**International Journal of Automotive Technology and Management**

ISSN online: 1741-5012 - ISSN print: 1470-9511
https://www.inderscience.com/ijatm

# Industry 4.0 and lean augmentation? Digital transformation in the German and Japanese automotive industry

Martin Schröder, Takefumi Mokudai, Hajo Holst

**DOI:** 10.1504/IJATM.2024.10068681

**Article History:**

| | |
|---|---|
| Received: | 24 July 2024 |
| Last revised: | 06 November 2024 |
| Accepted: | 08 November 2024 |
| Published online: | 28 January 2025 |

# Industry 4.0 and lean augmentation? Digital transformation in the German and Japanese automotive industry

## Martin Schröder*

College of Policy Science,
Ritsumeikan University,
2-150 Iwakura-cho, Ibaraki-shi,
Osaka 567-8570, Japan
Email: m-schroe@fc.ritsumei.ac.jp
*Corresponding author

## Takefumi Mokudai

Faculty of Economics,
Kyushu University,
744 Motooka, Nishi-ku,
Fukuoka 819-0395, Japan
Email: mokudai.takefumi.076@m.kyushu-u.ac.jp

## Hajo Holst

Institute of Social Sciences,
University of Osnabrück,
Seminarstraße 15,
49074 Osnabrück, Germany
Email: haholst@uni-osnabrueck.de

**Abstract:** This paper explores digital transformation trajectories in the German and Japanese automotive industry based on case studies. Cases include both follow-up investigations of previously analysed cases and additional cases. Previous research on digitalisation in both countries observed that German and Japanese automotive firms follow distinct patterns of utilising digital technologies which can be stylised as bottom-up experimentation in Japan and top-down implementation in Germany. This investigation finds that some firms encounter issues with bottom-up experimentation and implement top-down initiatives to counteract arising issues. Further, it is found that firms deviate from national patterns, suggesting that factors besides nationality influence digital transformation approaches.

**Keywords:** automotive industry; digitalisation; digital technologies; digital transformation; Industry 4.0; lean production; lean augmentation; multiple-case study; Germany; Japan.

**Reference** to this paper should be made as follows: Schröder, M., Mokudai, T. and Holst, H. (2024) 'Industry 4.0 and lean augmentation? Digital transformation in the German and Japanese automotive industry', *Int. J. Automotive Technology and Management*, Vol. 24, No. 6, pp.1–27.

**Biographical notes:** Martin Schröder is an Associate Professor at the College of Policy Science, Ritsumeikan University, Japan and Visiting Researcher at the Research Institute of Automobile and Parts Industries, Waseda University, Japan. His research interests are regional economic integration in ASEAN, the political economy of the automotive industry, and digitalisation in the automotive industry.

Takefumi Mokudai is a Professor at the Faculty of Economics at Kyushu University, Japan. He received his PhD from Hiroshima University, Japan (2001). His current research topics include the interaction of digitalisation and lean production, the strategic flexibility in R&D investments, and the new business creation from the academia-industry collaboration.

Hajo Holst is a Professor for Sociology at the Institute for Social Sciences at Osnabrück University, Germany. He has conducted several projects on the transformation of work and economy. His current research topics include the dynamics of digitalisation and decarbonisation in the car industry, the long-term effects of the COVID pandemic on the world of work, work and migration as well as the socio-ecological transformation of agriculture.

This paper is a revised and expanded version of a paper entitled 'Do varieties of digitalisation matter? From Industry 4.0 in Germany and lean augmentation in Japan towards digital transformation' presented at the 32nd International Colloquium of GERPISA, Bordeaux, 25–28 June 2024.

## 1 Introduction

Digitalisation has been a topic for the automotive industry for at least a decade. It has occupied the industry under distinct labels such as Industry 4.0, digital technology-based business models such as mobility-as-a-service (MaaS), and more recently digital transformation (hereafter: DX). This sequence is peculiar as the concept of DX predates those of Industry 4.0 and MaaS.

This paper focuses on digitalisation in the German and Japanese automotive industries. More specifically, this study aims to examine how firms in Germany and Japan utilise digital technologies and how local context interact with digitalisation approaches to influence DX trajectories. Previous research suggests that firms in both countries follow rather particular approaches to utilise digital technologies (Holst et al., 2020; Mokudai et al., 2021). This paper is mainly aiming to investigate dynamic developments over time, especially since the COVID-19 pandemic occurred after the aforementioned research was conducted.[1] Longer-term study is important as Mokudai and colleagues (2021) have identified potential long-term issues with the Japanese approach of lean augmentation, suggesting that Japanese firms may have to alter their approach to address said issues. Therefore, follow-up investigations help to clarify if said issues manifest and how firms deal with said manifestations. Similarly, the German approach to Industry 4.0 has been criticised for being overly focussed on automation and self-regulating systems, overlooking the importance of workers for keeping these production processes operational (Pfeiffer, 2016) and being contradicted by increasing product variety which at least in the automotive industry still requires human workers to handle different products and their production processes flexibly (Jürgens, 2023).

This paper is structured as follows: Section 2 will review literature on digitalisation in general and in the automotive industry in particular. Section 3 outlines the research methodology. Section 4 provides an overview over the research findings which are discussed in Section 5. Finally, Section 6 summarises the research findings and their implications for future research.

## 2 Literature review

### *2.1 Digital transformation and Industry 4.0*

The literature on DX predates the literature on digitalisation of industry embodied by concepts such as Industry 4.0 or the internet of things (IoT). While early contributions seldomly sought to define DX, it was rather claimed and described how digital technologies enabled business transformation.[2] Despite the absence of definitions, early contributions analysed well how digital technologies could transform business. Andal-Ancion and colleagues (2003) observed that digital technologies could be used to implement novel and different forms of mediation. Concretely, classic disintermediation means that technology is used to basically cut out middlemen to conduct business directly with customers, remediation means that technology is used to interact with middlemen more intensely to create additional value for customers, and network-based mediation means that digital technologies are used to create a network of actors which creates some kind of value for participants and/or customers. Berman (2012) proposed a model to explain different pathways of digital transformation approaches. One path focuses on the creation and integration of digital operations before addressing the customer value proposition later. Another path focuses on changing the value proposition using digital technologies before considering how to integrate digital operations. The third path is to address operations and value proposition simultaneously. By what may be regarded as a reinterpretation of Berman's (2012) model against an organisational background, it has been claimed that DX has four dimensions relevant for any business, namely the use of technologies, changes in value creation, structural changes, and financial aspects (Matt et al., 2015).

Differing from the preceding DX literature, the concept of Industry 4.0, which was first expressed in 2011, has a rather strong emphasis on automation, optimisation of production, and process improvement (Kagermann et al., 2013; Thoben et al., 2017). Industry 4.0's emphasis on this narrow range of operational aspects was so strong that some researchers argued that the full potential of digital technologies could only be realised if it included aspects such as innovation and novel business models (Calabrese and Falavigna, 2022). In essence, these authors argued for a return to the broader DX perspective which had outlined operational improvements as one of its aspects besides the creation of new or refined value propositions, and which had stressed that both aspects should be combined to achieve DX.

Regarding DX implementation, Verhoef and colleagues (2021) observed that few scientific works have addressed the question which growth strategies incumbent firms should use when digitally transforming. Further, several studies (Moeuf et al., 2018; Müller et al., 2018; Masood and Sonntag, 2020) have emphasised DX issues, especially for small- and medium-sized enterprises (SMEs). However, a recent literature review found research to be mostly limited to German cases, conceptual, and lacking foundation in primary data (Mittal et al., 2018).

## *2.2 Automotive industry: Industry 4.0, lean augmentation, and digital transformation*

Digitalisation as a potential enabler of refined value propositions has been studied in the automotive industry. Mostly, studies suggested that business model innovation could result in car sharing, ride sharing, or ride hailing services (Frank et al., 2019; Lasmar et al., 2019; Rachinger et al., 2019) as alternatives to the traditional business model of selling cars to owner-users. Other researchers have highlighted the potential positive environmental impacts of such sustainable mobility business models (Cohen and Kietzmann, 2014). However, recent studies show that car sharing is not profitable (Lagadic et al., 2019) and ride sharing/hailing firms such as Lyft or Uber lost billions in their attempts to establish global mobility service platforms. Thus, while there certainly are digital technology-based business models that seek to challenge the business model of incumbent carmakers, these business models still need to proof their economic viability.

Numerous studies have addressed digitalisation in the automotive industry along the lines of Industry 4.0, mostly exploring operations, including its (expected) effects on productivity and employment (Calabrese and Falavigna, 2022; Moniz and Candeias, 2022), profitability (Sommer et al., 2021), or national industry (Llopis-Albert et al., 2021). It should be noted that most of these studies present evidence that digitalisation is progressing rather slowly and often lacks significant impact on productivity or employment. Pfeiffer (2016) presents case study evidence that strongly suggests that even highly automated production lines inside and outside the automotive industry require experienced workers to keep these lines operational. In his recent monograph on the history of automation in the automotive industry, Jürgens (2023) highlights the incremental nature of past automation processes and emphasises that attempts toward full automation were regularly contradicted by increasing product variety which demands flexible operations.[3] Similarly, Pardi (2019) asserts that the automotive industry is rather undergoing gradual change and not an industrial revolution.

Another stream of research observed distinct patterns of digitalisation approaches. Most researchers have emphasised a mixture of national and firm characteristics, frequently including distinct conceptualisations of lean production (Holst et al., 2020; Krzywdzinski, 2021a, 2021b; Mokudai et al., 2021; Moro and Virgillito, 2022). Still others argue that these different conceptualisations in Germany and Japan can be explained through differing Varieties of Capitalism (Schröder et al., 2024). Mokudai and colleagues (2021) argue that Japanese automotive firms mainly utilise digital technologies along the lines of their lean production practices and hence dub this approach lean augmentation. Against the background of the preceding discussion on DX, their findings show that Japanese automotive firms mainly use digital technologies to optimise operations. Business model innovation through digital technologies is of lesser importance.

What is missing from current studies is the time dimension of digitalisation efforts in Germany and Japan. Although studies increasingly call for the study of DX, there are few studies that study such transformations over time. A notable exception is Carbonell's (2020) sociological study on the introduction of a digitised production line at PSA's Mulhouse plant in France. Our study seeks to address digitalisation and DX trajectories by revisiting some firms previously studied as well as expanding the scope of the study to additional German and Japanese cases. Further, previous research on Japanese cases was conducted before the COVID-19 pandemic started. As various studies have documented this pandemic as a significant factor for the acceleration of digitalisation of work and workplaces in Germany (Krzywdzinski et al., 2022; Delicat et al., 2024), a first glance at the impact of the pandemic on digitalisation in Japan can be taken. While the number of case firms that could be revisited and studied is admittedly limited, conducting investigations over a longer time horizon helps to explore DX-related issues and firm responses. Further, our research is based on primary data and thus departs from survey-based identification of DX implementation issues towards description of actual DX implementation cases from Germany and Japan.

## 3 Methodology

The study uses a multiple-case research design. As the usage of digital technologies is still a rather novel phenomenon and the aim of the research is to investigate how firms utilise digital technologies in Germany and Japan, and how local context interacts with digitalisation, using a case study design is an appropriate research approach [Yin, (2018), p.9]. Further, in multiple-case research design seeks to elaborate on a phenomenon, all cases must share a common characteristic or condition, which is sometimes referred to as the quintain (Stake, 2006). According to Stake (2006, p.23), a multiple-case research design thus should select cases based on three questions:

- Is the case relevant to the quintain?
- Do the cases provide diversity across contexts?
- Do the cases provide good opportunities to learn about complexity and contexts?

This approach is compatible with theoretical sampling (Eisenhardt, 1989), which also emphasises that cases should share some criteria to allow meaningful comparisons and analysis. For our study, the quintain is digitalisation in the automotive industry. This quintain is expanded as we asked all firms to elaborate on the relationship between digitalisation and production in line with previous studies (Holst et al., 2020; Mokudai et al., 2021). Our cases provide diversity across contexts as they contain firms of different sizes, two different countries with differing institutional arrangements, different positions in the value chain, and different interpretations of lean production. These differences allow us to learn about how their position in the value chain, size or firm strategy influences their approach to deploying digital technologies. To analyse empirical observations, it applies a classification pattern developed by Mokudai and colleagues (2021).

Regarding the choice of study subject, Germany and Japan have been chosen for the following reasons. First, the automotive industry of both countries is of outstanding importance for the national economy. Second, Japan is the origin of production management techniques popularised as lean production (Womack et al., 1990).

Findings from field research in Germany and Japan are reported. Field research in Japan was conducted in 2022 and 2024, because the COVID-19 pandemic only allowed two on-site visits during 2022. In three cases, field research was conducted at firms that had been investigated in 2019 (Holst et al., 2020; Mokudai et al., 2021), meaning that it was possible to investigate developments and challenges which can be divided into pre- and post-COVID-19 pandemic settings. Visits contained interviews and plant tours except for two cases. Basic information about case firms is summarised to document the variety of firms within the sample (Table 1). Regarding the classification of our findings, we employ a classification developed by Mokudai and colleagues (2021) who differentiated digitalisation efforts in three areas (operations, kaizen, and HR development) with a total of 12 subareas. Following this classification pattern allows us to document changes over time in some studied cases. Visits lasted between 3 and 7 hours. Only in one case it was possible to interview shop floor staff and company union representatives. Field research in Germany was conducted during spring 2023 (Table 2). Studied case firms all are connected to the automotive industry, including four original equipment manufacturers (OEM), one construction machinery manufacturer, six first-tier supplier, one precision measurement device producer which mainly supplies automotive firms, and a start-up firm specialising in digital shopfloor management. Firm visits lasted between 2.5 and 6 hours. In all German cases except the start-up, visits included factory tours which lasted between 1 and 2 hours. In most German cases, interviewees belong to management and works councils, in two cases roundtable discussions with representatives from both parties could be conducted. Further, we conducted interviews with IG Metall, the most significant union in the German automotive sector, and with the Japan Council of Metalworkers' Unions (JCM) to better understand organised labour's perspective on DX issues.

**Table 1** Overview of studied firms

| *Firm* | *Headquarters* | *Type* | *Products* | *Number of employees* |
|---|---|---|---|---|
| A | Germany | OEM | Vehicles | 104,400 |
| B | Japan | OEM | Vehicles | 30,770 |
| C | Germany | Supplier | Chassis components, clutches, E-axles | 168,700 |
| D | Germany | OEM | Vehicles | 684,000 |
| E | Germany | Start-up | Digital shopfloor management tools | 10 |
| F | Germany | Supplier | Precision measuring equipment | 1,760 |
| G | Japan | OEM | Vehicles | 380,800 |
| H | Japan | Supplier | Body parts, exhaust system | 10,617 |
| J | Japan | Supplier | Tyres | 7,705 |
| K | Japan | OEM | Construction machinery | 2,151 |
| L | Japan | Supplier | Metal stampings (door, exhaust system, and production tools) | 1,928 |
| M | Japan | Supplier | Metal parts | 432 |

**Table 2** Overview of interview location and interviewees

| *Firm* | *Country* | *Interviewees* | *Factory visit* | *Date* |
|---|---|---|---|---|
| A | Germany | Head of digitalisation, senior manager (digital transformation and shopfloor planning), manager (guided vehicles), manager (in-plant AGV) | O | 13 Mar. 2023 |
| | Japan | Head of logistics, senior manager (logistics), Manager (logistics), manager (production line), managers A&B (logistics service provider (external)) | O | 27 Jul. 2022 |
| | | Manager (logistics), manager (plant automation), company union vice president and company union executive committee member | O | 28 Feb. 2024 |
| B | Japan | Plant manager, senior manager (production) | O | 24 Nov. 2022 |
| C | Germany | Plant manager, manager (production engineering), manager (HR), manager (R&D), manager (logistics), works council chairperson, works councillor (senior analyst) | O | 7 Mar. 2023 |
| D | Germany | Head of digitalisation, manager (production engineering), manager (shift leader), head of plant works council | O | 8 Mar. 2023 |
| E | Germany | Manager (customer support and implementation) | X | 9 Mar. 2023 |
| F | Germany | Vice president (head of global production system) | O | 10 Mar. 2023 |
| G | Japan | Project general manager (assembly division), general manager A (production engineering), general manager B (human resources), group manager (human resources) | O | 21 Nov. 2019 |
| | | General manager (DX), project general manager (DX) | X | 22 Feb. 2024 |
| H | Japan | Chief officer (production centre), deputy chief officer (production centre) | O | 26 Feb. 2024 |
| J | Japan | General manager (tyre business), general manager (sales), general manager (sales west japan), general manager (OE relations) | O | 27 Feb. 2024 |
| K | Japan | Factory general manager, general manager (global IT), manager (fabrication system), manager (global IT), manager (DX system), manager (manufacturing IoT), manager (works technical section), manager (IT) | O | 29 Feb. 2024 |
| L | Japan | Division manager (engineering), general manager (advanced engineering centre), 2x manager (advanced engineering manager), assistant manager (advanced engineering centre) | O | 13 Nov. 2019 |
| | Japan | Division manager (engineering), general manager (advanced engineering centre), 2x manager (advanced engineering manager), assistant manager (advanced engineering centre) | O | 1 Mar. 2024 |

Note: O – factory tour conducted; X – factory tour not conducted.

**Table 2** Overview of interview location and interviewees (continued)

| *Firm* | *Country* | *Interviewees* | *Factory visit* | *Date* |
|---|---|---|---|---|
| M | Japan | Chief technology officer, chief consultant | X | 20 Nov. 2019 |
| | | CEO | X | 26 Feb. 2024 |

Note: O – factory tour conducted; X – factory tour not conducted.

Instead of following the proposed research agenda of Verhoef and colleagues (2021) that seeks to formulate prescriptions (what strategies incumbent firms *should* use), we merely seek to formulate descriptions (what strategies incumbent firms *actually* use) that may inform firms, collective actors such as business associations, unions, or public sector actors about potential applications of digital technologies. This research strategy is influenced by Hirsch-Kreinsen's (2019) finding that the utilisation of digital technologies is highly path-dependent and therefore idiosyncratic. Highly path-dependent implementation suggests that firms either address specific needs or deal with specific constraints, meaning that a prescription-oriented research approach is either too generic or suggesting solutions that cannot be implemented by many firms. Further, while the research contrasts context-specific aspects at the national level, it also highlights aspects which are non-conforming with the national tendency at the firm level. Following Pfeiffer and colleagues (2024), this contrasting approach is chosen to indicate complexities, inconsistencies, and non-simultaneity of DX processes.

It seems necessary to expound problems of our research methodology. There are two methodological caveats that influence the analysis of our results. First, we explicitly draw on previous round of field research in Japan which was conducted before the COVID-19 pandemic. Regarding the impact of the pandemic, several Japanese cases reported that digitalisation in general, i.e., not just in manufacturing and immediately related functions such as logistics, became more prominent. This included more flexible forms of work. Second, the difference in time is exacerbated by another major transformation in the automotive sector, namely powertrain electrification. As powertrain electrification is completely changing the vehicle energy source and powertrain, it marks the departure from the industries long-enduring dominant design centred on the internal combustion engine (ICE) [Alochet et al., (2023), p.67]. Hence, electrification led to investments into completely new production lines which allow firms to follow a greenfield approach[4]. One consequence of this shift is that we visited several production lines which are not only using digital technologies but also produce electric vehicle (EV) components. As EV components have a significantly lower product variety in comparison to functionally similar ICE components, this arguably supports a tendency towards (digital) automation as lower product variety also means that individual stations will experience lower variability in option content. As high variability in option content is typically addressed through relatively greater labour use (number of operators assigned to a station) (Fisher and Ittner, 1999), lower variability in option content induced by lower product variety makes automation more attractive for firms as the need for flexibility, typically the strength of human operators over machinery and robots, is decreasing.

So far, possibilities to study similar production lines in Japan were limited. Partly, this is due to the fact that several Japanese carmakers are more hesitant towards EVs, especially battery electric vehicles (BEVs).

Thus, digitalisation and powertrain electrification may be regarded as independent but conflating trends. While it is too early to make claims with certainty, electric powertrain production may become more highly automated than ICE powertrain production as the properties of the product technology allow it.

## 4 Observations

### *4.1 Context differences between the German and Japanese automotive industry*

Before presenting findings from specific cases, we want to highlight factors which distinguish the context of German and Japanese cases. First, as discussed in the preceding section, the German automotive industry is more proactive in the shift to BEVs. This effort means that German firms are substantially changing both the product and its production process. Comparatively, Japanese OEMs are less united in the question of transitioning to EVs.

Second, labour is a factor that strongly differentiates Germany and Japan. In Germany, the fear that (digital) automation and the transition to BEVs will reduce employment was common. In Japan, labour shortage and labour qualification were important topics. Labour shortage takes two forms. The first form is a general lack of Japanese who are willing to work in manufacturing. The rapidly aging workforce and Japan's aging society mean that only few young Japanese could fill this void. Thus, firms increasingly resort to non-Japanese workers to fill open job postings. Another issue is a specific shortage of employees with digital skills. Especially for suppliers, hiring IT experts is difficult as those people prefer to work in other industries and in metropolitan areas. It should be added that JCM interviewees pointed out labour shortages and their support for digital automation to potentially keep employment in Japan instead of overseas outsourcing.

Regarding labour qualification, most firms resort to a mixture of internal training and commercial online courses. Regarding the latter, several firms indicated that they would prefer more tailored courses and hence consider developing internal curricula. Regarding internal training, firms seek to develop skills inside their firms for their specific purposes and needs, which is in line with theoretical perspectives on the organisation of Japanese capitalism (Schröder et al., 2024).

Table 3 summarises the findings of our multiple-case study. The table follows a classification pattern developed for a previous study (Mokudai et al., 2021) to allow comparison over time in a limited number of Japanese cases. The overview suggests significant differences between German and Japanese cases, for instance in maintenance.

**Table 3** Summary of multiple-case study findings

| *Firm* | | *A* | | *B* | *C* | *D* | *F* |
|---|---|---|---|---|---|---|---|
| *Type* | | *OEM* | | *OEM* | *Supplier* | *OEM* | *Supplier* |
| *Location* | | *GER* | *JPN* | *JPN* | *GER* | *GER* | *GER* |
| Operations | Processing | | x | | | O | |
| | Assembly | | | O | O | | x |
| | Inspection | O | | O | O | x | |
| | Inventory and logistics | O | O | O | | O | |
| | Maintenance | O | O | x | O | O | |
| | Production planning and control | x | x | O | x | x | |
| Kaizen | Data collection | O | O | O | O | O | |
| | Data analysis | x | | O | x | x | |
| | Solution generation | | | | | x | |
| | Implementation | | | | | | |
| HR development | HRD by digital technologies | x | x | | O | | x |
| | HRD for digital technologies | O | x | O | O | O | |
| *Firm* | | *G* | *H* | *J* | *K* | *L* | *M* |
| *Type* | | *OEM* | *Supplier* | *Supplier* | *OEM* | *Supplier* | *Supplier* |
| *Location* | | *JPN* | *JPN* | *JPN* | *JPN* | *JPN* | *JPN* |
| Operations | Processing | | O | O | O | O | O |
| | Assembly | | O | | O | O | |
| | Inspection | O | | O | O | x | |
| | Inventory and logistics | O | | | O | O | |
| | Maintenance | O | | | | O | O |
| | Production planning and control | | O | x | O | O | |
| Kaizen | Data collection | O | O | O | O | O | O |
| | Data analysis | O | O | O | O | O | O |
| | Solution generation | | | | O | O | O |
| | Implementation | | | | | | |
| HR development | HRD by digital technologies | | O | O | | x | |
| | HRD for digital technologies | O | O | O | | O | O |

Notes: O – digital technologies are in use (IoT, CPS, AI, etc.; excluding conventional information and communication technologies, such as barcodes, e-kanbans, LCD andons).
x – under study or experimentally implemented.
*Firm E has been excluded as it provides software tools for other firms but does not deploy them in its own operations.

## *4.2 Digital transformation trajectories of Japanese firms*

In two cases, plants in Japan studied in 2019 could be re-examined in 2024 (Tables 4 and 5). Another Japanese firm studied in 2019 could also be investigated again, but the visit was limited to the firms newly established DX office.

**Table 4** Digital transformation trajectory of firm M

| | | *2019* | *2024* |
|---|---|---|---|
| Operations | Processing | x | X |
| | Assembly | | |
| | Inspection | | |
| | Inventory and logistics | | |
| | Maintenance | X | X |
| | Production planning and control | | |
| Kaizen | Data collection | X | X |
| | Data analysis | X | X |
| | Solution generation | | |
| | Implementation | | |
| HR development | HRD by digital technologies | | |
| | HRD for digital technologies | X | X |

While the graphical representation in Table 4 suggests that there may have been limited progress in M's digitalisation effort, this is not the case. While the areas of use cases have not expanded, use cases have been added. For example, data collection was expanded as the supplier started to track and visualise energy consumption of machinery since 2021. Collecting hourly data from machines was implemented, including *net* (or better: processing) *power*, *stop* (or better: downtime) *power*, and *standby power*. This format made it immediately clear when electricity would be used outside working hours and illustrate the waste of electricity. M's conceptualisation is based on Toyota's idea of *net work* (*shoumi sagyou*) which emphasises that only work which adds value is important, everything else is either necessary but not value addition or simply waste. Consequently, *net power* should be maximised and *stop power* and *standby power* should be reduced as much as possible.

The visualisation of energy consumption allowed to identify various countermeasures, including complete shutdowns or standby operations (of machinery with long warm-up). These measures allowed to reduce electricity consumption by 26% in only four months. This example shows that data collection was expanded towards areas that are not necessarily covered by traditional *kaizen*. Further, it demonstrates that it is important to choose the 'correct' format to visualise problems, i.e., the problem of electricity waste only becomes visible if hourly electricity consumption is monitored.

Overall, firm M is a representative of lean augmentation as digital technologies are used to address specific issues in production. Furthermore, as Table 4 indicates, the area of digitalisation efforts may be limited to several activities but can nevertheless be effective in economic terms.

**Table 5** Digital transformation trajectory of firm L

| | | *2019* | *2024* |
|---|---|---|---|
| Operations | Processing | X | X |
| | Assembly | X | X |
| | Inspection | x | x |
| | Inventory and logistics | | X |
| | Maintenance | x | X |
| | Production planning and control | | X |
| Kaizen | Data collection | X | X |
| | Data analysis | x | X |
| | Solution generation | | X |
| | Implementation | | |
| HR development | HRD by digital technologies | | x |
| | HRD for digital technologies | | X |

Firm L has the explicit vision to operate an unmanned production facility, ideally 24 h per day on 365 days per year. As Table 5 indicates, use of digital technologies in various new application realms occurred since 2019. For one of its door assembly lines, several automation measures were introduced. The line is fed by autonomous mobile robots[5] (AMRs) which withdraw, transport, and load necessary palletised inputs from an automated warehouse. Several in-line quality checks have been automated with digital technologies, but final quality inspection is still conducted by an operator. While the firm aims to fully automate quality inspection, it was stated that this was challenging. Table 6 compares the older door assembly lines against the new, digitally automated line.

**Table 6** Comparison between old and new door assembly lines of firm L

| | *Old lines* | *New line* |
|---|---|---|
| Cycle time | 52 sec | 50 sec |
| Operators | 5 | 1 |
| Changeover time | 150 sec | 60 sec |
| Parts palletising | Manned | Unmanned |
| Number of robots | 32 | 79 |

*Source:* Interview with firm L

The comparison between the lines documents the effect of digital automation in this application. Line speed increased slightly, and changeover time decreased significantly. This is important as the line is capable of assembling doors for five different car models. The number of robots more than doubled and the number of operators was reduced by 80%. Further, as the line involves fewer workers, it can be built more compactly, decreasing the space required by about 20%.

In the realm of *kaizen*, progress between 2019 and 2024 mainly lies in visualisation for data analysis. While visualisation was a main area of activity in 2019, it has been deployed in 2024. For instance, key performance indicators (KPIs) are displayed for all machines in the die shop. Regarding the effect of automated data collection and visualisation, it was stated that one person would spend 490 h per year with data collection and entry previously and that automated collection and visualisation reduced this time to 300 h per year. The reason why humans are still needed for this task is that automated collection can only be performed for commonly used and known indicators. However, as problem analysis for *kaizen* also requires inquiry into issues that involve novel issues and their related indicators, automation reduces human effort but does not eliminate it fully.

L started to use digital twin to simulate the creation of an additional assembly line[6] at a German subsidiary. According to interviewees, one benefit of the digital twin was that it allowed dynamic simulation of related indicators (such as inter-process inventory volume and its space requirements against sufficient space for safe worker movement).

Despite the proactive use of digital technologies, firm L provides a clear example of still existing limitations of said technologies. It produces production tools such as press dies. Said dies must be calibrated for each press individually. Even if L and a customer have an identical press model, these presses will have unique quirks that can lead to differing production results between presses. Thus, even if a press is simulated based on firm L data, the identical press model at a customer may 'behave' differently. Thus, firm L lamented that it was still necessary to dispatch staff to each customer to jointly set up customer presses to achieve desired production results. Hence, it may be said that the problem is that a simulation treats identical press models as perfect replicas, while no such thing as a prefect replica exists in reality.

Regarding a refined value proposition through digital technology, L's case illustrates difficulties. An overseas subsidiary specialised in tooling proposed to OEM customers to share data on tools, including machinery data of these customers. Key idea behind this proposal was that production machinery has unique quirks which lead to different production results. Thus, exchanging data would allow firm L to conduct analyses and simulations not just based on their production machinery, but also on those of customers. This may allow reducing time and manpower demand for calibrating production tools at customer plants. According to interviewees however, this suggestion was rejected by customers due to concerns over leakage of confidential data. Thus, DX is not just a problem of refining value propositions but if customers regard these propositions as valuable (and safe).

Regarding the Japanese approach to engage DX through internal training, L illustrates potential issues to this approach. One is that firms hardly hire additional staff to master DX. Instead, existing staff should acquire needed competences for this transformation. In L's case, this means that responsibilities for learning about digital technologies or managing DX processes are added to existing tasks. This can lead to overburdening of individuals. A manager of firm L stated that Japan simply lacked a job description approach, which lead to the situation that management concluded that DX staff had too many tasks. However, instead of increased hiring, L planned to involve more staff in DX, some in roles focussed on promotion and planning of DX and some in roles that focussed on executing DX.

What is remarkable about L is that it highlights that not all Japanese firms follow a lean augmentation approach. Its pursuit of an unmanned production facility rather corresponds to the vision of Industry 4.0, highlighting that while country-specific factors and patterns exist, these do not determine firm behaviour and strategy. Simultaneously, the case has clear Japanese characteristics in the realm of qualification where its approach of internal training encounters issues of overburdening individuals tasked with spearheading DX efforts.

### *4.3 Lean augmentation? Towards systematic deployment of digital technologies and issues with digital transformation of business models*

In this subsection, we present cases from Japan that illustrates the lean augmentation approach practiced by several Japanese firms as well as cases which deviate from this approach. Further, we describe the DX activities of a German firm in Japan.

Firm B engaged digitalisation rather late and displays many aspects of lean augmentation. According to interviewees, digitalisation was only strategically addressed since 2021. However, the OEM employed numerous digital technologies in its digitalisation model plant which was reopened in 2022 after extensive modernisation. Renovation included the introduction of new assembly lines. Further, the plant's paint shop was completely new, marking a shift from a worker-operated paint shop to a robotised paint shop without workers. Firm B's case highlights some characteristics of lean augmentation.

First, it clearly approached digitalisation from the perspective of its production system, very much in line with what Mokudai and colleagues (2021) called lean augmentation. Specifically, the carmaker uses Ohno's (1988) renowned definition of seven kinds of waste (*muda*) and identified digital technologies which could help to address each kind of *muda* (Table 4).

**Table 4** Types of muda and digital technology solutions

| *Type of muda* | *Digital technology to address muda* |
|---|---|
| Over processing | Automated inspection |
| Defects | Predictive maintenance |
| Waiting | Zero defects |
| Motion | Autonomous robots |
| Transportation | Logistics automation |
| Inventory | Operational optimisation |
| Overproduction | Management automation |

*Source:* Based on firm B presentation documents

To address the connection between *muda* and digital technology, a few examples should be explained. Regarding overproduction, firm B seeks to utilise AI, business intelligence, and model-based development to visualise waste in production and product development. As many production-related data used to be collected and stored in local databases, the networking of existing databases as well as connecting them to analytical tools is a step to automate parts of production management. As visualisation of waste is an integral part of lean which inter alia has been formalised as value stream mapping (Rother and Shook, 2009; Martin and Osterling, 2014), novel technologies are used to support and augment lean production. Regarding defects, they are a waste because they use materials and energy to make items that cannot be used in production but must be scrapped. As defects can be caused by production equipment that is not well maintained or calibrated, predictive maintenance is used to address these issues. Predictive maintenance uses data of production machinery to predict when a process is going to need maintenance in order to keep turning out products that meet product specifications[7]. Finally, excessive inventory may be addressed through digitalisation. For instance, the OEM used to print product information in paper catalogues. In the past, every time minor product modifications were made, new product information was printed and outdated catalogues disposed. By abandoning paper catalogues and replacing them with entirely web-based catalogues disposal of outdated print materials is no longer necessary.

These examples demonstrate that firm B is not influenced by any sort of vision such as Industry 4.0. Instead, it evaluates digital technologies through the lens of its established production system and management philosophy. By asking how a novel technology helps to minimise unwanted *muda*, firm B subjugates technologies to existing lean management logic. This may be regarded as an example of how an institutionalised mindset at the firm-level interacts (or not) with a foreign vision of digitalisation. Apparently, firm B's conceptualisation of lean production immunises it against techno-deterministic and techno-optimistic visions.

This however does not mean that firm B does not utilise digital technologies. The renovated plant features camera-vision-based machine learning (ML) for automating press part inspection and in-station inspection processes as well as camera-vision and sensor-based final inspection (speed, brake, emission, leakage, shower, and hammering tests, plus tire model and tire pressure check). While applications are strongly concentrated in assembly and inspection, this may be explained by firm B's described strategic emphasis on minimising cost and *muda*. Thus, the OEM seems to only deploy digital technologies when they allow to achieve cost or time savings.

Overall, firm B takes a highly pragmatic approach to digitalisation. First, this is expressed by clearly subjecting digital technology deployment to lean production grounded evaluation. Thus, while the OEM clearly utilises novel technologies, they are framed and interpreted against the existing lean philosophy. Second, interviewees stated that technology and human operators must work together to achieve improved results. By emphasising that some inspection tasks still required human sensitivity to touch and smell, one manager expressed the idea that digital technologies were sophisticated tools which however could not match human senses.

Firm H is another representative case for lean augmentation. While novel technologies are utilised, the DX effort is remarkable as it caused the firm to reconsider current practices. For instance, its internal review found that time gaps between issuing and receiving *kanban* amounted to three days. To address this gap, firm H is in the process of introducing a digitised *kanban* system. Starting from shipping operations in 2023, the system is introduced in assembly operations in 2024 and should be extended to press operations in 2025. So far, this reformed *kanban* system has eliminated a control room and *kanban* board so that information from shipping is now directly linked to production lines. Eliminating the two stages of control room and *kanban* board resulted in 16 h time savings. While this reform is part of H's DX effort, we have *not* identified it as use of novel digital technologies since our methodology does not consider e-*kanban* as being novel. Nevertheless, firm H's case is noteworthy as it demonstrates that firms can achieve remarkable time savings within their processes by engaging DX even if they use older technologies.

Further, firm H is representative of lean augmentation as it enhanced existing production machinery with sensors to collect data on production (output, parts number, machine downtime/line stoppage, delay). These data – representative of the digital shadow – are aggregated in the plant's control office. While the control office used to rely on handwritten information from the shopfloor for tasks such as production control, production planning, and material purchase planning, the digitised data collection now greatly reduces the manpower and time requirements for these tasks. While it took around four hours to collect data on a single line, this time has been greatly reduced. Furthermore, as firm H operates five other plants near the visited plant, it plans to network data from all these plants in the future to establish more centralised control and to explore the possibility to treat these six plants as an integrated network. This idea dubbed 'virtual one factory' certainly indicates that Japanese firms are pursuing more centralised control. However, it must be mentioned that the interviewed managers expressed that more centralised control could lead managers to distance themselves from the *gemba* (literally 'real place', meaning shopfloor). However, they emphasised that the Toyota production system was the basis for the system they seek to create which means to them that *all employees* should participate in the maximisation of value-added, not just managers (potentially out of touch with the *gemba*).

The case of firm G demonstrates the limitations of the lean augmentation approach particularly well. Informants mentioned that one of their biggest issues was the proliferation of local, i.e., plant-specific, applications of digital technologies. While many applications are solutions to real-world issues on a particular shopfloor, firm G's digitalisation office seeks to promote standards to allow firm-wide assessments and more importantly *kaizen*. Without a standard, the implementation of *kaizen* becomes impossible as only the standard allows the quantification of improvements. Thus, while the bottom-up approach helped to engage G's workforce in the DX and produce quick gains, the lack of a systematic vision and approach means that firms at some point must introduce standards to enable systematic improvements via *kaizen*. Thus, while the previous approach was largely bottom-up experimentation with novel technologies, findings indicate a top-down effort towards standardisation.

German firm A's operations in Japan provide examples that country-specific factors matter. Although firm A formulated a DX vision in 2016, this vision is based on principles, not on concrete solutions to be globally implemented irrespective of local context. Each subsidiary plant is required to follow formulated principles, but the implementation is explicitly the task of the local management. However, when it came to implementation in Japan, the initial implementation approach was led by German high-ranking managers in a top-down manner and included seemingly little possibilities for shopfloor operators and managers to participate in DX. Thus, implementation encountered resistance on the shopfloor and made little progress. This situation only changed in 2019 when Japanese mid-level managers were taking a moderating role that facilitated the digitalisation initiative by explaining management aims to shopfloor staff and simultaneously listening to bottom-up feedback on issues caused by top-down implementation. Supported by new German top managers, the DX approach was increasingly seeking to involve workers. The basic idea is signalling to workers that digitalisation may allow them to make their work more efficient or requiring less effort. Thus, while management explicitly stated that projects should 'give a push' to workers, the aim of the push is worker participation, not worker compliance. This example illustrates that Japanese workers and shopfloor managers are expecting to be involved in the implementation of production-related processes and technologies and may silently resist if they are not engaged in such a way. The changed management policy towards implementation suggests that German top managers understood that a top-down style was not producing results and hence decided to change their implementation strategy.

Concerning the aforementioned principles, they are expressed in ten key KPIs which must be pursued. One manager who is an Indian national explained that firm A's Indian subsidiary would not implement certain costly technical solutions and instead rely on workers and managers who are inexpensive compared to higher wage countries such as Germany and Japan. Thus, firm A's policy demonstrates that instead of a purely technical vision, German automotive firms realise that local context and conditions matter, especially concerning a solution's economic viability.

Regarding end-to-end integration, Japan provides an example how regulation may influence the feasibility to implement a technical vision. While firm A's Japanese plant seeks to advance integration between it and its suppliers, the OEM clearly identified a threshold. In Japan, a regulation prevents large firms to force SMEs to invest in utilising electronic data interchange, e.g., to receive customer orders. Hence, firm A still implements a paper-based *kanban* system with SME suppliers. Firm A therefore takes a pragmatic approach and first seeks to advance digital technology supported horizontal integration between itself and willing, typically larger first-tier suppliers. This example highlights that country-specific factors such as regulation clearly exert influence of the feasibility to transfer a technologically conceived vision from Germany to other countries such as Japan.

### *4.4 High-level automation of electric vehicle component production, increasing automation in logistics, and practical issues of realising Industry 4.0 in Germany*

In this subsection we present cases from Germany to illustrate issues related to the pursuit of Industry 4.0, an ideal type DX vision pursuit by larger firms in the country.

In two particular cases, firm C and firm D, we witnessed high levels of production process automation in production of EV components, namely E-axle and EV traction battery. In case of firm C, only 18 persons are needed per shift to operate the E-axle assembly line which has an annual production capacity of 150,000 units. Various digital technologies such as predictive maintenance or an *andon* system that automatically distributed information to concerned functions in case of abnormal processing conditions are utilised to ensure that the line is stopped as little as possible. Firm C informants clearly marked the high degree of automation as a cost saving measure to keep the German plant cost competitive.

Firm C experiences significant change from the shift towards electromobility. This has various consequences that are partly addressed by digital technologies. First, as the overall labour demand is going to decrease due to lower mechanical complexity of EV components, the supplier increasingly relies on temporary workers to meet current labour requirements but prepare for future decreasing requirements. This reliance on more temporary workers however means that these workers frequently lack knowledge related to specific tasks or processes. To address this issue, the supplier created a searchable, firm-internal database that documented processes not through bulky manuals but through short demonstrative videos created by experienced workers. The short and demonstrative nature of these videos is another motivating factor as this makes it easier for apprentices to familiarise themselves with processes.[8] Second, as firm C has various divisions related to ICE technology, the management and works council have agreed to retrain at least 15,000 employees. However, we hesitate to label this activity as continuing vocational education and training as the retraining effort is reportedly mainly involving white-collar employees. Interviewees pointed out that white-collar workers are much more open to digitalisation and that blue-collar workers are much more concerned about becoming redundant. There is another caveat, however. At the plant, 80% of employees are white-collar workers, i.e., only a minority are blue-collar workers, directly in production. Representatives from labour and management both expressed uncertainty about the future organisation of work as the large share of workers indirectly related to actual manufacturing was perceived as a costly use of resources because these white-collar workers are largely specialists who are only occasionally needed to address issues within their area of expertise. Employing experts who are only needed one or twice per month led both sides to question the economic sustainability of such staffing. While no solution for the future of work could be identified, the continued collaboration between capital and labour represents a practical example for coordination within the German coordinated market economy.

In case of firm D, battery production occurs in two connected shops, battery housing and battery assembly, which have production capacity of 500,000 units per year in a three-shift system which however includes system stoppage on Sundays. Battery housing production has an automation ratio[9] of 95%, only seven people are needed per shift to oversee 220 handling robots, 70 welding robots, and 30 AMRs. The assembly shop is less automated and requires 29 people per shift. There are two reasons for lower automation: first, it is necessary to install wires, a task which robots cannot (yet) handle as wires are too delicate to be installed reliably. Second, firm D excluded some production tasks from automation which could technically be automated to avoid overly monotonous work on the assembly line.

Firm D is also remarkable as the battery shop relies almost entirely on automated material handling. In plant logistics completely rely on AMRs and conveyor systems. While the battery shop has a manual back-up to forward materials, it was pointed out that the manual forwarding would mean a productivity decrease of 50% and that forwarding relied on a single buffer inventory that would last for 1.5 h, meaning that production would completely stop if countermeasures could not be implemented within this timeframe. This novel battery shop embodies the possibility to implement an in-plant logistics system without forklifts. In a quasi-greenfield environment, the implementation appears unproblematic as no issues or major incidents were reported.

Contrarily, implementation in a brownfield environment is much more challenging. In case of firm A's German plant, the aim is also to establish in-plant logistics without forklifts. The motivation is clearly grounded in cost savings potential: A single AMR reportedly costs about EUR 65,000 and thus can easily be amortised if labour cost savings are presumed. While operators may still be needed to perform certain material placing, loading, and unloading tasks, labour requirements and costs may be drastically reduced. However, firm A currently only operates two AMRs in a trial and reports that the brownfield site makes the usage more difficult as there are many locations which are too narrow for the AMR to manoeuvre on its own. Thus, operators often must clear obstacles out of an AMR's path to enable its operation. Hence, while in-plant logistics can be almost completely automated in completely repurposed halls, reaching this level appears challenging in brownfield plants. Nevertheless, it must be expected that in-plant material handling will be increasingly automated in the future, resulting in lower labour demand.

Despite challenges, interviewees at firm A explained that they expect more implementations of digital technology use cases in logistics than in manufacturing. It was highlighted that integrating digital automation into manufacturing, especially assembly, is challenging as it tends to create rigidities. An important detail is the high product variety at firm A's German plant where statistically, it does not produce identical products within a whole year. This stands in significant contrast to the EV component lines discussed in previous paragraphs which highlights that the questions where and for which purpose digital technologies are used by firms are highly context-specific.

In comparison to the vision of Industry 4.0 as a self-regulating system (Kagermann et al., (2013), p.20], even large German automotive firms, which are commonly portrayed as the spearhead of Industry 4.0, still have a long way to go. Remarkably, several firms expressed scepticism towards a self-regulating production system. Quite in contrast, firms stressed the need to combine digital technologies and human skills and experience to make improvements within production processes.

In case of firm A, it was explained that different company functions need to cooperate to solve shopfloor problems. The German plant's DX policy requires each DX team to include shopfloor workers and shopfloor managers (typically mechanical or electrical engineers and skilled workers (*Meister*)) alongside AI and IT specialists. This was explicitly related to different kinds of knowledge hold by the employees within these different functions. For instance, IT and AI specialists lack production related know-how, meaning that they cannot identify plausible data sources to be used for problem analysis. In other words, their expertise lies in sophisticated ML methods but does not extend to production processes and machinery. On the other hand, mechanical engineers and workers possess production-related knowledge but lack ML expertise. It was pointed out that while shopfloor managers and operators gathered various production-related data, these were often unusable for ML as they lacked either data quality or data reliability to be utilised by what is essentially a statistical analysis method. Hence, AI specialists, mechanical engineers, and shopfloor workers had to collaborate to identify all potential factors influencing a production-related issue and determine a data collection method which meets the statistical requirements of ML. If ML identifies root causes of a problem, solving these issues is the task of mechanical or electrical engineers. Hence, specific roles in digital transformation and digitally supported *kaizen* can be identified: finding potential explanations for existing problems is a collaborative effort that actively utilises workers' knowledge, using statistical methods for verifying existing hypothesis for a problem's root causes is the task of AI specialists, and eliminating identified root causes is the task of engineers. On the one hand, this example strongly suggests that digital technology by itself is not particularly useful to achieve improvements. However, if the strengths of digital technology are combined with shopfloor workers' experience and managers' as well as engineers' design solution capabilities, firms can improve productivity. On the other hand, this example may be understood as representing a pragmatic solution to the problem that German firms tend to hire highly specialised staff for specific functional departments. Due to this functional specialisation, teams must be cross-functional to address problems.

While firm A's approach looks to be inclusive to workers, it appears necessary to contrast this with the Japanese labour perspective. According to a company union representative of firm A, workers stopped engaging in *kaizen* as work was intensified under German management. From this organised labour perspective, the traditional approach to *kaizen* that allowed workers to improve their own workplace and support others in doing the same has been replaced by *kaizen* carried out by experts.

## 5 Discussion

In this section, findings are contrasted against previous research.

First, a look at the overall change process of DX in the German and Japanese automotive industry should be taken. In the case of Germany, while a strong systematic focus on digitalisation concepts and strategies is still identifiable (cases A, C, and D), some case firms seek to experiment with digital technologies that address concrete shopfloor problems (firm A). In these experiments, there is some more room for bottom-up participation. In the case of Japan, one case firms (firm G) encountered issues rooted in the lean augmentation approach identified in previous works (Mokudai et al., 2021). To address the proliferation of island solutions and lacking coordination, firms started efforts to standardise data formats, systems, and solutions. Thus, while having started from different management approaches towards DX, German and Japanese case firms share the experience that their initial approaches have limitations and they start to incorporate counterforces, limited bottom-up involvement of workers in Germany and increased top-down management in Japan.

Second, regarding digitalisation of operations, cases clearly demonstrate that there are still limitations to digitalisation visions such as Industry 4.0. One limitation is that there are still differences between the real world and its representation through digital technologies as discussed in the case of firm L.

Third, regarding previous findings that showed that Japanese firms used digital technologies to compress time for data collection and visualisation but stuck to formulating solutions on the shopfloor (Holst et al., 2020; Mokudai et al., 2021), additional cases confirm this tendency but demand a more nuanced description. In case of firm J, automated data collection and analysis are implemented to speed up *kaizen*. However, the improvement formulation largely rests in the hands of engineers and the IoT team. Despite this deviation from other case firms, firm J also symbolises the continued high esteem of shopfloor operator knowledge as experts (engineers and IoT team) interview workers before formulating improvement measures. Similarly, firm K introduced automated data collection and analysis, including digital twin simulations. The initiatives at firm K are mainly concerned with improving quality and analysing deviations from process standards (process variability). These analyses are expert tasks, shopfloor operators have limited options to participate in *kaizen*. These deviations from the general pattern that seeks to involve shopfloor operators in *kaizen* activities may be explained by the characteristics of J's and K's production processes. Tyre production (firm J) is a highly complex yet standardised process, which has been closely monitored before digitalisation became a topic. Being rather like chemical process industries than an assembly industry, the improvement of such processes leaves little room for operator participation. Construction machinery production (firm K) is characterised by enormous product variety and very little repetition of task sequences on the assembly line. Thus, the analysis of production related data may require big data and ML to identify deviations from standardised processes and formulation of improvement measures.

Fourth, in relation to our analytical framework based on previous research (Mokudai et al., 2021), the larger number of cases and their analysis shows that firms have quite different ideas of what role digital technologies can play in 'solution generation'. We identified three distinct roles of digital technologies in solution generation. First, firms use digital technologies in an *inspirational* role for solution generation. For instance, firm M uses generative AI such as ChatGPT to formulate suggestions for production related issues based on a databases of curated past *kaizen* solutions. In M's view, the purpose of this tool is to inspire workers to create their own solutions based on past improvements. Second, firms use digital technologies in a *testing* role for solution generation. Firms K and L utilise digital twins to simulate the creation of new production lines or the integration of new products into existing production lines. In essence, the digital twin is used to test ideas for solutions generated by engineers. Third, firms could use digital technologies in a *generative* role for solution generation. In applications such as predictive maintenance, ML is currently used to anticipate issues and alert management and/or maintenance staff that maintenance should be conducted before the anticipated issue manifests itself. However, it is only a small step from the current use to a system where work schedules of maintenance staff are generated or altered based on ML insights in connection with enterprise resource planning systems. While none of the case firms used the technology in this capacity, engineering literature already advocates this kind of application (Lee et al., 2014; Haddara and Elragal, 2015). However, it should be emphasised that this generative role is rather initiating and supporting processes that lead to solutions instead of actually generating solutions itself.

Fifth, regarding business model modification via DX, our findings show that incumbent automotive firms find this rather difficult. Difficulties are rooted in different challenges. First, the case of firm G suggests that visions which should be achieved through DX could be insufficiently specific. Concretely, firm G wants to transform itself from a carmaker to a mobility company. Interviewees however clearly stated that they did not knew what a mobility company was, and that part of their management challenge was to give meaning to this term. While previous research documented that firm G approached digitalisation of operations in a manner to augment existing manufacturing operations, reformulating its business model is far more difficult as admitted by interviewed managers. Business model modification is also a challenge for German firms. A German manager of firm A in Japan stated that the systematic, vision-based approach to DX could itself be a problem. For him, focussing on a concept such as end-to-end integration could take precedence over practical considerations such as what firm A wanted to learn from 'better' data yielded by end-to-end integration. In other words, the focus on digitised and more networked data takes precedence over the question what should or could be learned from these data. Apparently, the implicit hope of firm A's approach is that ML or AI can find answers within these networked big data. Second, the case of firm L demonstrates that refined value propositions may depend on cooperation and/or customer acceptance, which may be difficult to attain. As data have been identified as a key resource by management literature (McAfee and Brynjolfsson, 2012; Davenport, 2014; LaValle et al., 2014), refined value propositions that require data sharing may be difficult to realise due to the perceived potential value of said data. Arguably, this is a concrete example for the general issue of data marketability which was described in the management literature (George et al., 2014).

## 6 Conclusions

Findings of this study can be summarised as follows. First, the digitalisation approaches of the German and Japanese automotive industries share the characteristic that their DX process mostly advances in the digitalisation of operations. DX as refined value proposition takes a backseat, partly because quickly identified opportunities such as automated driving or MaaS are either not yet deployable or struggle to find a sustainable business model. Second, German automotive firms are more systematic in the deployment of digital technologies. Instead of island solutions or selective enhancement of existing production equipment common in Japan, German firms tend to deploy completely new production lines with a wide range of digital technologies. Simultaneously, some Japanese case firms formulate DX visions that become increasingly systematic. However, this still mainly means that existing production equipment, databases, and management systems are integrated and enhanced by digital technologies. Where Japanese firms either create greenfield plants (firm K) or substantially renew existing brownfield plants (firm B), the deployment of digital technologies becomes systematic and various new technologies are introduced. This suggests that this finding may rather represent the different starting approaches to DX – top-down vision in Germany and bottom-up experimentation in Japan – than an end state. Thus, we would expect to see this difference to disappear over time as more and more Japanese firms formulate and implement digital technologies systematically to achieve business aims. While we expect German and Japanese approaches to be equally systematic in the long-term, there could be still differences in the use strategies of digital technologies. Just like Japanese firms developed low-cost automation (sometimes referred to as lean automation) (Fujimoto, 1997)[10] as distinct from high-tech automation which was inspired by Detroit automation (Hounshell, 1995, 2000), some German or Japanese firms may develop a distinct type of DX strategy that could inspire other firms to follow in their footsteps. A potential differentiation along the lines of 'high-tech digitalisation' and 'low(er)-cost digitalisation' should be explored by future research. Third, the currently more systematic German approach may be related to another transformation, namely powertrain electrification. As less complex electric powertrains arguably make automation easier and more economically attractive, the more systematic DX may be reinforced by BEV-focused powertrain strategies. In contrast, the less focussed powertrain strategies of Japanese OEMs may explain a less aggressive approach to digital technology deployment. However, the dual transformation of digitalisation and electrification certainly demands follow-up investigations to elaborate on these hypothetical linkages. Fourth, both the German Industry 4.0 and Japanese lean augmentation approaches have limitations that lead managers to deviate from ideal types. Several German firms do not believe that more automation will help them to become more competitive and hence seek to deploy digital technologies in a way that creates returns on investment such as reduced (unplanned) machine downtime, labour cost savings or improved flexibility and quality improvement. Similarly, some Japanese firms seek to deploy digital technologies in a more integrated and systematic manner to combat the proliferation of island solutions. Thus, while German firms deviate from top-down Industry 4.0 by searching for improvements in a more pragmatic way, Japanese firm deviate from bottom-up lean augmentation by searching for new, firm-wide standards and in some cases by larger-scale investment resembling the Industry 4.0 ideal-type.

Thus, despite counterexamples, German and Japanese firms use digital technologies in distinct ways. However, our cases suggest strongly that these differences are not determined by nationality of a firm and therefore should be (partly) reproducible in other contexts. Regarding practical implications of these findings, because German SMEs are often found to be unable to deploy the capital-intensive Industry 4.0 ideal type, our Japanese case findings demonstrate that firms can use digital technologies in a less capital-intensive way. While this may not meet Industry 4.0 standards, the economic benefits (time, effort, and cost savings) of a less high-tech focussed approach are evident and worthy of managerial consideration.

## Acknowledgements

This work was supported by JSPS KAKENHI Grant Number JP23K01559. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the author's organisation, JSPS or MEXT.

Parts of the research were funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) within the research programme 'The Digitisation of Working Worlds. Conceptualising and Capturing a Systemic Transformation' (SPP 2267), project number 442459396.

The authors would like to thank two anonymous referees for detailed comments but remain responsible for all errors.

## References

Alochet, M., MacDuffie, J.P. and Midler, C. (2023) 'Mirroring in production? Early evidence from the scale-up of battery electric vehicles (BEVs)', Industrial and Corporate Change, Vol. 32, No. 1, pp.61–111.

Andal-Ancion, A., Cartwright, P.A. and Yip, G.S. (2003) 'The digital transformation of traditional businesses', *MIT Sloan Management Review*, Vol. 44, No. 4, pp.34–41.

Berman, S.J. (2012) 'Digital transformation: opportunities to create new business models', *Strategy & Leadership*, Vol. 40, No. 2, pp.16–24.

Calabrese, G.G. and Falavigna, G. (2022) 'Does Industry 4.0 improve productivity? Evidence from the Italian automotive supply chain', *International Journal of Automotive Technology and Management*, Vol. 22, No. 4, pp.506–526.

Carbonell, J.S. (2020) 'The factory of the future? The contradictory restructuring of an assembly line in France', *Sociologia del Lavoro*, Vol. 158, pp.118–136.

Cohen, B. and Kietzmann, J. (2014) 'Ride on! Mobility business models for the sharing economy', *Organization & Environment*, Vol. 27, No. 3, pp.279–296.

Davenport, D. (2014) *Big Data @ Work: Dispelling the Myths, Uncovering the Opportunities*, Harvard Business Review Press, Boston.

Delicat, N., Herzog, L., Krzywdinski, M., Butollo, F., Wandjo, D., Flemming, J., Gerber, C. and Danyeli, M. (2024) 'Organisationswandel und *Wahrnehmung* der Akzeptanz von Digitalisierungsprozessen in Unternehmen infolge der COVID-19-Pandemie [Organisational change and perception of acceptance of enterprises' digitalisation processes due to the COVID-19 Pandemic]', in Pfeiffer, S., Nicklich, M., Henke, M., Heßler, M., Krzywdzinski, M. and Schulz-Schaeffer, I. (Eds.) (2024) *Digitalisierung der Arbeitswelten. Zur Erfassbarkeit einer systemischen Transformation* (*The Digitalisation of Working Environments. Towards Ascertainability of a Systemic Transformation*), pp.135–159, in German, Springer, Wiesbaden.

Eisenhardt, K.M. (1989) 'Building theories from case study research', *The Academy of Management Review*, Vol. 14, No. 4, pp.532–550.

Fisher, M.L. and Ittner, C.D. (1999) 'The impact of product variety on automobile assembly operations: empirical evidence and simulation analysis', *Management Science*, Vol. 45, No. 6, pp.771–786.

Frank, A.G., Mendes, G.H.S., Ayala, N.F. and Ghezzi, A. (2019) 'Servitization and Industry 4.0 convergence in the digital transformation of product firms: a business model innovation perspective', *Technological Forecasting and Social Change*, Vol. 141, pp.341–351.

Fujimoto, T. (1997) *Strategies for Assembly Automation in the Automobile Industry*, Edited by K. Shimokawa, U. Jürgens and idem., pp.211–237, Springer, Berlin and Heidelberg.

George, G., Haas, M.R. and Pentland, A. (2014) 'Big data and management: from the editors', *Academy of Management Journal*, Vol. 57, No. 2, pp.321–326.

Haddara, M. and Elragal, A. (2015) 'The readiness of ERP Systems for the factory of the future', *Procedia Computer Science*, Vol. 64, pp.721–728.

Hirsch-Kreinsen, H. (2019) *Industry 4.0 – A Path-Dependent Innovation*, Technical University of Dortmund Sociology Working Paper 56/2019.

Holst, H., Aoki, K., Herrigel, G., Jürgens, U., Mokudai, T., Müller, M., Schaede, C., Schröder, M. and Sinopoli, R. (2020) 'Gemba Digitalisierung: Wie japanische Automobilunternehmen IoT-Technologien einsetzen [Gemba digitalisation: how Japanese automotive companies apply IoT technology; in German]', *ZWF Zeitschrift für wirtschaftlichen Fabrikbetrieb*, Vol. 115, No. 9, pp.629–633.

Hounshell, D.A. (1995) 'Planning and executing 'automation' at Ford Motor Company, 1945-65: the Cleveland engine plant and its consequences', in Shiomi, H. and Wada, K. (Eds.): *Fordism Transformed: The Development of Production Methods in the Automobile Industry*, pp.49–86, Oxford University Press, Oxford.

Hounshell, D.A. (2000) 'Automation, transfer machinery, and mass production in the U.S. automobile industry in the Post-World War II era', *Enterprise & Society*, Vol. 1, No. 1, pp.100–138.

Jürgens, U. (2023) *Automatisierung und Arbeit in der Automobilindustrie: Von Henry Ford zur Industrie 4.0* [*Automation and Work in the Automobile Industry: From Henry Ford to Industry 4.0*], in German, Nomos, Baden-Baden.

Kagermann, H., Wahlster, W. and Helbig, J. (2013) *Recommendations for Implementing the Strategic Initiative INDUSTRIE 4.0: Final Report of the Industrie 4.0 Working Group*, Acatech – National Academy of Science and Engineering, München, Germany.

Krzywdzinski, M. (2021a) 'Automation approaches in the automotive industry: Germany, Japan, and the USA in comparison', *International Journal of Automotive Technology and Management*, Vol. 21, No. 3, pp.180–199.

Krzywdzinski, M. (2021b) 'Automation, digitalization, and changes in occupational structures in the automobile industry in Germany, Japan, and the United States: a brief history from the early 1990s until 2018', *Industrial and Corporate Change*, Vol. 30, No. 3, pp.499–535.

Krzywdzinski, M., Butollo, F., Flemming, J., Gerber, C., Wandjo, D., Delicat, N., Herzog, L., Bovenschulte, M. and Nerger, M. (2022) *Wachsende Kluft zwischen vorreiterunternehmen und Nachzüglern* (*The Deepening Chasm between Vanguard and Laggard Firms*), Weizenbaum Series 24, in German, Weizenbaum Institute, Berlin.

Lagadic, M., Verloes, A. and Louvet, N. (2019) 'Can carsharing services be profitable? A critical review of established and developing business models', *Transport Policy*, Vol. 77, pp.68–78.

Lasmar Jr., E.L., Gandia, R.M., Sugano, J.Y., de Souza, T.A. and Rodriguez, D.Z. (2019) 'New business models and the sharing economy: impacts and challenges for the traditional automotive industry', *International Journal of Automotive Technology and Management*, Vol. 19, Nos. 3–4, pp.301–320.

LaValle, S., Hopkins, M.S., Lesser, E., Shockley, R. and Kruschwitz, N. (2014) *Analytics: The New Path to Value*, MIT Sloan Management Review and IBM Institute for Business Value [online] https://sloanreview.mit.edu/projects/analytics-the-new-path-to-value/.

Lee, J., Kao, H.A. and Yang, S. (2014) 'Service innovation and smart analytics for Industry 4.0 and big data environment', *Procedia CIRP*, Vol. 16, pp.3–8.

Lloopis-Albert, C., Rubio, F. and Valero, F. (2021) 'Impact of digital transformation on the automotive industry', *Forecasting and Industrial Change*, Vol. 162, p.120343.

Martin, K. and Osterling, M. (2014) *Value Stream Mapping: How to Visualize Work and Align Leadership for Organizational Transformation*, McGraw-Hill Education, New York.

Masood, T. and Sonntag, P. (2020) 'Industry 4.0: adoption challenges and benefits for SMEs', *Computers in Industry*, Vol. 121, p.103261.

Matt, C., Hess, T. and Benlian, A. (2015) 'Digital transformation strategies', *Business & Information Systems Engineering*, Vol. 75, No. 5, pp.339–343.

McAfee, A. and Brynjolfsson, E. (2012) 'Big data: the management revolution', *Harvard Business Review*, Vol. 90, No. 10, pp.60–68.

Mittal, S., Khan, M.A., Romero, D. and Wuest, T. (2018) 'A critical review of smart manufacturing & Industry 4.0 maturity models: implications for small and medium-sized enterprises (SMEs)', *Journal of Manufacturing Systems*, Vol. 49, pp.194–214.

Moeuf, A., Pellerin, R., Lamouri, S., Tamayo-Giraldo, S. and Barbaray, R. (2018) 'The industrial management of SMEs in the era of Industry 4.0', *International Journal of Production Research*, Vol. 56, No. 3, pp.1118–1136.

Mokudai, T., Schröder, M., Müller, M., Schaede, C., Holst, H., Sinopoli, R., Jürgens, U., Herrigel, G. and Aoki, K. (2021) 'Digital technologies as lean augmentation: a preliminary study of Japanese automotive manufacturers', *International Journal of Automotive Technology and Management*, Vol. 21, No. 3, pp.228–249.

Moniz, A.B. and Candeias, M. (2022) 'Challenges in productivity and labour relations: artificial intelligence in the automotive sector in Portugal', *International Journal of Automotive Technology and Management*, Vol. 22, No. 2, pp.222–244.

Moro, A. and Virgillito, M.E. (2022) 'Towards Factory 4.0? Convergence and divergence of lean models in Italian automotive plants', *International Journal of Automotive Technology and Management*, Vol. 22, No. 2, pp.245–271.

Müller, J.M., Buliga, O. and Voigt, K-I. (2018) 'Fortune favours the prepared: how SMEs approach business model innovations in Industry 4.0', *Technological Forecasting and Social Change*, Vol. 132, pp.2–17.

Ohno, T. (1988) *Toyota Production System: Beyond Large-Scale Production*, CRC Press, Boca Raton.

Pardi, T. (2019) 'Fourth industrial revolution concepts in the automotive sector: performativity, work and employment', *Journal of Industrial and Business Economics*, Vol. 46, No. 3, pp.379–389.

Pfeiffer, S. (2016) 'Robots, Industry 4.0 and humans, or why assembly work is more than routine work', *Societies*, Vol. 6, No. 2, pp.1–26.

Pfeiffer, S., Nicklich, M., Henke, M., Heßler, M., Krzywdzinski, M. and Schulz-Schaeffer, I. (Eds.) (2024) *Digitalisierung der Arbeitswelten. Zur Erfassbarkeit einer systemischen Transformation* (*The Digitalisation of Working Environments. Towards Ascertainability of a Systemic Transformation*), in German, Springer, Wiesbaden.

Rachinger, M., Rauter, R., Müller, C., Vorraber, W. and Schirgi, E. (2019) 'Digitalization and its influence on business model innovation', *Journal of Manufacturing Technology Management*, Vol. 30, No. 8, pp.1143–1160.

Rother, M. and Shook, J. (2009) *Learning to See: Value-stream Mapping to Create Value and Eliminate Muda*, Version 1.4, Lean Enterprise Institute, Cambridge.

Schröder, M., Mokudai, T., Müller, M. and Metternich, J. (2024) 'Varieties of digitalisation? Theoretical explanations of German and Japanese digitalisation approaches in the automotive industry', *Vienna Journal of East Asian Studies*, Vol. 15, No. 1, pp.3–31.

Sommer, S., Proff, H. and Proff, H. (2021) 'Digital transformation in the global automotive industry', *International Journal of Automotive Technology and Management*, Vol. 21, No. 4, pp.295–321.

Stake, R.E. (2006) *Multiple Case Study Analysis*, Guilford Press, New York.

Thoben, K-D., Wiesner, S. and Wuest, T. (2017) ''Industrie 4.0' and smart manufacturing – a review of research issues and application examples', *International Journal of Automation Technology*, Vol. 11, No. 1, pp.4–16.

Verhoef, P.C., Broekhuizen, T., Bart, Y., Bhattacharya, A., Dong, J.Q., Fabian, N. and Haenlein, M. (2021) 'Digital transformation: a multidisciplinary reflection and research agenda', *Journal of Business Research*, Vol. 122, pp.889–901.

Vial, G. (2019) 'Understanding digital transformation: a review and a research agenda', *Journal of Strategic Information Systems*, Vol. 28, No. 2, pp.118–144.

Womack, J.P., Jones, D.T. and Roos, D. (1990) *The Machine that Changed the World*, Rawson Associates, New York.

Yin, R.K. (2018) *Case Study Research and Applications: Design and Methods*, Sage Publications, Thousand Oaks.

## Notes

1 A potential explanation of these differences through their distinct national varieties of capitalism has been developed (Schröder et al., 2024). While this is an interesting question, this paper seeks to only investigate if these previously identified patterns are stable or converging over time. Analysis from the varieties of capitalism perspective is omitted in order to provide a more detailed description of developments.

2 In a recent literature review, Vial (2019) observed that most existing definitions of DX were flawed as they were either tautological, conflating the process with an (expected) outcome, or unnecessarily exhaustive. While this may reflect general issues with defining complex socio-economic change processes, this finding compels us to follow his definition of DX as "a process that aims to improve an entity by triggering significant changes to its properties through combinations of information, computing, communication, and connectivity technologies" [Vial, (2019), p.118].

3 While Jürgens (2023) clearly acknowledges that automation technologies have become more flexible over time, he maintains that increasing product variety (so far) thwarted the progress of automation in final assembly shops.

4 To be clear, we visited new production lines which are however placed in reused halls at existing production locations. Hence, these are technically brownfield sites that are extensively renewed with the latest technologies akin to greenfield sites.

5 For AMRs, autonomous means that the vehicle is manoeuvring based on a map of its environment and sensor data instead of moving back-and-forth along predefined routes marked by magnetic or colour tapes or being completely hardwired as in automated guided vehicles.

6 We decided to categorise this use of digital twin simulation under *kaizen* as 'solution generation'. However, we emphasise that this label may be regarded as an inappropriate overextension of the term *kaizen* which is usually applied to smaller and gradual improvement of existing production facilities. The digital twin use of L rather corresponds to *kaikaku* which can be translated as reform and is used to describe major overhauls of production facilities. Firm K was categorised in the same way as it uses digital twin applications that allow the integration of product design information when designing the production process, including simulation of the planned process before the process reaches production ramp-up.

7 Predictive maintenance basically combines data on past failures, various other data from the point of failure occurrence (time series correlation), and current process (monitoring) to predict when a failure is going to occur. To illustrate, an easily understandable example from firm C is used: Microsoft Power BI identified a correlation between out-of-spec output and damper performance and damper positioning (the tool used in the production process moves up-and-down, the damper is used to reduce additional horizonal movement). The constant up-and-down will over time cause the damper positioning to change minutely but enough to influence the output negatively. Power BI can forecast when the position of the damper will have changed 'enough' to cause out-of-spec output. Based on that forecast, recalibration of the damper will be scheduled to occur before the predicted time.

8 Interviewees observed another, unexpected benefit from implementation. Apprentices or other young workers were apt in creating videos via apps and mobile devices, something the older, experienced workers with the task-related skills found difficult. In practice, creating the videos became a cross-generational activity that reportedly improved relations between different age cohorts.

9 Automation ratio is defined as the number of all automated tasks at all stations divided by the total number of tasks at all stations.

10 While labels are commonly used to describe distinctly different approaches, we favour Fujimoto's (1997) description of different but not mutually exclusive automation strategies. Thus, while there may exist different DX strategies, they do not have to be mutually exclusive.