction has increased continuously, that is, the major challenge for the companies was to achieve mastery in increasingly complex automation. This was driven by several developments:

- There was a growing need to reduce vehicle weight (to lower fuel consumption), which led to an increased use of aluminum and plastics (including carbon) alongside the usual steel in the bodywork.[30] It is much more difficult to weld aluminum than steel because the material reacts much more to heat. This has led to a further development of laser technology, but also to an increased use of gluing techniques that do not generate heat.[31] The increasing use of plastic parts has also resulted in an increased use of gluing in car body construction.
- The requirements for vehicle safety, body strength, and thus the quality of the joining processes have increased. Since the 1990s, the use of laser welding has therefore become more and more widespread in automotive plants,[32] with German manufacturers being at the forefront of introducing this technologies in mass production (Jürgens/Meißner 2005).[33] In addition, since the mid-2000s, the use of multi-robot cells in car body construction has increased, which is placing new demands on programming.[34] In these cells, several robots work together: one grips a part, while others process this part or check the quality.
- Since the 1990s, quality requirements have led to an increasing use of inline measuring devices and geometry stations, since any deviation, even one in the millimeter range, can affect the rigidity of the bodywork and the fit of parts. In the 2010s, production lines in car body construction were already equipped with devices that could register several hundred to several thousand measuring points and provide data on the quality of the welding process.

Third, a particular challenge has been to reconcile automation and flexibility, especially in view of the continuing increase in model variants. Some companies—such as Daimler and Volkswagen—began restricting the flexibility of body shop lines from the 1990s onwards, with each line producing one model family only.[35] The price of particular advanced technology was to limit flexibility. Other companies continued to seek flexibility, which required the development of complex clamping devices that could flexibly accommodate components of different sizes and with different gripping

---

[30] AP May 2017

[31] AP May 2010; AP June 2011

[32] AP April 1992, April 1998

[33] AP October 1992, December 1996, AP April 2008, AP June 2013

[34] AP April 2006

[35] AP Special Edition S Class 1998

points.[36] Japanese companies were particularly successful in making car body construction processes more flexible. The successes were not the result of a sophisticated digitalization strategy (or even artificial intelligence), but were the product of well-thought-out product architectures with regard to their “manufacturability” (Fujimoto 1997; Adler et al. 1999). A prime example is the New Global Body Line introduced by Toyota in the early 2000s (cf. Brown 2004). As early as the 1990s, several vehicle models could be produced on Toyota’s body shop lines; the flexibility was based on a sophisticated system of gripping tools and pallets used to grip and position the parts of the car bodies to be welded. However, changing the gripping tools took time and their storage required a lot of space. The central innovation of the New Global Body Line was the introduction of a universal gripping tool, which was moved from above the car into the interior of the car body and was used to fix the parts in place during the welding process. By standardizing the gripping points over a large number of vehicle models, the company could produce up to eight models on one welding line with the same tool. Toyota has estimated the savings in production equipment costs to be 50% and in the ramp-up costs of new models to be 70% because the equipment hardly had to be changed (Brown 2004).

Thus, the development of manufacturing techniques in the body shop since the 1990s has been characterized less by an increase in automation—car body manufacturing in all plants of German, American and Japanese manufacturers has been largely automated for some time—than by an incremental increase in complexity. Progress in productivity is very much based on innovations in product architecture (this is also the conclusion of the study by Jürgens 2020, which is based on a longitudinal analysis at company level).[37]

---

[36] AP October 2007; AW June 2004 and December 2013

[37] Potentially disruptive approaches are still a long way from being actually feasible. For example, robot manufacturer KUKA is working on a modular concept for car body manufacturing that moves away from the herringbone principle and the rigid interlinking of stations (AP September 2016). The idea is to create a modular structure of flexible robot stations that can be flexibly approached by AGVs with the car body parts to be processed (Kuka 2016). However, the concept is still far from being implemented in practice. The use of 3D printing could also be disruptive, as it would completely replace the joining processes commonly used today. Since the middle of the 2010s, 3D printing has become established in the automotive industry in Germany, the United States, and Japan in the field of prototype construction (AW November 2013). Individual manufacturers such as BMW are also already building in individual small series of a few hundred to a few thousand pieces of printed parts within their vehicles (AP September 2015). However, the technology is also still a long way from being used in mass production.

Digitalization in the Indirect Areas: Towards the "Digital Factory"

The so-called "indirect" areas, which include product development, planning, production control, quality assurance (and many other areas), have undergone a profound technological change since the 1990s. This change can be described by the term digitalization. In this paper, digitalization is understood as having two aspects. The first of these is the development of software systems, the standardization of data, and the collection, processing, and provision of this data. The second aspect is the use of the data thus created for the automation of calculations, tests, simulations, and evaluation processes. Digitalization thus opens up new possibilities for human workers, but at the same time creates the basis for automation and automates data processing.

There have been several drivers of digitalization in the automotive industry, many of which have been evident since the 1990s (and even earlier). First, competition in the industry has led manufacturers to greatly increase model diversity while at the same time shortening model cycles (Chanaron/Lung 1999). Second, since the 1990s, regulatory requirements for vehicle safety and vehicle efficiency (e.g., in terms of fuel consumption) have increased (Krzywdzinski 2019). Both developments have massively increased the development cost of vehicles and directed the companies' attention to potential productivity increases in this area. Lean production approaches were consistent with this quest for productivity; they focused on optimization concepts for product development, planning, plant commissioning, maintenance, and logistics. In the 2000s and even more so in the 2010s, two new innovation topics that would require massive investments by companies in development capacities came into focus: electric mobility and autonomous driving (McKinsey 2016; Groshen et al. 2019).

As early as the 1980s, it was clear that Japanese automotive companies were much faster and more efficient than their European and American competitors, not only in production but also in product development (Fujimoto 2000). And indeed, research showed that the strength of Japanese companies in this area was not based on superior technical solutions but on their more efficient organizational structures (Fujimoto 1997; Adler et al. 1999). Nevertheless, the search for rationalization in indirect areas also led to investment in technical improvements.

The following section examines digitalization in the automotive industry, focusing on product development, planning, and production control. There were certainly comparable developments in other areas, such as supply chain management,[38] but these are not included for reasons of space.

The digitalization approaches of the 1990s—the first phase considered here—can be characterized as follows:

- *Product development and planning*: Automotive companies in Germany, the United States, and Japan focused on promoting the use of computer-aided design (CAD) software. In 1992, Daimler reported that the new Rastatt plant was the first factory to be designed and planned 100% using CAD.[39] CAD became the standard for supplier companies as well.[40] Based on CAD, new applications that changed the development and design process were created in the 1990s. New techniques such as stereolithography[41] or fused deposition modeling[42] used CAD data for rapid prototyping and accelerated the development process, as prototypes could be produced quickly and easily. The first software programs that used CAD data to simulate material behavior in the manufacturing process came onto the market and thus reduced the need for subsequent testing,[43] but these were applications specialized for individual processes. The use of CAD was also meant to facilitate simultaneous engineering. The idea was for automobile manufacturers to cooperate directly with suppliers and equipment manufacturers during the development of vehicles and parts and to exchange data in order to develop parts and systems simultaneously (and not one after the other).[44] Japanese companies pioneered simultaneous engineering (Fujimoto 2000), but European and American companies followed suit. VW reported a reduction in the development time for the new Passat from 72 to 27 months due to simultaneous engineering.[45] In the 1990s, however, simultaneous engineering was still hampered by the lack of data standards, which made it difficult to transfer CAD data between companies. It was only in the second half of the 1990s that uniform data standards for CAD were developed at all.[46]

---

[38] The implementation of lean production and its core idea of just-in-time delivery were important drivers of the development of software-based supply chain management systems (Lamming 1996; MacDuffie/Helper 1997; Mudambi/Helper 1998). This included the development of digital communication for the detailed call-off of parts from suppliers. Ford already used digital communication for supplier call-offs at the beginning of the 1990s, and Daimler plants were also equipped accordingly for new product ramp-ups (AP February 1993, July 1993).

[39] AP July 1992

[40] AP September 1992

[41] The curing of a photopolymer under the influence of a light/laser.

[42] The application of molten thermoplastic raw material through a thin nozzle.

[43] AP April 1995, October 1999

[44] AP September 1992

[45] AP December 1996

[46] AP April 1997

- *Production control and quality assurance*: In the 1990s, the first steps were taken towards creating comprehensive connected networks in production, with the aim of better visualizing processes and simplifying production control.[47] Projects involving machines that were equipped with sensors whose data were to be used for preventive maintenance were also launched.[48] However, in the 1990s, these networks still encountered considerable problems. Only in the course of the 1990s did automobile factories switch from parallel wiring (where a separate line is laid for each signal) to serial wiring (a single line can transmit several signals; a fieldbus organizes communication based on a protocol); this considerably reduced the networking effort.[49] Even then, however, there was still no uniform standard for different manufacturers' fieldbuses, causing high integration costs for companies.[50] Digitalization in production was further promoted by the advent of computer aided quality (CAQ) concepts.[51] The main drivers here were lean production and the emergence of certified quality assurance systems.[52] In the 1990s, process-quality-related certification became a must for all automotive plants and suppliers and generated considerable documentation requirements. As a result, production lines were increasingly equipped with digital measuring devices, which were miniaturized in the 1990s and replaced the manual measuring devices that had been widely used until then.[53] The Six Sigma concept spread the idea of statistical process control, which had long been established in Japan and the USA (Petersen 1999; Leitner 1999),[54] throughout the German automotive industry. The first software packages developed specifically for the automotive industry came onto the market.

The 1990s can thus be seen as a period in which the first digitalization concepts were diffused in the automotive industry; however, due to a lack of standards, poor data quality, and limited networking technology, these were not able to reach their potential and resulted in specialized isolated solutions.[55] There is little information about differences between German, American, and Japanese companies in the implementation of digital

---

[47] AP April 1995, June 1995, Special Edition A Class 1997

[48] AP June 1995, April 2000

[49] AP April 1992

[50] AP February 1995

[51] AP May 1992

[52] A pioneer of this development was Ford's Q1 certification system developed at the beginning of the 1980s. The first version of the global quality assurance standard ISO 9000ff was published in 1987.

[53] AP July 1998

[54] AP May 1992

[55] See e.g., AP Special Edition Audi A4 2001

technology in this period. A study by Liker et al. (1992) concluded that there were hardly any differences in the use of CAD between American and Japanese companies in the early 1990s. In one of the few company studies, Okamuro (2000) showed that Toyota had an advantage over its European competitors in the use of CAD in product development and in the exchange of data with its suppliers—which Okamuro linked to the particularly close relationship between Japanese car manufacturers and their suppliers. However, German manufacturers had largely caught up by the end of the 1990s, and they also made much greater efforts than the Japanese to harmonize CAD data within the global STEP standard (Standard for the Exchange of Product Model Data). The still largely isolated digitalization projects of the 1990s culminated in the 2000s in an intensive discussion about the "Digital Factory"— more than ten years before the beginning of the Industry 4.0 discussion. In principle, the "Digital Factory" was supposed to integrate all systems, but the focus was primarily on product development and production planning, with the promise that it would halve development and planning times. Companies saw enormous potential for cost reduction in this field, especially since the number of vehicle models offered by companies and their complexity increased at the same time.

Virtually all automotive companies (VW, Audi, Daimler, BMW, GM, Ford, but also many suppliers such as Bosch) developed plans for the "Digital Factory" and declared it to be a central goal for the coming years—even if it soon became apparent that developments were progressing much more slowly than had been hoped.[56] German companies such as Daimler, BMW, and Audi saw themselves as pioneers,[57] while the American companies positioned themselves somewhat more cautiously. A senior manager of Ford's Powertrain Division described his own company as a "cautious adopter of new technology, but wants to be a fast second adopter" (AW 3 April 2013). Unfortunately, there is little information about developments in the Japanese automotive industry.

With regard to the areas examined here, the following developments can be identified in the 2000s:

- *Product development and planning*: The first central element of the "Digital Factory" was a further digitalization of product development. The focus was on developing so-called "virtual prototypes" and the use of virtual reality and simulations (of crash tests, vibrations, noise development, etc.) in order to reduce the effort in-

---

[56] AP April 2002; AP June 2002; AW October 2004 und April 2008

[57] AP October 2010, October 2012

volved in developing, producing and testing prototypes.[58] Companies also sought to use product development data directly for digital production planning.[59] The companies hoped to enable the systematic use of virtual reality and material flow simulations as well as virtual commissioning, i.e. (partially automatic) programming of machines and production lines based on digital planning. The companies were pursuing ambitious goals, and Daimler announced that it intended to completely digitalize factory planning by 2005.[60]

- *Production control and quality assurance*: In the 2000s, the so-called industrial Ethernet became widely used in automotive plants.[61] The Ethernet is a technology developed in the 1990s to locally network PCs in offices. In the 2000s, the industrial version of Ethernet became widely available, enabling local networks to be implemented in factories with significantly higher data rates than before; this met the safety and real-time requirements of the industrial environment. With the industrial Ethernet, networks were now cheaper and much more efficient. This enabled the proliferation of manufacturing execution systems (MES), which facilitated the monitoring of production processes.

The hopes placed in the “Digital Factory” were only partially met. In the course of the 2000s, industry experts repeatedly noted that there was still a lack of precise material and process data and that there was no standardization of data.[62] By the end of the 2000s, a true integration of systems from product development through planning, manufacturing, logistics, and maintenance still had not occurred.[63] The hoped-for halving of the planning time for new vehicle models was considered unrealistic early on.[64] In 2008, the head of the “Digital Factory” project for Daimler’s body shops said: “We got off to a massive start and ran into a massive wall” (AP January 2008: 54). It was only in the second half of the 2000s that activities to develop data standards intensified. A group coordinated by Daimler began to develop an automotive-specific format for automation data. This would meet the needs of production planning and commissioning (AutomationML) and would be used as an open standard for the self-description of devices, machines, systems, control systems, and network components.[65] With

---

[58] AP Special Edition C Class 2000; AP March 2007

[59] AP Special Edition BMW 7 2001; AP April 2002

[60] AP April 2002

[61] AP February 2001; AP February 2002

[62] AP October 2002; AP August 2005

[63] AP January 2008; AP December 2010; AP October 2013

[64] AP October 2002

[65] AP April 2004; AP June 2007

German companies playing a key role, the development of the "Open Platform Communications—Unified Architecture" standard (OPC UA) began. The first version was published in 2010 and it is now increasingly becoming the dominant standard for machine networks (the industrial internet of things) in Europe (Lechowski/Krzywdzinski 2019). In the second half of the 2000s, integrated software solutions for digital product development, production planning, simulation, and commissioning also came onto the market in the form of product lifecycle management (PLM) systems.[66]

The "Digital Factory" was additionally boosted by the discussion on Industry 4.0, which began in 2012, although it should be noted that automotive companies were rather indifferent to the first publications on Industry 4.0. Initial comments emphasized that the automotive industry had been working on the "Digital Factory" for over a decade, that it was aware of the difficulties, and that the Industry 4.0 concept did not provide any new approaches or solutions.[67] In addition, the idea of self-organization of production, which was emphasized in the original Industry 4.0 publications (Acatech/Forschungsunion 2013; Spath et al. 2013), was seen as incompatible with the precise takt planning and strict interlinking of processes that dominate the automotive industry. The idea of self-organization implies that production is a decentralized system of independent agents, each of which reacts to the other. By contrast, in the lean production systems dominating the automotive industry, production is a precisely defined (deterministic) chain of production steps that is set in motion by customer orders.

Despite initial skepticism about the idea of Industry 4.0, German companies in particular continued to work on digitalizing manufacturing. With regard to the areas this paper looks at, the following points should be emphasized:

- *Product development and planning*: Due to the availability of data and software systems, more and more companies started using virtual commissioning to shorten production ramp-up processes during model changes.[68] The PLM software packages covered more and more areas of production planning.
- *Production control and quality assurance*: The increasing standardization of machine communication through standards such as OPC UA, the progressive equipping of production equipment with sensors, and the development of the mobile internet led to further networking in factories. Audi reported in 2016[69] that for the first time, all the shops in its automobile plants were connected with one another and that it

---

[66] AP September 2006; AP October 2007; AP October 2010

[67] AP February 2013

[68] AP June 2017

[69] AP November 2016

had established a central production control center that allows production, material flows, and individual bodies to be tracked across all shops. Technologies such as RFID have become increasingly affordable and robust, and car manufacturers and suppliers have responded by developing specific standards for the use of these technologies in the automotive sector.[70] Software development also progressed in the 2010s. In the press plants, for example, the rapid progress in equipping presses with sensors in the 2010s made it possible to collect precise data for process monitoring and control. These data could then enable the tools in the presses to react immediately if deviations from the desired status were detected.[71] However, it is important to stress that press plants were relatively advanced in terms of "smart" control loops.[72] The press shops were also an example of how networking between OEMs and equipment manufacturers has increased: Data from the presses could be used for simulations in product development and process planning.[73] However, fragmentation of the data remained a problem. At the end of the 2010s, German companies therefore began to increase their investment in their IT architectures, as illustrated by the cooperation between VW, Siemens, and Amazon to develop a VW-specific industrial cloud.[74]

The developments described here did not just take place in Germany; they also happened in American automobile companies.[75] However, there were important differences between the companies in both countries regarding their ambitions to develop their own digitalization competencies. A good example of this relates to the establishment of an industrial cloud for networking equipment in the companies. In the above-mentioned example of the cooperation between VW, Siemens, and Amazon in setting up a cloud for the VW Group, VW has sought to acquire its own development competencies itself. This is reflected in the company's stated goal of bringing together 5,000 computer scientists and software developers in the newly founded "Car.Software" unit in order to develop 60% of the software required in-house in future (the group currently estimates that 10% of the software used by the company is developed in house) (Volkswagen 2019; see also Cacilo/Haag 2018). General Motors has also been working on a project to develop an industrial cloud for its global factories since 2014.[76]

---

[70] AP June 2011

[71] AP September 2015, AP January 2017; AP December 2018

[72] AP September 2018

[73] AP December 2014

[74] AP June 2019

[75] AW October 2004, December 2006, April 2008, August 2012, April 2013, February 2014

[76] AMS July 2017; see also AMS August 2019

The partners for this are the Japanese robot manufacturer Fanuc and the US network manufacturer Cisco. Interestingly, according to press reports, the responsibility for data analysis in terms of condition monitoring and preventive maintenance seems to have been outsourced to Fanuc.

The ambitions of the German car manufacturers and suppliers are particularly evident in the model factories, where new forms of digital technologies are being tested. One example is Daimler's Factory 56 in Sindelfingen (Daimler 2020). According to the original plans, Factory 56 was due to start production in 2020 as a pure final assembly facility for the Daimler group's luxury vehicles. It was to represent a new concept of modular assembly, with AGVs transporting all the required materials and the vehicles themselves. The aim was also to systematically test the use of big-data analyses and artificial intelligence in production. However, at the time of writing, Factory 56 had not yet started production, so it remains to be seen how much of the original plans can actually be realized.

Summary

The conclusions that arise as a result of this analysis of the development of automation and digitalization approaches in the automotive industry contradict the dominant arguments in today's discussions. There has been no major automation push in automotive production since the 1990s. Areas such as car body construction were already automated in the 1980s and 1990s and a gradual further development of the technology is underway in these areas—even if it can be assumed that there was catch-up automation in the 1990s and 2000s for latecomers, especially in the supplier sector. The assembly processes remain a bastion of manual work.

In contrast, the work processes in development, planning, quality assurance, and production control have undergone a massive digitalization process since the 1990s. Product development and planning account for a significant proportion of the total costs of the automotive industry, and increasing the efficiency of these processes has been one of the main objectives of the industry since the 1990s. According to the companies, developments such as CAD, CAQ, various simulation software packages, virtual reality, and the integrated concepts of PLM software have led to considerable reductions in the time required for development and planning. However, it must be emphasized that the productivity gains in these areas have not been systematically researched. In particular, it is unclear how technical and organizational innovations intertwined. Technical innovations can only reach their full potential if they are accompanied by the development of suitable organizational structures. For example, the integration of data and software systems is only feasible and can only unleash its full potential if it occurs within structures that promote cross-functional and cross-divisional cooperation.

All of these developments have taken different forms in the three countries examined here—Germany, the United States, and Japan. With regard to manufacturing processes, the available data suggest that German companies have made the greatest attempts to push automation and digitalization, while Japanese companies in particular seem to have moved away from the goal of automation, especially in the assembly sector. As far as the American automotive industry is concerned, the reporting in the press suggests that companies have been very reluctant to invest in automation and digitalization, especially since the global economic crisis.

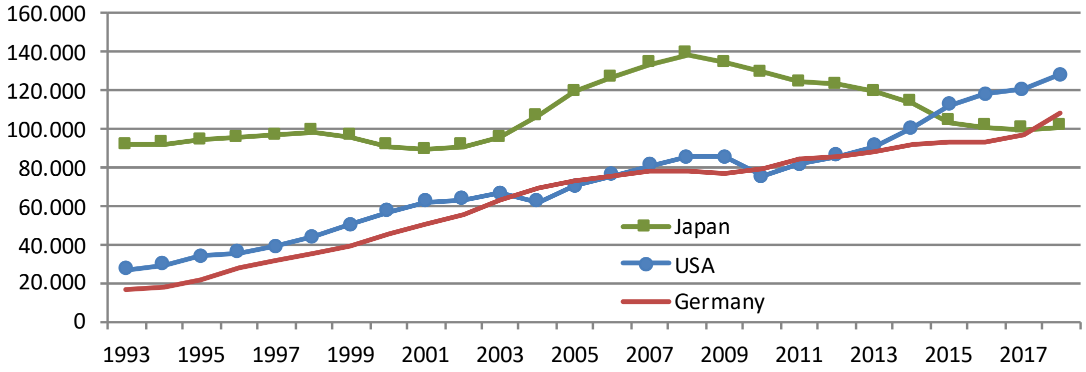
4.2. Changing Automation Levels – Analysis of the Robot Statistics

In both the public and academic debates, the number of robot installations and the robot density (industrial robots per thousand employees) have become the indicator par excellence for automation. What does this indicator show us? How does the development of robot use relate to the development of automation and digitalization approaches described in the previous section?

As Figure 2 shows, the use of industrial robots in the German and American automotive industry has increased continuously. While, in the early 1990s, about 10,000–30,000 robots each were installed in the automotive industry in both countries, by 2018 this number had risen to 128,000 in the United States and 108,000 in Germany.

The situation in Japan was somewhat different. The statistics show that about 90,000 industrial robots were already installed in the Japanese automotive industry in the early 1990s. This number remained constant in the 1990s, but the Japanese figures before 2000 are difficult to interpret because it was not until 2000 that the definitions of industrial robots used in Japan and the other countries were harmonized. The Japanese figures before 2000 overestimated the number of industrial robots compared to Germany and the USA. The figures after harmonization show an increase to a peak of 139,000 robots by 2008, after which the robot population fell back to around 100,000 by 2018. During this period, there has been no major revision of the methods used to survey the robot population, and there has been a corresponding decrease in new installations, so it is assumed here that the decline reflects a real trend.

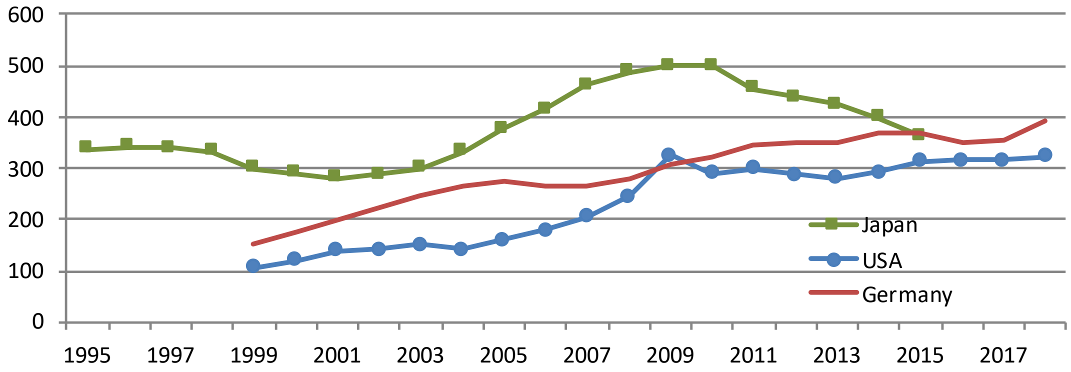
Figure 2: Stock of industrial robots in the automotive industry in Germany, Japan, and the United States, 1993–2018



Source: IFR, own calculations.

The larger number of robots in the United States compared to Germany and Japan must be considered in light of the size of the automotive industry in the three countries. Since robots are only used in industrial production processes, the robot density has been calculated below as the stock of robots per 1000 blue-collar workers, with blue-collar workers including both direct production workers and workers in indirect functions such as maintenance, commissioning, and others (Figure 3). It should also be noted that automotive companies generally work in two or three shifts. As no statistical data on shift systems in the automotive industry are available, it was assumed that the two-shift mode is characteristic of the automotive industry in the three countries studied. Arguably, this somewhat underestimates the robot density, since at least some of the companies utilize three-shift systems.

Figure 3: Stock of industrial robots in the automotive industry per thousand blue-collar workers in Germany, Japan, and the United States, 1995–2018 (assumption: Two-shift system)



Source: Own calculations based on IFR, BLS, VDA.

In the United States, robot density increased from about 100 robots per thousand blue-collar workers in the 1990s to 320 in 2018, but it should be noted that robot density has hardly increased since 2009, which may reflect the limited investment by companies in their production equipment since the economic crisis. A continuous increase in robot density can be observed in Germany, although here too growth has slowed down somewhat over the last decade. In 2018, 390 robots were used per thousand blue-collar employees.

In Japan, the robot density reached its peak in 2008 with 500 robots per thousand blue-collar employees, only to decline again to 360 robots in 2015. For the years after 2015, there are as yet no occupational statistics available for Japan that would enable calculations of the number of blue-collar workers. However, the number of robots installed has remained largely constant, and employment has also remained stable in these years, so that a largely constant robot density can be assumed.

The decline in robot density in the Japanese automotive industry after 2008 is remarkable because it contradicts the perception widespread in today's debates. It is consistent with our account of developments in Japanese companies, which have tended to abandon automation in assembly. The car body manufacturing is, of course, highly automated in Japanese automotive companies. The Japanese companies are, however, cautious about automation if it could restrict flexibility. The decline of the number of robots in the body shop could be related to changes in the product architecture and the introduction of simpler equipment (as in the case of the Global Body Line of Toyota), or to the abandonment of automation steps, for instance regarding material handling.

The contrast between the development of robot density and the qualitative analysis of automation approaches is striking. The qualitative analyses make it clear that the robot density indicator by no means reflects the development of automation levels. First, the above analysis has shown that automation takes many forms and is only performed by robots in some work processes: mainly in welding, painting, and material handling. This means that the focus on robot density might underestimate the extent of automation, for instance in mechanical engineering which relies on machine tools and not on robots. Second, the example of car body construction in particular shows that an increase in the number of robots does not necessarily mean a rising level of automation, but rather reflects the increasing complexity of the equipment and the manufacturing process, as well as the variety of machining processes and materials. This implies that the robot density indicator overestimates automation.

5. Changing Occupational Structures in the Automotive Industry Since the 1990s

To what extent are automation and digitalization approaches connected to changes in employment structures in the automotive industry? In the following, we will approach this question step by step. This section starts by looking at changes in employment volume and then moves on to analyze the composition by occupations.

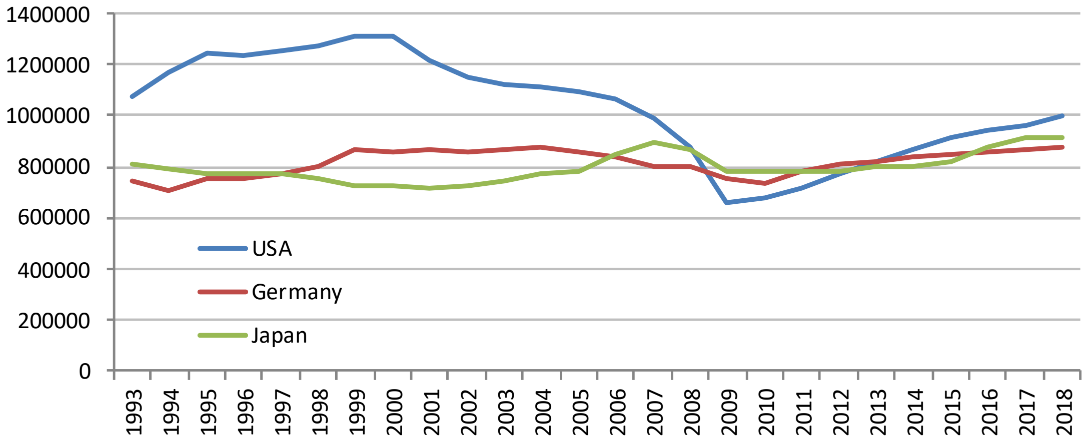
5.1. Employment and Production

In terms of employment volume, the national automotive industries in Germany, the United States, and Japan are relatively similar, although there have been differences in the development of employment over time. It should be noted that it is not possible here to account for structural differences in the composition of the various national industries and their links to other countries: For example, the German automotive industry is closely intertwined with that of its Central Eastern European neighbors (Krzywdzinski 2014; Jürgens/Krzywdzinski 2010 and 2009) and the automotive industry in the United States is closely integrated with that of Mexico (Klier/Rubenstein 2010); in contrast, the automotive industry in Japan is less integrated with the industry in Japan's Southeast Asian neighbors (Kobayashi et al. 2015).

As Figure 4 shows, Germany and Japan had relatively constant employment volumes in the period examined here, at around 800,000 persons in each country. In the case of Germany, the 1990s began with a crisis in which employment fell to just over 700,000 persons. However, it recovered in the second half of the 1990s and again reached levels well above 800,000. In the global economic crisis around 2008, employment again declined to levels around 700,000, only to climb again in the following years to 880,000 in 2018. In the case of Japan, the 1990s were characterized by a slow decline in automobile employment, which reached its lowest point in 2001, with around 720,000 persons employed in the industry. After that, employment rose to well over 800,000 before falling again to values below 800,000 during the global economic crisis and then rising to 916,000 by 2018.

Employment in the American automotive industry took a more dramatic course. It rose until the end of the 1990s and peaked in the year 2000 at over 1,300,000 employees. After that, it fell continuously and reached its lowest point in the global economic crisis at 660,000 people. The global economic crisis was a massive rupture in the American automotive industry, which pushed the manufacturers GM and Chrysler to insolvency (and Ford to near insolvency); ultimately, a rescue package from the American government was needed to resolve it (Klier/Rubenstein 2012). The crisis was particularly pronounced in the United States because the collapse in demand caused by the global economic crisis overlapped with a prolonged decline in the market shares of the Big Three in their home market: From the mid-1990s until the outbreak of the crisis, this market share fell from around 75% to below 50% (Klier/Rubenstein 2012). The crisis had dramatic consequences for the companies: Costs had to be reduced over a period of years (Goolsbee/Krueger 2015). In addition, the companies suffered an enormous loss of knowledge and skills due to the elimination of several hundred thousand jobs within a few years. Although employment rose again from 2009 and reached almost 1,000,000 people in 2018, knowledge and skills had to be rebuilt (Katz et al. 2013).

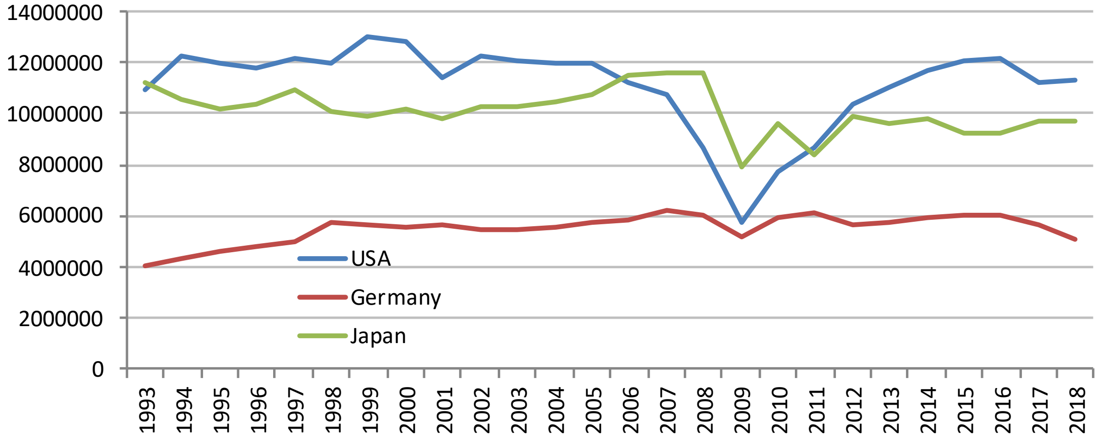
Figure 4: Employment in the automotive industry in Germany, Japan, and the United States (1993–2018)



Source: BLS, VDA.

The employment decline in the years of the global economic crisis is also reflected in production trends (Figure 5). This slump was particularly severe in the United States. While annual production was around 12 million vehicles in the 1990s, it collapsed by half during the crisis but recovered to values between 11 and 12 million by 2018. In Japan, production was around 10 million vehicles in the 1990s, rose to just under 12 million just before the crisis, and then slumped to 8 million, before leveling off at values around 10 million vehicles. In Germany, production in the early 1990s was at a low point of around 4 million vehicles per year; it subsequently rose to values of around 6 million and then slumped only briefly and weakly during the global economic crisis. However, in 2017/8, a slump was recorded again—in this case triggered by the so-called “dieselgate” scandal.

Figure 5: Vehicle production in Germany, Japan, and the United States (1993–2018)



Source: OICA (Production Statistics), VDA (International Auto Statistics).

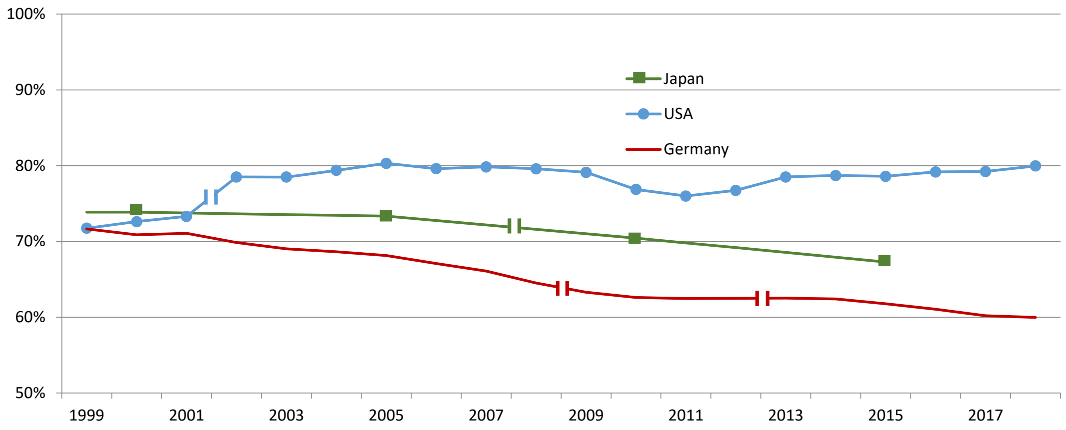
5.2. Occupational Structure of the Workforce

The three countries examined differ considerably in terms of their employment structures. The analysis will begin by looking at the development of the share of blue-collar workers in total employment (Figure 6) and will then turn to the share of engineers and computer scientists. Blue-collar workers are defined as workers in production, logistics, and construction (although the latter group is found only in small numbers in the automotive industry).

In the case of the American automobile industry, the share of blue-collar workers has remained surprisingly constant at around 80% since the 1990s. The absolute numbers of blue-collar workers employed have followed the general trend in the industry: These declined sharply during the crisis of 2009 and then recovered to nearly 800,000 workers in 2018. The trend in Germany deviated significantly from this. Here, there was a continuous decline in the share of blue-collar workers in total employment, from around 70% at the end of the 1990s to 60% in 2018. Given the positive employment trends in the sector, this decline does not mean that there was any loss of employment in absolute terms; in fact, the number of blue-collar workers remained relatively stable during the period under review, at around 500,000. Nevertheless, the extent of the change is remarkable: There has been a very evident and ongoing loss of importance of manufacturing employment. The situation is similar, even if less dramatic, in Japan. Here, the share of blue-collar workers declined from over 70% in the late 1990s to

67% in 2015, but given the positive employment trends in the industry, this was not associated with an absolute decline in the number of workers, which reached over 570,000 people in 2015.

Figure 6: Share of blue-collar workers (production, logistics, construction) in the total employment in the automotive industry in Germany, Japan, and the United States

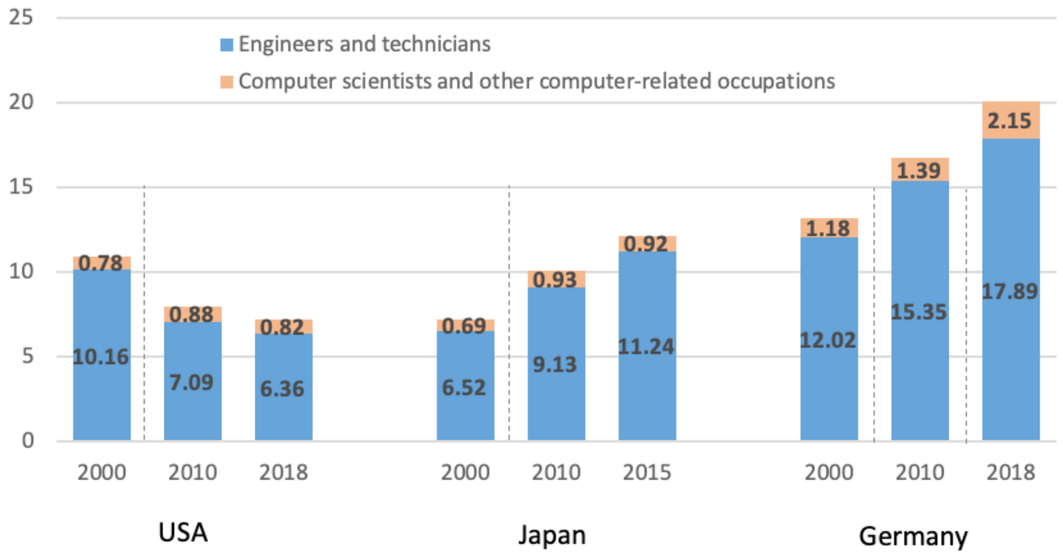


Source: Own calculation based on BLS, SBJ, and BA. Major statistical revisions are marked by ||.

In contrast to blue-collar workers, the share of engineers and computer scientists in employment in the automotive sector is increasing (Figure 7). This analysis only considers employment in the automotive industry itself—the employees of machine/equipment builders and IT service providers who work for automotive companies but are not themselves assigned to the automotive industry are not included. This implies that the analysis shows the extent to which car manufacturers and automotive suppliers themselves create employment in engineering and IT jobs. It cannot say anything about the extent to which automotive companies buy in corresponding expertise externally. In the USA, the BLS data from 2002 onwards show that, as a proportion of the total automotive industry workforce, engineers made up 6–7%. This figure did not differ for car manufacturers and suppliers. Prior to 2002, the proportion of engineers was higher, at around 10%, but a major change in the industry statistics occurred in 2002, meaning that the decrease after 2002 may be a statistical artefact. The stable share of engineers from 2002 onwards means that their numbers followed overall employment trends in the industry. The figure decreased to a low of 40,000–50,000 people until the crisis in 2009 and then slowly increased again to reach 63,000 in 2018. The term "engineers" here refers to all persons in the "architecture and engineering occupations" (17-0000), which, in the case of the automotive industry, mainly includes engineers (environmental engineers, industrial engineers, mechanical engineers, materials engineers, miscellaneous engineers) and drafters and engineering technicians. In the American system, the latter usually have a two-year post-high-school (but non-university) education at technical schools or community colleges. Drafters and engineering technicians account for about a quarter of all engineers and technicians in the American automotive industry.

The proportion of computer scientists in the American automotive industry rose slowly from about half a percent of the total automotive workforce at the beginning of the 2000s to just under 1% in 2018. Here, the term "computer scientist" refers to all groups of activities in the category "computer and mathematical occupations" (15-0000). In the case of the automotive industry, this category mainly includes software developers and programmers, database and systems administrators, network architects, computer support specialists, and operations research analysts and statisticians. In absolute terms, the numbers of computer scientists employed in the industry decreased only slightly during the economic crisis in 2009 from over 6000 to just over 5000 people. Since then, employment in the computer professions has risen, reaching 8200 people in 2018.

Figure 7: Share of engineers/technicians and computer scientists in the total employment in the automotive industry in Germany, Japan, and the United States



Source: Own calculation based on BLS, SBJ, and BA. Dashed lines mark major revisions of the industry and/or occupational classifications that limit the comparability of the data.

Trends in the employment of engineers and computer scientists in Japan differ from those in the United States—although here, too, there was a major change in the statistics between 2000 and 2010 that must be taken into account.[77] The data show an

---

[77] The absolute figures are based on the classification used in the respective census years.

increasing share of engineers in the total automotive industry workforce, from 6–7% in the early 2000s to over 11% in 2015. In absolute terms, this means that the number of engineers almost doubled, from about 50,000 in the 1990s to about 100,000 in 2015. Here, the category engineers mainly includes “transportation equipment engineers” and “machinery engineers”; in addition, there are “electrical and telecommunications engineers,” “metal engineers,” “chemical engineers,” and others. In the Japanese statistics, there is no category comparable to the American engineering technicians. Some studies indicate that Japanese companies in the automotive sector also have a group of employees comparable to engineering technicians (Shibata 2009), but it is unclear in which statistical category these employees are categorized. It is therefore possible that the figures shown here underestimate the development in Japan.

The share of computer scientists in the Japanese automotive industry has also risen, from 0.7% in 2000 to 0.9% of total employment in 2015. In absolute terms, this means an increase from around 6,000 to over 8,000 people. In the Japanese statistics, the computer scientist category is fairly undifferentiated and includes “system designers,” “software developers,” and “other data processing and communication engineers.”

Once again, the strongest change dynamics can be seen in Germany, although here, too, the figures must be interpreted with caution due to statistical revisions.[78] In this case, the statistics show that engineers and technicians accounted for 12% of total automotive industry employment in 2000, and this share rose to around 18% by 2018. In absolute terms, this means an increase in the number of engineers and technicians from about 70,000–80,000 to about 160,000. As Schwarz-Kocher et al. (2019) have argued, this development was driven by both car manufacturers and automotive suppliers. The category of engineers and technicians is highly differentiated in the German statistics, and we do not list all the individual activity groups here. In principle, the engineer category includes persons whose work requires a master’s or master’s-equivalent university degree (defined as “expert level” in the German 2010 classification of occupations (KldB)). Technicians are persons whose work requires a bachelor’s degree or a technician’s diploma (a non-university, post-high-school qualification) (“specialist level”). Technicians make up about one third of the group of engineers and technicians in the German automotive industry.

The number of computer scientists is also increasing in Germany. As a proportion of total automotive industry employment, their share rose from about 1% in 2000 to over 2% in 2018. In absolute figures, this means an increase from about 7,000 to

---

[78] The absolute figures according to WZ93 and KldB1988 respectively WZ2008 and KldB2010.

about 19,000 people. This group is also recorded in great detail in the German statistics (KldB2010) and includes computer scientists without specialization, business information scientists, technical computer scientists, IT system analysts, IT application consultants, IT network technologists, IT system administrators, software developers, programmers, and database developers.

The differences in the development of the number of engineers and computer scientists in the German, American, and Japanese automotive industries are striking. There is reason to argue that they reflect the differences in the digitalization and automation approaches of German, Japanese and American companies, and especially the high-tech orientation of German companies. However, alternative explanations are also conceivable and will be briefly discussed here.

One possible reason pertains to their different outsourcing and skill-acquisition strategies. For example, American companies may be outsourcing their design and development activities to a particularly high degree, or they may be developing their competences in the field of new technologies primarily through acquisitions, whereby the acquired companies remain formally independent and are not recorded statistically in the automotive industry. German companies, on the other hand, might try to build up the same competences internally.

This question is difficult to answer with the available data. It certainly plays a role that the American companies have considerably globalized their product development activities. Even if all car manufacturers have a global structure of development centers (Florida/Kenney 1994; Calabrese 2001; Lara/Carillo 2003), this applies most strongly to American companies. In the case of Ford, passenger car development takes place mainly in the development center in Cologne (Germany), while the product development in the United States itself is concentrating on pickups. General Motors has also largely shifted the development of passenger cars abroad (China and Korea; until the sale of Opel, also Germany), while the company's American development activities are focusing primarily on pickups and vans. According to interviews with automotive experts, more than 85% of the passenger cars produced in the U.S. are developed abroad, and this also applies to the majority of SUV models. Only in the case of pickups and sports cars is product development still predominantly located in the U.S. This is certainly reducing the proportion of engineers and computer scientists in employment in the American automotive industry.

The structure of the industry may be another reason for the differences. The German and Japanese automotive industries are strongly dominated by domestic companies, which have both their production and product development sites in the respective countries. In the American automotive industry, by contrast, transplants of Japanese and German automotive manufacturers and suppliers play a very important role (Florida/Kenney 1991; Rubenstein 2002). These transplants produce for the American market, but the product development activities are not located in the USA.

In addition, studies show a significant growth in the outsourcing of design and engineering activities by American companies (MacPherson/Vanchan 2010). However, in the automotive industry, this applies to all countries, including Germany (VDA 2015)—the question of whether outsourcing processes were more pronounced in the United States than elsewhere cannot be answered with the available data. However, it is clear that European (and above all German) companies are particularly strong in the area of engineering services (VDA 2015).

The externalization of engineering and software development skills may also have taken the form of acquisitions. Indeed, American companies have invested massively in tech start-ups since 2016. General Motors took over the mobility services start-up Sidecar in 2016, and in the same year, it invested more than half a billion dollars in the autonomous driving start-up Cruise Automation. In 2017, it expanded its portfolio to include the lidar technology developer Strobe. Since 2016, Ford has acquired several mobility services providers (Chariot, Autonomic.AI, TransLoc), AI startups (SAIPS), and autonomous driving startups (Argo AI, Quantum Signal AI), Even FiatChrysler invested in this area, in StartMeUp, an autonomous driving startup, and in LeddarTech (specializing in lidar technology).

The start-ups and IT companies discussed here employ a larger number of highly qualified computer scientists and engineers. Hence, if we take these into account, this somewhat reduces the gap in the number of engineers in the American and the German automotive industry. Cruise Automation—by far the largest of the start-ups acquired—employed around 1,000 developers in 2019 and planned to double this number soon (The Newswheel 2019). However, it should be noted that German car manufacturers are also investing in tech start-ups. In 2017, for example, Volkswagen took a multi-billion dollar stake in Argo AI (and is cooperating with Ford here); it also bought the lidar startup Aeva, the mobility services startup Split Finland Oy, and the mobile payment provider PayByPhone. Daimler invested primarily in mobility services start-ups (Chauffer Privé, Flinc, Ridescout, CleverTaxi, MyTaxi, Taxibeat), but it also acquired Torc Robotic, a start-up specializing in autonomous driving for trucks, for a three-digit million euro amount in 2019. The German car manufacturers have also set up large venture capital funds to expand their involvement in the start-up sector. So far, Japanese car manufacturers have been very reluctant to invest, but Toyota launched a

Toyota AI Ventures fund in Silicon Valley in 2018. In the same year, Renault-Nissan also established a similar fund.

The investments made by American car companies in software start-ups can therefore put the differences in the employment of engineers and computer scientists between the American, German, and Japanese car industries into perspective; however, they cannot eliminate them. Moreover, German companies are massively expanding their engineering and software development capacities, whereas this does not seem to apply to American companies to the same extent.

5.3. Structural Change within the Production Workforce

How did employment change within the production workforce? The basic structure of the occupational statistics is similar for all three countries examined here and allows to distinguish five major occupational groups:

- Assembly workers: This group includes workers engaged in manual production work. In the case of car manufacturers, this group is mainly found in the assembly areas that have so far only been automated to a limited extent.
- Metal workers: This group is to be found in metal production (especially foundries), metalworking (e.g. operating machine tools), metal construction (especially welding processes in car body construction) and toolmaking.
- Maintenance and commissioning of production equipment.
- Other production occupations: These include, for example, textile workers (e.g. upholsterers in seat manufacture), painters or quality control workers.
- Shop floor supervisors (in Germany the “Meister” level).

The exact breakdown of these five occupational groups differs considerably in the national statistics. It should be noted that these groups do not directly reflect the distinction between skilled and semi-skilled workers, which is central to research in the sociology of work. Discussions in the sociology of work about the course of automation processes and their consequences have revolved around the question of the extent to which there is a re-professionalization of production work and a reduction of highly standardized, repetitive work content (cf. Kern/Schumann 1984; Jürgens et al. 1993; Schumann et al. 1994; Kuhlmann 2004) or rather a deskilling trend (Braverman 1974). The official occupational statistics can only provide very indirect answers to this question. For example, the occupational groups in the maintenance and commissioning of production facilities are certainly almost exclusively made up of skilled workers. In the assembly and metalworking activity groups, however, there are both skilled and semi-skilled workers - the official statistics do not provide any information about the ratio.

What the statistics can tell us is the ratio of manual production work on the product compared to control work in automated processes. As the qualitative analysis has shown, manual work in the automotive industry is heavily concentrated in assembly areas. We can therefore use the development of assembly-related occupations as an indicator of the importance of manual work. The processes of metal production and machining, on the other hand, have been highly automated for a long time - the activities here consist mainly of control work.

Table 1: Occupational composition of production workers in the U.S. automotive industry

	1999	**2007**	**2012**	**2018**
Total	674,600 (100%)	738,400 (100%)	532,000 (100%)	732,300 (100%)
Assemblers and Fabricators (51-2000)	n/a	319,800 (43.3%)	248,600 (46.7%)	377,000 (51.5%)
Metal and Plastic Workers (51-4000)	n/a	n/a	154,200 (29.0%)	185,200 (25.3%)
Of which:				
Computer Control Programmers and Operators (51-4010)	*11,500 (1.7%)*	*15,500 (2.1%)*	*16,200 (3.0%)*	*13,910 (1.9%)*
Forming Machine Operators (51-4020)	*13,600 (2.0%)*	*n/a*	*8,600 (1.6%)*	*8,000 (1.1%)*
Machine Tool Operators (51-4030)	*42,600 (6.3%)*	*53,200 (7.2%)*	*30,000 (5.6%)*	*35,700 (4.9%)*
Machinists (51-4040)	*14,800 (2.2%)*	*32,500 (4.4%)*	*23,500 (4.4%)*	*23,600 (3.2%)*
Molders, molding machine operators (51-4070)	*14,700 (2.2%)*	*n/a*	*8,500 (1.6%)*	*15,000 (2.0%)*
Tool and die makers (4110)	*16,100 (2.4%)*	*19,700 (2.7%)*	*15,600 (2.9%)*	*14,300 (1.9%)*
Welding workers (4120)	*40,800 (6.0%)*	*46,700 (6.3%)*	*35,500 (6.7%)*	*44,850 (6.1%)*
Other Production Occupations (51-5000 bis 51-9000)	n/a	n/a	65,800 (12.4%)	80,000 (10.9%)
Of which:				
Painting workers (51-9120)	*15,100 (2.2%)*	*14,700 (2.0%)*	*11,200 (2.1%)*	*14,000 (1.9%)*
Inspectors (51-9060)	*34,500 (5.1%)*	*31,500 (4.3%)*	*22,200 (4.2%)*	*31,100 (4.2%)*
Installation and maintenance occupations (49-000)	58,800 (8.7%)	61,900 (8.4%)	38,800 (7.3%)	50,400 (6.9%)
First-line supervisors (51-1000)	27,500 (4.1%)	33,900 (4.6%)	24,600 (4.6%)	39,700 (5.4%)

Source: Author based on BLS. Major revisions of statistical classifications that limit the comparability of data are marked by bold lines.

Table 1 presents the trends for the U.S. automobile industry. It shows remarkable stability in the occupational structure. The most important changes are:

- The proportion of assembly workers has slightly increased. In absolute terms, although the numbers of assembly workers collapsed during the crisis of 2008/09, it then returned to a high level.
- The proportion of workers in metal occupations, by contrast, is declining. This relative decrease has mainly affected machine operators, while there has been hardly any change in the share of welding and painting workers, i.e., workers in the areas most affected by the use of robots in automotive engineering. This could be an indicator that, in recent decades, automation has not so much led to a direct substitution of human labor by robots—areas such as car body construction have been highly automated for some time and the major employment effects occurred a long time ago. Important changes in process technologies seem to relate primarily to digital process control technologies, which can, for instance, enable a smaller number of workers to operate a larger machine park.
- The share of maintenance and installation professions is decreasing. This could be related to new process control techniques, but it could also be due to an increasing implementation of preventive maintenance. Organizational changes may also be underway, such as a greater integration of maintenance tasks into production teams.

Table 2: Occupational composition of production workers in the U.S. automotive industry in 2018

	Motor vehicle manufacturing (NAICS 3361)	**Motor vehicle body and trailer manufacturing (NAICS 3362)**	**Motor vehicle pats manufacturing (NAICS 3363)**
Total	187,600 (100%)	121,000 (100%)	423,900 (100%)
Assemblers and Fabricators	141,100 (75.2%)	60,600 (50.0%)	175,200 (41.3%)
Metal and Plastic Workers	14,900 (7.9%)	31,500 (26.0%)	138,800 (32.7%)
Other Production Occupations	10,400 (5.5%)	16,500 (13.6%)	53,200 (12.5%)
Installation and maintenance occupations	11,100 (5.9%)	6,400 (5.3%)	33,000 (7.8%)
First-line supervisors	10,000 (5.3%)	6,000 (4.9%)	23,600 (5.6%)

Source: Author based on BLS.

The trends outlined above apply to both car manufacturers and suppliers, albeit at very different levels. In the case of car manufacturers (NAICS 3361), assembly workers even account for 75% of production workers (Table 2). The press and body shops are highly automated and employ few workers. The picture is different for suppliers. In this case, almost 33% of the production workers still work in metal production and processing occupations; here, too, however, 41% of the production workers are still working in assembly operations.

In the case of the Japanese occupational statistics (Table 3), it should be noted that the occupational designations tend to focus more on organizational areas and refer less to the specific function of the employees than is the case in the U.S. statistics. Furthermore, shop floor supervisors are not recorded as a separate category. However, very similar trends as in the USA are evident here.

- Assembly employment has remained largely stable in absolute terms and is gaining relative importance within the group of production workers. The share of assembly employment in Japan is significantly higher than in the USA, but note that it also includes shop floor supervisors. Given that the production teams in Japan are rather small (and the number of shop floor supervisors is accordingly high), the proportion of assembly workers is could be similar to American levels.

Table 3: Occupational composition of production workers in the Japanese automotive industry

	1995	2005	2010	2015
Total	629,300 (100%)	567,200 (100%)	553,600 (100%)	561,600 (100%)
Assembly workers (JSOC 51a-51f)	299,300 (47.6%)	352,400 (62.1%)	331,200 (59.8%)	351,000 (62.5%)
Metal Workers (JSOC 49a-49j/581-585)	241,700 (38.4%)	143,200 (25.2%)	156,000 (28.2%)	145,800 (26.0%)
Of which:				
Machine tool workers (JSOC 49d)	*29,900 (4.7%)*	*28,800 (5.1%)*	*19,600 (3.5%)*	*16,900 (3.0%)*
Metal press workers (JSOC 49e)	*27,300 (4.3%)*	*18,300 (3.2%)*	*12,700 (2.3%)*	*11,700 (2.1%)*
Welding process workers (JSOC 49i)	*24,200 (3.8%)*	*18,200 (3.2%)*	*15,300 (2.8%)*	*14,200 (2.5%)*
Machine inspection workers (JSOC 581-585)	*(included in other subcategories)*	*(included in other subcategories)*	*73,600 (13.3%)*	*71,700 (12.8%)*
Other Production Occupations	54,700 (8.7%)	44,500 (7.8%)	40,000 (7.2%)	37,700 (6.7%)
Of which:				
Painting workers	*19,700 (3.1%)*	*16,900 (3.0%)*	*15,900 (2.9%)*	*14,900 (2.6%)*
Maintenance and repair workers (JSOC 551-555)	28,400 (4.5%)	24,300 (4.3%)	26,300 (4.7%)	27,100 (4.8%)

Source: Author based on SBJ. Occupational categories based on 2015 JSOC. Major revisions of statistical classifications that limit the comparability of data are marked by bold lines.

- The share of employees in metalworking occupations has decreased. In contrast to the USA, however, the decrease has affected almost all occupations, including welding process workers (and painting workers). This trend was particularly marked in the years 1995–2005, but continued thereafter—although the data is difficult to interpret due to the introduction of a new occupation (the "machine inspection workers"[79]). Again, this suggests that the employment-relevant developments in the field of automation in recent decades have not affected manual work or substituted for it but rather have led to a greater digitalization of process control, which has led to automated metalworking equipment being operated by a smaller group of employees. The declining numbers of body shop workers, in contrast to the trend in the United States, could also be related to efforts to automate insertion activities using material-handling robots.

The proportion of maintenance workers in Japan is lower than in the United States, which is plausible in view of the greater integration of maintenance activities into the tasks of production teams (Adler 1995; Jürgens 2015). It is not possible to calculate a breakdown by car manufacturers and suppliers with the Japanese census data used here.

When seeking to interpret trends in occupational composition in the German automotive industry (Table 4), there are several challenges. The first difficulty is that the German statistics do not focus as clearly as the Japanese statistics on the organizational areas in which workers are employed (e.g., assembly, maintenance, etc.) and at the same time the occupations are much broader than in the American statistics. For example, it is not possible to pin down the group of assembly workers exactly. While the American and Japanese occupational statistics identify assembly workers as a separate group, this is not the case in Germany. In the analysis presented here, the following KldB1988 occupational groups were classified as assembly-related: machine and equipment assemblers, general assemblers, machine fitters, electrical equipment assemblers and helpers. In KldB2010, the new occupational classification introduced in 2010, the occupations have been grouped together to an even greater extent. Based on the equivalence tables for the transition from KldB1988 to KldB2010, the following occupations have been classified as assembly-related: not-specialized occupations in machine-building and operating occupations (*Maschinenbau- und Betriebstechnikberufe*), machinery and equipment assemblers (*Maschinen- und Gerätezusammenset-*

---

[79] "Machine inspection workers" is the term used by the SBJ to translate the Japanese category. This category is somewhat mysterious, given that it includes around half of all workers in metalworking occupations. According to the description provided by the SBJ, these workers are "engaged in the inspection of intermediate and final products in the production activities of various machines" (SBJ 2015). This could include quality control workers, but also the machine operators responsible for feeding and checking parts produced by the machines.

zer), technical occupations in the automotive industry (*Kraftfahrzeugtechnikberufe*), and occupations in electrical engineering (*Elektrotechnikberufe*). However, this classification is not very clear-cut: For example, the category of technical occupations in the automotive industry includes occupations that are common in assembly areas but also found in other areas. The same problem applies to maintenance activities—these cannot be precisely narrowed down. Here, the German statistics differentiate between specialized occupations in machinery and equipment assembly (technical service staff in maintenance and repair), mechatronics and automation technology, and technical occupations in the maintenance of electric machines. Again, the classification is not very clear-cut, because mechatronics technicians are a kind of universal occupation in the automotive industry and are used in maintenance but also in the operation of automated equipment.

The second major difficulty in interpreting the data relates to the two major statistical changes that took place between 2008 and 2012: There was a major revision of sector classifications and of occupational classifications. Therefore, in order to capture trends in occupational groups, the analysis considered developments between 1999 and 2007 and between 2013 and 2018 separately and only identified a general trend if both coincided.

- In general, it should be noted that, in the German automotive industry, the proportion of workers in assembly activities—as far as these can be narrowed down—is significantly lower than in the United States and Japan. This could be due to the shift of labor-intensive production processes (assembly) to the low-wage countries of Central and Eastern Europe in recent decades, particularly among automotive suppliers (Jürgens/Krzywdzinski 2009 and 2010; Krzywdzinski 2014; Schwarz-Kocher et al. 2019)—the slightly higher automation of assembly processes in German automotive plants compared with those Japan and the United States cannot explain this large difference. There is no clear trend in the share of assembly employment in the German automotive industry over the past 10–20 years.

Table 4: Occupational composition of production workers in the German automotive industry

	1999	2007	2013	2018
Total	394,200 (100%)	410,400 (100%)	458,800 (100%)	487,500 (100%)
Assembly-related occupations	113,100 (28.7%)	135,500 (32.9%)	163,800 (35.7%)	169,800 (34.7%)
Metal occupations	185,500 (47.0%)	180,300 (44.0%)	152,000 (33.1%)	161,300 (33.1%)
Of which:				
Metal-making occupations	*5,100 (1.3%)*	*4,500 (1.1%)*	*7,400 (1.6%)*	*7,700 (1.6%)*
Metalworking occupations	*93,800 (23.8%)*	*89,900 (21.9%)*	*68,700 (15.0%)*	*69,300 (14.2%)*
Occupations in metal constructing and welding	*59,900 (15.2%)*	*57,700 (14.0%)*	*25,900 (5.6%)*	*26,200 (5.4%)*
Precision mechanics and toolmaking	*13,600 (3.4%)*	*13,000 (3.2%)*	*12,700 (2.8%)*	*11,500 (2.4%)*
Plant and machine operators	*13,000 (3.3%)*	*14,600 (3.6%)*	*37,200 (8.1%)*	*46,500 (9.5%)*
Other production occupations	61,800 (15.7%)	60,400 (14.7%)	82,000 (17.9%)	91,000 (18.7%)
Of which:				
Color coating and varnishing	*20,600 (5.2%)*	*16,200 (3.9%)*	*12,300 (2.7%)*	*11,900 (2.4%)*
Technical occupations in quality control	*19,500 (4.9%)*	*21,400 (5.2%)*	*25,400 (5.5%)*	*26,100 (5.4%)*
Automation-related occupations: technical staff in maintenance, mechatronics, automation and control technologies	19,000 (4.8%)	19,200 (4.6%)	39,100 (8.5%)	43,400 (9.0%)
Supervisors in production	11,200 (2.8%)	11,400 (2.8%)	19,200 (4.1%)	19,000 (3.9%)

Source: Author based on BA. Major revisions of statistical classifications that limit the comparability of data are marked with bold lines.

- The metalworking occupations do not show a clear trend. However, there are clear shifts between different subgroups. The share of occupations in metalworking, welding and toolmaking is decreasing. At the same time, the proportion of machine and plant operators is increasing significantly. This could be related to technical changes, such as the automation of the remaining manual welding work or the insertion activities in car body construction. It could be also partly due to changes in the companies' reporting practices. There is a shift towards broader occupations (such as the mechatronics technicians) that are used across different company areas—it is possible that workers who were previously categorized in metalworking occupations (e.g., welders) are now classified as plant operators.
- The occupations in the field of maintenance/automation/mechatronics technology account for a higher share of employment than is the case in the United States and Japan. Throughout the entire period under consideration here, the share of these

automation-related occupations in the German automotive industry has increased. An explanation could be the increasing complexity of process technologies in the automotive industry, which German companies are responding to by modernizing occupational profiles and increasing manpower (Krzywdzinski 2020; Kuhlmann 2004).

The changing composition of the production workforce presented here applies equally to car manufacturers and car suppliers but at different levels (see Table 5). Assembly workers account for a significantly higher proportion of the production workforce at car manufacturers than at automotive suppliers, while the opposite is true for the metalworking occupations. This is due to the fact that central metalworking processes (casting, mechanical processing of parts and components, welding of parts and components) are carried out by suppliers rather than by the car manufacturers themselves. The metalworking processes at the automobile manufacturers (stamping, welding of the car body) have been highly automated for a long time, with the result that the assembly areas have a much larger share in terms of employment.

Table 5: Occupational composition of production workers in the German automotive industry in 2018

	Manufacturing of motor vehicles and engines (WZ2008 291)	**Manufacturing of vehicle bodies and trailers (WZ2008 292)**	**Manufacturing of motor vehicle parts and components (WZ2008 293)**
Total	232,500 (100%)	26,900 (100%)	228,100 (100%)
Assembly-related occupations	99,800 (42.9%)	10,000 (37.4%)	59,600 (26.1%)
Metal occupations	50,600 (21.8%)	9,800 (36.4%)	100,800 (44.2%)
Other production occupations	42,200 (18.1%)	4,300 (16.0%)	44,500 (19.5%)
Automation-related occupations	28,700 (12.4%)	1,400 (5.2%)	13,300 (5.8%)
Supervisors in production	10,500 (4.5%)	900 (3.2%)	7,700 (3.2%)

Source: Author based on BA.

As we explained above, the occupational composition does not provide any precise information about the share of skilled and semi-skilled workers. For the 1990s, there are case studies of German automobile factories (Schumann et al. 1994; Kuhlmann 2004) that provide information on the employment structures in the assembly areas and body shops. In the 1990s, automation had changed the structures in car body manufacturing significantly. At the beginning of the 1990s, 60–70% of the production workforce in car body shops performed manual work on the product (welding, surface treatment etc.); about 20–30% of the workforce consisted of semi-skilled machine operators and inserters and a maximum of 10% of the workforce was skilled workers operating automated equipment. In 2000, the workforce of modern body shops consisted of about 30% automated equipment operators (skilled workers), about 40–50% (often semi-skilled) machine operators and inserters, and 20–30% manual workers on the product (e.g., surface treatment and rework with a relatively high share of skilled workers) (Kuhlmann 2004: 245).

In assembly areas, at the end of the 1990s, up to 10% of the production workforce was skilled workers (mainly operators of automated equipment), about 25–40% upper-level semi-skilled workers (mainly machine operators and workers with more complex manual tasks), and about 25–40% lower-level semi-skilled workers (Kuhlmann 2004: 178).

Because automation levels in the body shop and in assembly only changed gradually, the associated structures have likely only changed at a slow pace. A slight increase in the proportion of skilled workers and a slight decrease in semi-skilled workers would be expected—due to the increasing complexity of the technologies and car manufacturers' recruitment practices. After all, these companies are attractive employers and can recruit workers with vocational training, even for jobs that do not necessarily require vocational training.

How can we summarize the findings of this section? In principle, there is little evidence in the employment data for the automotive industry since the 1990s that technological change has prompted an automation of manual activities in assembly. Assembly employment (along with, incidentally, logistics employment) has been astonishingly stable.

On the other hand, a slow decrease in manufacturing employment is evident in the occupations typical of highly automated areas, such as machine operation but also welding. This could be explained by the automation of the few remaining manual activities (e.g., the replacement of manual parts insertion by material handling robots), or by the increasing efficiency of digital process control techniques, which allow a smaller number of workers to operate ever bigger and more complex production processes.

6. Conclusions

The present study leads to a number of conclusions. Firstly, it should be emphasized that technological change in the automotive industry should not primarily be understood as entailing an increase in automation. From the 1990s to the 2010s, the automation levels in press shops, body shops, and mechanical processing remained stable and very high (often close to full automation)—at least if we disregard the latecomers to automation, especially among small and medium-sized enterprises. The major developments have been an ever-increasing complexity of technology, the combination of different materials, higher precision, and greater flexibility. In assembly processes, on the other hand, automation has remained relatively limited since the 1990s. These differences between assembly and body construction reflect the material and technical characteristics of the respective production processes.

This suggests that robot density indicator, which is currently very popular in research, should be treated with much more caution and circumspection—its value as an indicator of automation seems questionable. Since the 1990s, robot density in the automotive industry has tripled, but the levels of automation have remained largely the same.

The fixation on robots may also prompt us to overlook the fact that changes in employment structures has been driven less by production automation than by digitalization in the indirect areas of development, construction, or even planning. On the one hand, the use of digital tools has enormously reduced the effort required for calculations, simulations, and data exchange. At the same time, however, this has been more than compensated for by the rapidly increasing complexity of development and planning processes due to increasing model diversity, shorter model cycles, increasing component diversity, growing demands regarding safety and quality, and the globalization and fragmentation of logistics chains. These developments would not have been possible without digitalization. In recent years, electromobility and autonomous driving have added to the expansion of companies' development capacities. Knowledge work is gaining more and more importance in the automotive industry.

The historical analysis allows for some general considerations on the future of automation and digitalization.

- It shows that deriving automation potentials at the level of individual professions or tasks (e.g. Frey/Osborne 2013; Dengler/Matthes 2018) is only of limited use. Rather, the material and technical conditions of automation must be considered at the level of entire manufacturing processes. Individual assembly activities are surely highly routine, which is why Frey and Osborne (2013) expect a 98% probability that assembly workers will be threatened by automation. However, an examination of the assembly processes in the automotive industry shows that the diversity of individual activities as well as of part and model variants, the fluctuations in production volumes and product mix, and a manufacturing environment in which robots can only move with difficulty (e.g. the interior of the car) have so far provided very difficult conditions for assembly automation.

- The analysis of automation processes must also take into account the evolution of product architectures. This point has only been briefly addressed in the analysis presented here because there were no radical changes in product architectures in automotive engineering over the last two decades. Nevertheless, it is important to note that product architectures influence the ability to automate. To stay with the example of assembly, the shift from internal combustion engines to electric motors, for example, reduces the complexity of the automobile powertrain - this could facilitate the automation of assembly steps in the engine compartment.
- In addition, the products themselves are subject to major change. The abstract estimation of automation potentials at the level of occupations or tasks (Frey/Osborne 2013; Dengler/Matthes 2018) is based on a static model which ignores product changes. In the case of the automotive industry, the increasing demands on the quality and safety of cars drove the digitalization of processes and the development of new manufacturing technologies; the pressure to reduce vehicle weight due to rising environmental standards led to the use of new materials and in turn changed manufacturing processes; innovations in the area of drive technologies and the steps towards autonomous driving added even more complexity to the products. These developments have enormously increased the requirements in the field of product development and production planning, and digitalization has often meant providing the tools to cope with these new requirements. Certainly, some calculation and simulation processes have been automated - but at the same time the complexity of development and planning has increased so much that employment expanded considerably.

The second important conclusion of this study concerns the differences in the automation and digitalization approaches of the German, Japanese, and American automotive industries. The diversity of corporate strategies is often overlooked in the current discussion, which often assumes a universal and global trend of automation and digitalization. The industries in the three countries under study have exhibited different understandings and assessments of the performance, costs, and advantages of automation technologies. The German automotive industry has maintained its focus on high-tech automation and is driving technological developments in car body construction (such as laser technology, the use of new materials such as aluminum); it has persisted with its efforts to automate assembly (even if they have so far borne relatively little fruit); and it is one of the pioneers of the “Digital Factory.” Japanese companies have been somewhat more skeptical about technology and have attached great importance to the flexibility and the ability to control complexity in production. American companies, on the other hand, seem to be treating investment in manufacturing technology as of relatively subordinate importance at present. They went through a massive crisis in 2009 and have had to focus their resources particularly strongly on innovation topics such as electric mobility and autonomous driving. However, the weakness of U.S. carmakers in terms of organizational innovation could also play a role, which authors such as Helper and Henderson (2014) have attributed to rigid organizational structures and the lack of trust between actors within the companies (labor and management) and in industry (automobile manufacturers and suppliers).

This conclusion also leads to a general reflection on the future of automation and digitalization. It illustrates that there is a variety of development paths and that it is still open to what extent the path of an offensive digitalization and automation will prove successful at all. The pioneering role of the German automotive industry could be an advantage or could prove to be expensive overengineering - not for the first time, by the way (Jürgens/Naschold 1994).

To what extent can the effects of the respective automation and digitalization approaches on employment structures be identified? In principle, caution is advisable at this point because the descriptive approach of the analysis pursued here does not allow causal relationships to be identified.

The third major conclusion of this study is that in all three countries, employment in manual assembly activities has been surprisingly stable. There is little sign of a decrease in assembly employment. Over a long period of time, there is evidence of a decreasing share of employment in the occupations used in highly automated areas—typically in machine operation, but also in welding and painting activities. This may partly be the result of the automation of insertion activities by material handling robots. It also appears that increasing digitalization is enabling greater efficiency in the control, operation and maintenance of equipment.

It is evident that the investments in the digitalization of product development and planning, which can be considered collectively under the heading “digital factory,” have not been accompanied by a reduction in employment in engineering areas. On the contrary, especially in the case of the German automotive industry, which has invested particularly heavily in the digital factory, a massive increase in employment in engineering and computer-related occupations has been evident. Certainly, the increasing importance of electric mobility and autonomous driving technologies are doing their part to support growth in the employment of engineers and computer scientists.

As a fourth conclusion, it is important to emphasize the different employment dynamics in Germany, the United States, and Japan, which might reflect the differences in automation and digitalization approaches, but also different work models.

The German automotive industry is undergoing a long-term change: The share of blue-collar workers in total employment is declining; within the production workforce there is a shift towards higher shares of skilled workers; and the share of engineers and computer scientists is rising sharply. This can be seen as a continuation of the professionalization strategies that the German automotive industry has already used to respond to technological change in recent decades. The Japanese automotive industry has exhibited a similar, albeit somewhat slower, trend. By contrast, the employment structures in the American automotive industry appear to be frozen and the share of engineers and computer scientists is strikingly low, at least in comparison with Germany and Japan.

Some of these differences could be explained by the limitations of the statistics used here. For example, American companies have globalized their product development activities much more than their German and Japanese competitors. This explains a part of the differences between countries in the number of engineers. It is also quite probable that the changes in employment structures in the German automotive industry is not just due to technology or automation, but is linked to the massive relocation processes of production from Germany, especially to Central Eastern Europe (Jürgens/Krzywdzinski 2009, 2010)—yet, there is also no systematic comparison between the three countries studied in this instance, so it is not possible at this point to estimate the relative significance of the technical changes and the relocation of production. It is noteworthy, however, that in the case of the Japanese automotive industry, which has experienced much less relocation of production abroad, a change in employment structures comparable to Germany can also be observed (albeit a slower one). It should also be emphasized that the American industry has seen a marked shift of production to low-wage locations (in this case to Mexico), but the occupational composition of the workforce in the American automotive industry has remained remarkably stable. These developments could suggest that automation and digitalization approaches could be a driver of the employment changes described here, independently of the geographic restructuring of production networks.

The differences between the countries beg the question of which conclusions can be drawn with regard to the future competitiveness of the three countries examined here. The changes in employment structures in the German automotive industry point to an attempt on the part of the industry to build up its own competences with regard to digitalization and automation; by contrast, in the American automotive industry, the strategy of buying digitalization competences from external companies is emerging. This contradicts a thesis that has often been voiced in the public debate, namely that German industry is lagging behind its competitors in America and Asia with regard to digitalization.

However, the danger of over-engineering must be pointed out again. Moreover, the future of the automotive industry will not depend solely on automation and digitalization approaches. The development of future-proof products, i.e. sustainable vehicles adapted to modern mobility concepts, will be decisive. In the near future, this will not only mean a change towards electric mobility and autonomous driving, but also changes in the importance of individual ownership of vehicles. These are major strategic challenges that automotive companies must face.

7. References

Acatech (2015), *Smart Maintenance für Smart Factories,* München/Berlin: Acatech

Acatech/Forschungsunion (2013), *Umsetzungsempfehlungen für das Zukunftsprojekt Industrie 4.0.* Abschlussbericht des Arbeitskreises Industrie 4.0, München/Berlin: Acatech.

Acemoglu, Daron, & Restrepo, Pascual (2017), *Robots and jobs: Evidence from US labor markets*, NBER Working Paper No. 23285, Cambridge, MA: National Bureau of Economic Research.

Acemoglu, Daron, & Restrepo, Pascual (2018), *Artificial Intelligence, Automation and Work*, NBER Working Paper 24196, Cambridge, MA: National Bureau of Economic Research.

Adler, Paul (1988), Managing flexible automation. *California Management Review* 30(3): 34-56.

Adler, Paul (1995), 'Democratic Taylorism': the Toyota production system at NUMMI. In: Steve Babson (ed.). *Lean work: Empowerment and exploitation in the global auto industry.* Detroit: Wayne State University Press, pp. 207-219.

Adler, Paul, & Cole, Robert (1993), Designed for Learning: A Tale of Two Auto Plants. *Sloan Management Review* 34(3): 85-94.

Adler, Paul, Goldoftas, Barbara, & Levine, David I. (1999), Flexibility versus efficiency? A case study of model changeovers in the Toyota production system. *Organization Science* 10(1): 43-68.

Aksoy, Cevat Giray, Berkay, Ozkan, & Philip, Julia (2019), *Robots and the Gender Pay Gap: Evidence from Europe*, Paper presented at the 2nd IZA/CREA Workshop: Exploring the Future of Work, 5./6. December 2019, Bonn: IZA

Arntz, Melanie, Gregory, Terry, & Zierahn, Ulrich (2017), Revisiting the risk of automation. *Economics Letters* 159: 157-160.

Autor, David H., Levy, Frank, & Murnane, Richard J. (2003), The skill content of recent technological change: An empirical exploration. *The Quarterly Journal of Economics* 118(4): 1279-1333.

Baethge-Kinsky, Volker, Kuhlmann, Martin, & Tullius, Knut (2018), Technik und Arbeit in der Arbeitssoziologie – Konzepte für die Analyse des Zusammenhangs von Digitalisierung und Arbeit. *AIS-Studien*, 11(2): 91-106.

Berggren, Christian (1997), Advanced automation or alternative production design? A reflection on the new Japanese assembly plants and the alternative approach of Volvo Uddevalla. In: Koichi Shimokawa; Ulrich Jürgens, & Takahiro Fujimoto (eds.), *Transforming Automobile Assembly*. Berlin: Springer, pp. 335-343.

Boes, Andreas; Kämpf, Tobias; Gül, Katrin; Langes, Barbara; Lühr, Thomas; Marrs, Kira, & Ziegler, Alexander (2016), Digitalisierung und 'Wissensarbeit'. Der Informationsraum als Fundament der Arbeitswelt der Zukunft. *Aus Politik und Zeitgeschichte (APUZ)*, 66 (18-19): 32-39.

Boudette, Neal (2018), Inside Tesla's Audacious Push to Reinvent the Way Cars Are Made, *New York Times* 30.6.2018, https://www.nytimes.com/2018/06/30/business/tesla-factory-musk.html (12.5.2020).

Boyer, Robert, & Freyssenet, Michel (2000), *Productive Models. The Conditions of Profitability*, London: Palgrave Macmillan.

Braverman, Harry (1974), *Labor and Monopoly Capital*, New York: Monthly Review Press.

Brown, Stuart (2004), Toyota's Global Body Shop. *Fortune Magazine* 9.2.2004. Available at: https://archive.fortune.com/magazines/fortune/fortune_archive/2004/02/09/360102/index.htm (12.5.2020).

Bundesagentur für Arbeit (2010), *Beschäftigungsstatistik: Umstellung der Klassifikation der Wirtschaftszweige von WZ 2003 auf WZ 2008*, Nürnberg: Bundesagentur für Arbeit. Available at: https://statistik.arbeitsagentur.de/cae/servlet/contentblob/4370/publicationFile/116196/Methodenbericht-Beschaeftigungsstatistik-Umstellung-Klassifikation.pdf (12.5.2020).

Bureau of Labor Statistics (BLS) (2010), *What's New in the 2010 SOC*, Washington, DC: BLS. Available at: https://www.bls.gov/soc/soc_2010_whats_new.pdf (12.5.2020).

Butollo, Florian, Jürgens, Ulrich, & Krzywdzinski, Martin (2018), Von Lean Production zur Industrie 4.0. Mehr Autonomie für die Beschäftigten?. *Arbeits- und Industriesoziologische Studien* 11(2): 75-90.

Cacilo, Andrej, & Haag, Michael (2018), *Beschäftigungswirkungen der Fahrzeugdigitalisierung*, Study Nr. 406, Düsseldorf: Hans-Böckler-Stiftung.

Calabrese, Giuseppe (2001), R&D globalisation in the car industry. *International Journal of Automotive Technology and Management* 1(1): 145-159.

Carbonero, Francesco; Ernst, Ekkehard, & Weber, Enzo (2020), *Robots Worldwide: The Impact of Automation on Employment and Trade*, IAB Discussion Paper 7/2020, Nürnberg: IAB.

Chanaron, Jean-Jacques, & Lung, Yanick (1999), Product Variety, Productive Organization, and Industrial Models. In: Yannick Lung; Jean-Jacques Chanaron; Takahiro Fujimoto, & Daniel Raff (eds.), *Coping with Variety. Flexible Production Systems for Product Variety in the Auto Industry*, Aldershot: Ashgate, pp. 3-34.

Christensen, Clayton (1997), *The Innovator's Dilemma*, Boston: Harvard Business School.

Coffey, Dan, & Thornley, Carole (2006), Automation, motivation and lean production reconsidered. *Assembly Automation* 26(2): 98-103.

Cusumano, Michael (1985), *The Japanese automobile industry: Technology and management at Nissan and Toyota*, Cambridge, MA: Harvard University Asia Center.

Daimler (2020), „Factory 56". Mercedes-Benz Cars steigert Flexibilität und Effizienz in der Produktion. Available at: https://www.daimler.com/innovation/produktion/factory-56.html (12.5.2020).

Daito, Eisuke (2000), Automation and the Organization of Production in the Japanese Automobile Industry: Nissan and Toyota in the 1950s. *Enterprise & Society* 1(1): 139-178.

Dengler, Katharina, & Matthes, Britta (2018), The impacts of digital transformation on the labour market: Substitution potentials of occupations in Germany. *Technological Forecasting and Social Change* 137: 304-316.

Director General for Policy Planning (Statistical Standards) (2007), *Japan Standard Industrial Classification* (Rev. 12, November 2007). Historical Background and Revision, Tokyo: Ministry of Internal Affairs and Communications, Available at: https://www.soumu.go.jp/english/dgpp_ss/seido/sangyo/san07-1.htm (12.5.2020).

Director General for Policy Planning (Statistical Standards) (2009), *Comparison Table of Groups*, Tokyo: Ministry of Internal Affairs and Communications, Availalbe at: https://www.soumu.go.jp/main_content/000327410.pdf (12.5.2020).

Director General for Policy Planning (Statistical Standards) (2013), *Japan Standard Industrial Classification* (Rev. 13, October 2013). Historical Background and Revision, Tokyo: Ministry of Internal Affairs and Communications, Available at: https://www.soumu.go.jp/english/dgpp_ss/seido/sangyo/san13-1.htm (12.5.2020).

Evers, Maren, Krzywdzinski, Martin, & Pfeiffer, Sabine (2019), Wearable Computing im Betrieb gestalten. Rolle und Perspektiven der Lösungsentwickler im Prozess der Arbeitsgestaltung. *Arbeit – Zeitschrift für Arbeitsforschung, Arbeitsgestaltung und Arbeitspolitik* 28(1): 3-27.

Florida, Richard, & Kenney, Martin (1991), Transplanted organizations: The transfer of Japanese industrial organization to the US. *American Sociological Review* 56(3): 381-398.

Florida, Richard, & Kenney, Martin (1994), The globalization of Japanese R&D: the economic geography of Japanese R&D investment in the United States. *Economic Geography* 70(4): 344-369.

Fraunhofer Institut für Produktionstechnik und Automatisierung (IPA) (1988), *Fortschritte in der Montage*, Dokumentation der 19. IPA-Arbeitstagung, Stuttgart: Fraunhofer IPA.

Frey, Carl Benedikt, & Osborne, Michael (2013), *The Future of Employment*, Oxford: Oxford Martin School.

Freyssenet, Michel (1999), Competitive strategies, industrial models and assembly automation templates. In: Anna Comacchio; Giuseppe Volpato, & Arnaldo Camuffo (eds.), *Automation in Automotive Industries*, Berlin: Springer, pp. 31-45.

Fujimoto, Takahiro (1992), *Why Do Japanese Companies Automate Assembly Operations?*, Discussion paper for the Berlin Workshop on Assembly Automation, Berlin (WZB), November 1992, Available at: http://www.cirje.e.u-tokyo.ac.jp/research/dp/92/f15/dp.pdf (12.5.2020)

Fujimoto, Takahiro (1997), Strategies for Assembly Automation in the Automobile Industry. In: Koichi Shimokawa; Ulrich Jürgens, & Takahiro Fujimoto (eds.), *Transforming Automobile Assembly*, Berlin: Springer, pp. 211-237.

Fujimoto, Takahiro (2000), Shortening Lead Time through Early Problem Solving – A New Round of Capability-building Competition in the Auto Industry. In: Ulrich Jürgens (ed.), *New Product Development and Production Networks*, Berlin: Springer, pp. 23-53.

Giordano, Lorraine (1992), *Beyond Taylorism. Computerization and the New Industrial Relations*, Basingstoke: Macmillan.

Goolsbee, Austan, & Krueger, Alan (2015), A Retrospective Look at Rescuing and Restructuring General Motors and Chrysler. *Journal of Economic Perspectives* 29(2): 3-24.

Graetz, Georg, & Michaels, Guy (2018), Robots at work. *Review of Economics and Statistics* 100(5): 753-768.

Groshen, Erica, Helper, Susan, MacDuffie, John Paul, & Carson, Charles (2019), *Preparing U.S. Workers and Employers for an Autonomous Vehicle Future*, Upjohn Institute Technical Report No. 19-036. Kalamazoo, MI: W.E. Upjohn Institute for Employment Research.

Günther, Georg, Benisch, Michael, Dankl, Andreas, & Isopp, Jutta (2015), *Roadmap der Instandhaltung 4.0*. Salzburg: Salzburg Research.

Helper, Susan, & Henderson, Rebecca (2014), Management Practices, Relational Contracts, and the Decline of General Motors. *Journal of Economic Perspectives* 28(1): 49-72.

Heßler, Martina (2014), Die Halle 54 bei Volkswagen und die Grenzen der Automatisierung. Überlegungen zum Mensch-Maschine-Verhältnis in der industriellen Produktion der 1980er-Jahre. *Zeithistorische Forschungen* 11(1): 56-76.

Hirsch-Kreinsen, Hartmut (2018), Einleitung: Digitalisierung industrieller Arbeit. In: Hartmut Hirsch-Kreinsen; Peter Ittermann, & Jonathan Niehaus (eds.), *Digitalisierung industrieller Arbeit: die Vision Industrie 4.0 und ihre sozialen Herausforderungen*. Baden-Baden: Nomos, pp. 13-32.

Hirsch-Kreinsen, Hartmut, & ten Hompel, Michael (2015), Digitalisierung industrieller Arbeit: Entwicklungsperspektiven und Gestaltungsansätze. In: Birgit Vogel-Heuser; Thomas Bauernhansl, & Michael ten Hompel (eds.), *Handbuch Industrie 4.0*, Berlin: Springer, pp. 1-20.

Hsieh, L.-H., Schmahls, T., & Seliger, G. (1997), Assembly Automation in Europe – Past Experience and Future Trends. In: Koichi Shimokawa; Ulrich Jürgens, & Takahiro Fujimoto (eds.), *Transforming Automobile Assembly*, Berlin: Springer, pp.19-37.

IFR (2019), World Robotics 2019, Frankfurt am Main: IFR.

Ingrassia, Paul, & White, Joseph (1994), *Comeback: the fall and rise of the American automobile industry*, New York: Simon & Schuster.

Jürgens, Ulrich (1995), Group work and the reception of Uddevalla in German car industry. In: Ake Sandberg (ed.), *Enriching Production. Perspectives on Volvo's Uddevalla Plant as an Alternative to Lean Production*, Aldershot: Avebury, pp. 199-216.

Jürgens, Ulrich (2015), Lean production. In: David Guest, & David Needle (ed.), *Wiley Encyclopedia of Management*, Vol. 5 (Human Resource Management), Hoboken, NJ: Wiley, pp. 1-3, https://doi.org/10.1002/9781118785317.weom050138.

Jürgens, Ulrich (2020), *Arbeit und Automatisierung in der Automobilindustrie* [Manuskript, im Erscheinen].

Jürgens, Ulrich (ed.) (1997), *New Product Development and Production Networks*, Berlin: Springer.

Jürgens, Ulrich, & Krzywdzinski, Martin (2009), Changing East-West Division of Labour in the European Automotive Industry. *European Urban and Regional Studies* 16(1): 27-42.

Jürgens, Ulrich, & Krzywdzinski, Martin (2010), *Die neue Ost-West-Arbeitsteilung. Arbeitsmodelle und industrielle Beziehungen in der europäischen Automobilindustrie*, Frankfurt/New York: Campus.

Jürgens, Ulrich, & Krzywdzinski, Martin (2016), *New Worlds of Work. Varieties of Work in Car Factories in the BRIC Countries*, Oxford: Oxford University Press.

Jürgens, Ulrich, & Meißner, Heinz-Rudolf (2005), *Arbeiten am Auto der Zukunft,* Berlin: sigma.

Jürgens, Ulrich, & Naschold, Frieder (1994), Arbeits- und industriepolitische Entwicklungsengpässe in der deutschen Industrie in den neunziger Jahren. In: Zapf, Wolfgang (ed.), *Institutionenvergleich und Institutionendynamik*, Berlin: sigma, pp. 239-270.

Jürgens, Ulrich, Malsch, Thomas, & Dohse, Knuth (1988), *Moderne Zeiten in der Automobilfabrik*, Berlin: Springer.

Jürgens, Ulrich, Malsch, Thomas, & Dohse, Knuth (1993), *Breaking from Taylorism. Changing Forms of Work in the Automobile Industry*, Cambridge: Cambridge University Press.

Jürgens, Ulrich, Wilhelm, Miriam; Ishida, Mitsuo, & Nakamura, Keisuke (2012), *Ein Vergleich der Personalsysteme bei Volkswagen und Toyota*, Berlin: WZB [unpublished report].

Katz, Harry, MacDuffie, John Paul, & Pil, Frits (2013), Crisis and recovery in the US auto industry: Tumultuous times for a collective bargaining pacesetter. In: Howard Stanger; Paul Clark, & Ann Frost (eds.), *Collective Bargaining Under Duress: Case Studies of Major North American Industries*, Champaign, IL: Labor and Employment Research Association, pp. 45-80.

Kern, Horst, & Schumann, Michael (1984), *Das Ende der Arbeitsteilung*, München: C.H. Beck.

Klier, Thomas, & Rubenstein, James (2010), The changing geography of North American motor vehicle production. *Cambridge Journal of Regions, Economy and Society* 3(3): 335-347.

Klier, Thomas, & Rubenstein, James (2012), Detroit back from the brink? Auto industry crisis and restructuring, 2008-11. *Economic Perspectives* 36(2): 35-54.

Kobayashi, Hideo, Yingshan, Jin, & Schroeder, Martin (2015), ASEAN economic community and the regional automotive industry: impact of ASEAN economic integration on two types of automotive production in Southeast Asia. *International Journal of Automotive Technology and Management* 15(3): 268-291.

Krafcik, John (1988), Triumph of the Lean Production System. *Sloan Management Review* 30(1): 41-52.

Krzywdzinski, Martin (2014), How the EU's Eastern Enlargement Changed the German Productive Model. The Case of the Automotive Industry. *Revue de la Régulation – Capitalisme, Institutions, Pouvoir* 15(1): 1–61.

Krzywdzinski, Martin (2016), *Technologie, Qualifikationen und international Arbeitsteilung. Anmerkungen zu der Diskussion über Industrie 4.0*. WZB Discussion Paper SP III 2016-301. Berlin: WZB.

Krzywdzinski, Martin (2017), Automation, Skill Requirements, and Labour-Use Strategies. High-wage and Low-wage Approaches to High-tech Manufacturing in the Automotive Industry. *New Technology, Work and Employment* 32(3): 247-267.

Krzywdzinski, Martin (2019), Globalisation, Decarbonisation and Technological Change. Challenges for the German and CEE Automotive Supplier Industry. In: Béla Galgóczi (ed.), *Towards a Just Transition. Coal, Cars and the World of Work*, Brussels: European Trade Union Institute, pp. 215-241.

Krzywdzinski, Martin (2020), Alternative Models of Lean Production: Germany. In: Thomas Janoski, & Darina Lepadatu (Hg.), *The International Handbook of Lean Production*, Cambridge: Cambridge University Press [forthcoming].

Krzywdzinski, Martin, & Ulrich Jürgens (2019), Transfer deutscher und japanischer Ansätze der Facharbeiterausbildung an die BRIC-Standorte. Volkswagen und Toyota im Vergleich. In: Michael Gessler; Martina Fuchs, & Matthias Pilz (eds.), *Konzepte und Wirkungen des Transfers Dualer Berufsausbildung*, Wiesbaden: Springer VS, pp. 281-319.

Kuhlmann, Martin (2004), *Modellwechsel. Die Entwicklung betrieblicher Arbeits- und Sozialstrukturen in der deutschen Automobilindustrie*, Berlin: sigma.

Kuka (2016), *Matrix-Produktion: Ein Beispiel für Industrie 4.0*, Augsburg: Kuka, Available at: https://www.kuka.com/de-de/branchen/loesungsdatenbank/2016/10/solution-systems-matrix-produktion (12.5.2020)

Lamming, Richard (1996), Squaring lean supply with supply chain management. *International Journal of Operations & Production Management* 16(2): 183-196.

Lara, Arturo, & Carrillo, Jorge (2003), Technological globalization and intra-company coordination in the automotive sector: the case of Delphi-Mexico. *International Journal of Automotive Technology and Management* 3(1): 101-121.

Lechowski, Grzegorz, & Krzywdzinski, Martin (2019), *Governing "digital transformation" through transnational technological standards*. Paper presented at the SASE Annual Conference, 27-29 June 2019, The New School, New York City.

Leitner, Peter (1999), Japan's post-war economic success: Deming, quality, and contextual realities. *Journal of Management History* 5(8): 489-505.

Liker, Jeffrey (2004), *The Toyota Way. Fourteen management Principles from the World's Greatest Manufacturer*, New York: McGraw-Hill.

Liker, Jeffrey, Fleischer, Mitchell, Nagamachi, Mitsuo, & Zonnevylle, Michael (1992), Designers and their Machines: CAD Use and Support in the US and Japan. *Communications of the ACM* 35(2): 77-95.

Liker, Jeffrey; Haddad, Carol, & Karlin, Jennifer (1999), Perspectives on Technology and Work Organization. *Annual Review of Sociology* 25: 275-596.

MacDuffie, John Paul (2013), Modularity-as-Property, Modularization-as-Process, and Modularity-as-Frame: Lessons from Product Architecture Initiatives in the Global Automotive Industry. *Global Strategy Journal* 3(1): 8-40.

MacDuffie, John Paul, & Helper, Susan (1997), Creating lean suppliers: diffusing lean production through the supply chain. *California Management Review* 39(4): 118-151.

MacDuffie, John-Paul, & Pil, Frits (1997), From Fixed to Flexible: Automation and Work Organization Trends from the International Assembly Plant Study. In: Koichi Shimokawa; Ulrich Jürgens, & Takahiro Fujimoto (eds.), *Transforming Automobile Assembly*, Berlin: Springer, pp. 238-254.

MacKenzie, Donald, & Judy Wajcman (1985), *The Social Shaping of Technology*, Milton Keynes: Open University Press.

MacPherson, Alan, & Vanchan, Vida (2010), The Outsourcing of Industrial Design Services by Large US Manufacturing Companies. *International Regional Science Review* 33(1): 3-30.

Malsch, Thomas (1987), Die Informatisierung des betrieblichen Erfahrungswissens und der „Imperialismus der instrumentellen Vernunft“. *Zeitschrift für Soziologie* 16(2): 77-91.

McKinsey (2016), *Automotive revolution – perspective towards 2030*, New York: McKinsey.

McLoughlin, Ian (1989), CAD – The ‘Taylorisation’ of drawing office work? *New Technology, Work & Employment* 4(1): 27-39.

McLoughlin, Ian (1990), Management, Work Organisation and CAD – Towards Flexible Automation? *Work, Employment & Society* 4(2): 217-237.

Milkman, Ruth, & Pullman, Cydney (1991), Technological change in an auto assembly plant: The impact on workers” tasks and skills. *Work and Occupations* 18(2): 123-147.

Mudambi, Ram, & Helper, Susan (1998), The ‘close but adversarial’ model of supplier relations in the US auto industry. *Strategic Management Journal* 19(8): 775-792.

Niimi, A.; Matsudaira, Y. (1997), Development of a New Vehicle Assembly Line at Toyota: Worker-oriented, Autonomus, New Assembly System. In: Koichi Shimokawa; Ulrich Jürgens, & Takahiro Fujimoto (eds.), *Transforming Automobile Assembly*, Berlin: Springer, pp. 82-93.

Noble, David (1979), Social Choice in Machine Design: The Case of Automatically Controlled Ma-chine Tools. In: Andrew Zimbalist (ed.), *Case Studies on the Labor Process,* New York: Monthly Review Press, pp. 18–50.

Nof, Shimon (2009), Automation: What It Means To Us Around the World. In: Shimon Nof (ed.), *Springer Handbook of Automation*, Berlin: Springer, pp. 13-52.

Okamuro, Hiroyuki (2000), CAD/CAM Utilization Patterns in japan and Germany. In: Ulrich Jürgens (ed.), *New Product Development and Production Networks*, Berlin: Springer, pp. 407-424.

Petersen, Peter (1999), Total quality management and the Deming approach to quality management. *Journal of Management History* 5(8): 468-488.

Pfeiffer, Sabine (2019), Produktivkraft konkret. Vom schweren Start der Leichtbauroboter. In: Florian Butollo, & Sabine Nuss (eds.), *Marx und die Roboter*, Berlin: Dietz, pp. 156-177.

Rammert, Werner (1999), Produktion von und mit „Wissensmaschinen“. Situation sozialen Wandels hin zur „Wissensgesellschaft“. In: Konrad Wilfried, & Wilhelm Schumm (eds.), *Wissen und Arbeit. Neue Konturen von Wissensarbeit*. Münster: Westfälisches Dampfboot, pp. 40-57.

Ro, Young K., Liker, Jeffrey K., & Fixson, Sebastian K. (2007), Modularity as a strategy for supply chain coordination: The case of US auto. *IEEE Transactions on Engineering Management* 54(1): 172-189.

Rothfelder, Jeff (2017), *At Toyota, the automation is human-powered*, Available at: https://www.fastcompany.com/40461624/how-toyota-is-putting-humans-first-in-an-era-of-increasing-automation (12.5.2020).

Rothstein, Jeffrey (2016), *When Good Jobs Go Bad. Globalization, De-Unionization, and Declining Job Quality in the North American Auto Industry*, New Brunswick: Rutgers University Press.

Rubenstein, James (2002), *The changing US auto industry: A geographical analysis*, London: Routledge.

Salerno, Mario Sergio (2001), The characteristics and the role of modularity in the automotive business. *International Journal of Automotive Technology and Management* 1(1): 92-107.

Salzmann, Harold (1989), Computer-Aided Design: Limitations in Automating Design and Drafting. *IEEE Transactions on Engineering Management* 36(4): 252-261.

Sandberg, Ake (1994), *Enriching Production. Perspectives on Volvo's Uddevalla plant as an alternative to lean production*, Aldershot: Avebury.

Schmitt, Bertel (2019), *Inside Toyota's Takaoka #2 Line*, Available at: https://www.thedrive.com/tech/26955/inside-toyotas-takaoka-2-line-the-most-flexible-line-in-the-world (12.5.2020).

Schulz-Schaeffer, Ingo (2008), *Technik als Gegenstand der Soziologie*, TUTS-Working Paper 3-2008, Berlin: Technische Universität Berlin.

Schumann, Michael, Baethge-Kinsky, Volker, Kuhlmann, Martin, Kurz, Constanze, & Neumann, Uwe (1994), *Trendreport Rationalisierung – Automobilindustrie, Werkzeugmaschinenbau, Chemische Industrie*, Berlin: sigma.

Schwarz-Kocher, Martin, Krzywdzinski, Martin, & Korflür, Inger (eds) (2019), *Standortperspektiven in der Automobilzulieferindustrie. Die Situation in Deutschland und Mittelosteuropa unter dem Druck veränderter globaler Wertschöpfungsstrukturen*, Düsseldorf: Hans-Böckler-Stiftung.

Shaiken, Harley (1984), *Work Transformed: Automation and Labor in the Computer Age*, New York: Holt, Rinehart, and Winston.

Shibata, Hiromochi (2009), A comparison of the roles and responsibilities of manufacturing engineers in Japan and the United States. *International Journal of Human Resources Management* 20(9): 1896-1913.

Spath, Dieter, Ganschar, Oliver, Gerlach, Stefan, Hämmerle, Moritz, Krause, Tobias, & Schlund, Sebastian (2013), *Produktionsarbeit der Zukunft-Industrie 4.0*, Stuttgart: Fraunhofer Verlag.

Statistics Bureau of Japan (2015), *Classification of occupations used for the 2015 census (Heisei 27-nen kokuseichōsa ni mochiiru shoku-gyō-bun-rui)*, Tokyo: SBJ.

Statistisches Bundesamt (2003), *Klassifikation der Wirtschaftszweige mit Erläuterungen* Ausgabe 2003, Wiesbaden: Statistisches Bundesamt, Available at: https://www.destatis.de/DE/ Methoden/Klassifikationen/Gueter-Wirtschaftsklassifikationen/Downloads/klassifikation-wz-2003-erlaeuterung.pdf?__blob=publicationFile (12.5.2020).

The Newswheel (2019), *GM's Cruise Automation Plans to Hire More Than 1,000 New Employees*, Available at: https://thenewswheel.com/gms-cruise-automation-plans-to-hire-more-than-1000-new-employees/) (12.5.2020).

VDA (2015), *Automotive Entwicklungsdienstleistung. Zukunftsstandort Deutschland*. Materialien zur Automobilindustrie Nr. 48. Frankfurt am Main: VDA.

Volkswagen (2019), *Volkswagen mit neuer Software-Einheit*, Available at: https://www.volkswagenag.com/de/news/2019/06/volkswagen-with-new-software-unit.html (12.5.2020).

Volkswagen (2020), *High-Tech am laufenden Band*, Available at: https://id3.vw-newsroom.com/de/high-tech-am-laufenden-band-5537 (12.5.2020).

Wajcman, Judy (2006), New connections: social studies of science and technology and studies of work. *Work, Employment and Society* 20(4): 773–786.

Wilkesmann, Uwe (2005), Die Organisation von Wissensarbeit. *Berliner Journal für Soziologie* 15(1): 55-72.

Williams, Karel, Haslam, Colin, & Williams, John (1992), Ford versus Fordism: The Beginning of Mass Production?. *Work, Employment and Society* 6(4): 517-555.

Womack, James, Jones, Daniel, & Roos, Daniel (1991), *The Machine That Changed the World. The Story of Lean Production*, New York: Harper Perennial.

8. Appendix: Additional Information on the Data Sources

Press Articles

The first major data source for the analysis is articles from the German industry journal *Automobil Produktion*. The analysis included all articles since 1992 that dealt with developments in automation and process technology as a core topic. A total of 393 articles were identified. In addition, the research involved searching for articles on the online platforms *Automation World* and *Automotive Manufacturing Solutions* using the keywords “automation” and the names of the American car manufacturers. The search resulted in 20 articles in *Automation World* and 21 in *Automotive Manufacturing Solutions* that dealt mainly with automation strategies. Japanese magazines and online platforms could not be researched due to the language barrier. As an alternative, a general online search was carried out for general reports on developments at the Japanese flagship manufacturer Toyota. In the end, five articles that offered comprehensive background reports were identified. The 439 articles found were each briefly summarized with regard to the most important keywords and statements. The contents were then evaluated according to organizational areas (assembly, body shop, press shop, paint shop, indirect areas), technology, and countries.

Statistics of the International Federation of Robotics

For Germany and Japan, the required information could be obtained directly from the IFR database. In the case of the USA, the data before 2016 had to be recalculated. The reason for this is that the IFR database does not show the stock of industrial robots for the USA until 2004, and the data up to and including 2015 is incorrect and much too low.[80] The U.S. robot figures have been recalculated using the IFR’s estimates of robot density in the US automotive industry, which the IFR reports in its print publications.

---

[80] The stock of industrial robots is calculated by the IFR based on information on new installations. When making this calculation, the IFR assumes a robot lifespan of 12 years. Because the IFR database only began providing information on new installations of robots in the United States from 2004 onwards, the information on robot stocks only meets the standard from 2016. The information on robot stocks for 2004 are, conversely, identical to the number of new installations for the year 2004; the total number of robots for 2004 equals the sum of new installations for 2004 and 2005, etc. This implies that the stock of industrial robots before 2004 was zero, which is, of course, entirely false. We informed the IFR statistics department of this error but have not received any substantive response in this regard.

With regard to the data for Japan, it should be noted that the definition of industrial robots was only harmonized between the IFR and the Japanese Robot Association (JARA) in 2000.

As a general rule, the information on robot stock is an estimate. The stock of industrial robots is calculated by the IFR on the basis of new installations in the past twelve years—in other words, a robot's service life of twelve years is assumed. As the IFR (2019: 22) itself states, the typical service life could also be higher, at around 15 years. In the experience of the author, however, the IFR could also be overestimating the service life of industrial robots, at least in the case of the automotive industry, since it is not uncommon for car manufacturers to replace production equipment when changing product generations—and a product generation is typically in production for well below 12 years.

Employment Statistics

A basic problem of the statistics used here is the changes in the underlying classification systems. These are explained in more detail here.

For the United States, data from the Occupational Employment Statistics (OES) of the Bureau of Labor Statistics (BLS) are used. Since the 1990s, there have been a number of changes in the underlying classification systems of the OES. With regard to occupational statistics, a major revision took place in 1999 when the Standard Occupational Classification (SOC) was introduced. In 2010, the revised SOC 2010 was introduced, but for 90% of all occupations and for the occupational categories relevant to this paper, the only revisions that were made were editorial in nature and did not substantially change the occupational content (BLS 2010). With regard to the industry coding system, a major revision took place in 2002. Prior to 2002, the Standard Industrial Classification (SIC) was used; in 2002, there was a switch to the North American Industry Classification System (NAICS), which was accompanied by substantial changes in the classification of establishments. This paper uses data from 1999 onwards, but it should be noted that in the case of the United States, the data before 2002 are not fully comparable with the later years.

For Japan, the Population Census of the Statistics Bureau of Japan (SBJ) is used. In the case of Japan, too, there were some changes in statistical concepts during the period under review. For occupational coding, the Japan Population Census uses the Japan Standard Occupational Classification (JSOC), which underwent two revisions during the period covered by this study, in 1997 and in 2009. While the 1997 revision was more editorial in character as far as the occupational groups discussed here are concerned, the 2009 revision brought about a considerable reorganization of occupations, resulting in a discontinuity in the data (Director General for Policy Planning (Statistical Standards) 2009). The present study has attempted to compensate for these discontinuities by comparing the classifications at the level of the individual occupations, although the comparability of the data remains somewhat limited. The Japan Standard Industrial Classification (JSIC) was used for the industrial classification for the years 1995–2015. In the period under review, the JSIC was revised in 2002, 2007 and 2013, but this did not imply any major changes with regard to the automotive industry (Director General for Policy Planning (Statistical Standards) 2007 and 2013).

The data for the case of the German automotive industry are from the Federal Employment Agency (BA). Since the 1990s, there have also been a number of changes in the underlying classification systems in Germany. In the case of occupational statistics, a fundamental change took place in 2012, from the Classification of Occupations Edition 1988 (KldB1988) to the Classification of Occupations Edition 2010 (KldB2010). The two classifications differ considerably in their systematics and the definition of individual occupations. Using the BA's tables of equivalence, this study attempted to achieve the most accurate possible fit of the data by matching at the level of individual occupations. However, the change in the classification represents such a large break that it limits the comparability of the data before and after 2012.

Table A1: Industry and occupational classifications in the data sets used

	Industry coding	**Occupational coding**
USA: Occupational Employment Statistics	1999–2001 SIC 2002–2018 NAICS	1999–2018 SOC
Japan: Population Census	1995–2015 SIC	1995–2005 JSOC 2010–2015 JSOC (major revision)
Germany: Employment statistics of the Federal Employment Agency	1999–2008 WZ1993, WZ2003 2008–2018 WZ2008	1999–2011 KldB1988 2013–2018 KldB2010

There were also changes in industrial classification during the period under review. In 2003, the Classification of Economic Activities 1993 (WZ1993) was replaced by the Classification of Economic Activities 2003 (WZ2003); however, this was a "careful update" of the classifications and, in the case of the automotive industry, did not involve any major shifts (Federal Statistical Office 2003). The Classification of Economic Activities 2003 (WZ2003) was in turn replaced by the Classification of Economic Activities 2008 (WZ2008) in 2008. In the case of the automotive industry considered here, the change meant that, according to WZ2003, some 74,000 of the 887,000 employees were reallocated to other economic sectors (mainly mechanical engineering and plant construction) and 133,000 employees who had previously been allocated mainly to the manufacture of IT technology, metal production, and rubber and plastic products were now allocated to the automotive industry. Overall, the composition of employment in the automotive industry thus changed by about 14% (Bundesagentur für Arbeit 2010). In particular, the changeover to WZ2008 brought about a shift that somewhat limits the comparability of the data.