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Digital technologies as lean augmentation: A preliminary study of Japanese automotive manufacturers

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Abstract: This paper explores how Japanese automotive manufacturers, whose production systems are characterised by the lean principle, address digital transformation. We conducted case studies of seven Japanese car makers and suppliers to investigate the interplay between lean production and digitalisation. We found that the firms selectively adopted digital technologies to enhance the existing lean production system. We labelled this type of digitalisation 'lean augmentation'. Further, we developed theoretical

hypotheses regarding the potential of digitalisation to limit *kaizen*, the roles of human involvement and organisational coordination in digitalised manufacturing, and the potential risk of lean augmentation being caught by what we term the 'lean trap'.

Key words: lean production, digital technologies, digitalisation, operations, *kaizen*, human resource development, lean augmentation, lean trap, technology-driven approach, organisation-oriented approach, multiple-case method, Japanese automotive industry

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1 Introduction

There has been growing interest in a new wave of digital technologies in the Japanese automotive industry, where 'lean' is the dominant production paradigm. One of the prominent triggers for digitalisation has been the initiative proposed by the German government, Industry 4.0[1]. In this paper, we focus on potential interactions between lean production and the latest generation of digital technologies, including networked, autonomously communicating machines, sensor-based data acquisition, so-called digital twins, as well as machine learning and other forms of artificial intelligence (AI). These new technologies evolved from older forms of information technology (IT). As Hirsch-Kreinsen (2018) points out, digital technologies have functional duality: while digitalisation potentially substitutes labour by automation, it can informate humans about various dimensions of the process. Firms have only recently begun to consider the second function of digital technologies going beyond the relatively simple function of automating a process.[2]

Recent production operations literature started exploring the interactions between novel digital technologies and lean production systems (Buer et al., 2018; Kolberg and Zühlke, 2015; Metternich et al., 2017; Mrugalska et al., 2017; Prinz et al., 2018)[3]. Many studies suggest that Industry 4.0 technologies can support lean manufacturing by automating data collection and visualisation, facilitating communication between workstations, tracking material flows and facility conditions, enhancing predictive maintenance capability, and so forth (Bauer et al., 2018; Dombrowski et al., 2017; Hoellthaler et al., 2018; Kimura, 2018; Kolberg et al., 2017; Lugert and Winkler, 2019; Prinz et al., 2018; Sanders et al., 2018; Wanger et al., 2017). Conversely, some studies argue that lean principles can serve as a foundation for the implementation of Industry 4.0 (Sanders et al., 2016; Sony, 2018; Wang et al., 2016). There are several empirical studies that show the positive (but not linear) impact on operational performance by the integration of Industry 4.0 and lean production systems (Rossini et al. 2019; Tortorella and Fettermann, 2018; Tortorella et al., 2020).

While many of these studies conduct case studies of manufacturing firms mainly in European countries, few empirical studies (Kimura, 2016, and Holst et al. 2020 are exceptions) about Japanese firms have been reported. How are Japanese automotive manufacturers accessing the potential of digitalisation, which digital technologies are they attempting to employ, and in what way are they doing so? This study explores how automotive-related manufacturers in Japan do (or do not) embrace digital technologies. Furthermore, it aims to contribute to the debate on the relationship between lean production and digitalisation. As the lean concept originated in Japan, in the form of the Toyota Production System (Bhamu and Sangwan, 2014; Holweg, 2007; Homer and Thompson, 2001; Jasti and Kodali, 2015; Pavnaskar et al. 2003), it allows us to investigate how the lean concept and digitalisation may be combined. Thus, the generation of working hypotheses for further research on the interplay between digitalisation and lean production is a secondary aim of this study.

The remainder of this paper is organised as follows. Section 2 reviews the academic discussion on lean production and digitalisation. After a brief explanation of the research methodology in Section 3, the results of the field research on automotive-related firms in Japan are described in Section 4. Section 5 discusses the implications of the findings and builds working hypotheses about the interactions between digitalisation and lean production. Section 6 concludes the paper.

2 Literature review on lean production and digitalisation

2.1 Lean production

The term ‘lean production’ was first used by Krafcik (1988) to describe operational performance gaps among Japanese, North American, and European automotive plants (Holweg, 2007). Although a vast literature has highlighted various aspects of the lean concept, the shared understanding is that the lean production system aims to reduce waste in production resources and activities while achieving high quality according to customers’ requirements. The content of lean production can be described from two perspectives (Bhamu and Sangwan, 2014; Bortolotti et al., 2015). One view considers lean production as a coherent system of practices and tools, such as just-in-time, pull system, *kanban*, lot size reduction, quick changeover techniques, and employee involvement (Shah and Ward, 2003). From the second perspective, lean production is a philosophy or principle that guides production practices and efforts to continuously improve productivity and quality (Womack and Jones, 1996).

As becoming lean is described as an endless journey to pursue perfection (Ohno, 1988; Womack and Jones, 1996), continuous improvement (*kaizen*) is a driving force to achieve lean processes.[4] *Kaizen* is indeed built into lean principles and practices. For example, while the reduction of work-in-process (WIP) is a goal to eliminate waste, it serves as a means to trigger *kaizen* by revealing potential problems (e.g. uneven cycle time, unstable machine availability, etc.) hidden under the WIPs (Ohno, 1988). In this regard, lean production traditionally prefers simple technologies. For instance, *kanban* cards are used to keep track of the WIPs. Since the movement and number of *kanban* cards always match those of the WIPs, managers and workers can change the level of inventory and improve the production flows by controlling *kanban* cards. In other words, *kanban* works as a shadow of the physical world.[5]

Experts also stress the importance of going to the actual place where the problem in question occurred (*Genchi Gembutsu* in Japanese) to identify the root causes before implementing *kaizen* (Imai, 2012; Ohno, 1988). This principle is consistent with the findings of the innovation literature. von Hippel (1994) and von Hippel and Tyre (1995) found that the information needed to solve a problem is often costly to acquire, transfer, and use in different locations—it is 'sticky' to the location. Their study suggests that 'doing' is a crucial element for problem-identification. When the required information is 'sticky' to a specific location, problem-solving should be carried out at that location.

The production operations literature studying Japanese production organisations report that the implementation of *kaizen* involves a great deal of employee involvement and organisational coordination (Fukuzawa et al., 2012; Iwao, 2017; Komatsu, 2006; Tamura, 2011). Iwao (2017) points out that *kaizen* is not a closed-loop activity on the shop floor but involves other organisations, such as other *kaizen* teams, logistics, production engineering, and product design departments. Komatsu (2006) also suggests that both vertical coordination among operators and horizontal coordination with other sections (e.g. production engineering, purchasing department, suppliers, etc.) are critical to materialising *kaizen* ideas. Shop floor engineers (*kojo gijutsu in*) must have technical expertise as well as the power to mobilise resources from other organisations. Through an in-depth case analysis of Japanese transplants in China, Aoki (2008) identified three different, yet interrelated, organisational capabilities and found that successful cases were able to achieve a healthy balance of capabilities within their organisation to encourage workers' self-initiative, facilitate cross-functional communication, and discipline workers.

2.2 Digitalisation: between vision and real-world implementation

Kagermann et al. (2013, p. 20) describe Industry 4.0 as 'networks of manufacturing resources (manufacturing machinery, robots, conveyor and warehousing systems and production facilities) that are autonomous, capable of controlling themselves in response to different situations, self-configuring, knowledge-based, sensor-equipped and spatially dispersed and that also incorporate the relevant planning and management systems'. Furthermore, proponents posit that Industry 4.0 rests on three integrations: vertical (between different layers of firm hierarchy), horizontal (between different functional departments of a firm and suppliers), and end-to-end (data-based, integrated life cycle management from design to production and eventual discontinuation) (ibid., p. 35). These integrations are mainly achieved through technology deployment.[6]

Despite this rather technical vision, digitalisation under the label of Industry 4.0 clearly acknowledges the socio-technical character of production. Following Rice (1963), a sociotechnical system can be described as an organisation that consists of interdependent social and technical subsystems. It has been observed that organisations tend to modify aspects of the social subsystem to accommodate the technical subsystem (Pasmore et al., 1982). Thus, rather than changing the technical subsystem, organisations (or management) prefer to train people to increase the efficiency of the deployed technology.

One question rooted in the socio-technical system concept is worker autonomy.

Therefore, recent studies addressed the question of whether digitalisation enhances or reduces worker autonomy. Studying cases from the German automobile industry, Butollo and colleagues (2018) mainly observed cases where autonomy is reduced but also pointed out that there are applications that may enhance autonomy. Analysing Italian industry cases, Cagliano and colleagues (2019) observed that lower levels of digitalisation are linked to strong standardisation of work and isolated jobs as well as centralised, managerial control over work organisation. Conversely, they found that higher levels of digitalisation are associated with multi-tasking jobs, decentralised decision-making at the team or worker level, and flat hierarchy. Thus, they concluded that the more interconnected production processes become, higher the degree of autonomy enjoyed by workers. Presumably, this is because higher interconnectedness results in higher complexity, and Italian firms apparently concluded that this complexity cannot be centrally managed. However, caution should be exercised against linking high-level automation to a particular labour-use strategy: Comparing highly automated plants in Germany and Central Eastern Europe, Krzywdzinski (2017) observed different skill requirements between plants in these two locations. The key point for the discussion on digitalisation is that similar technology does not automatically lead to a similar strategy. Evers and colleagues (2018) explored how wearable solution developers regard and perform their work. They found that the developers were aware of the social implications of their work and sought to balance technological possibilities, business aims, and social concerns. Finally, they found that most solutions are developed as island solutions: solutions that improve the efficiency of a particular task instead of a connected, integrated work process.

Hirsch-Kreinsen (2019) contrasted visions of transformative change with empirical observations that suggested incremental, path-dependent deployment of digital technologies in manufacturing industries. Depending on David's (1985) seminal paper, he explained that technical interrelatedness leads firms to adopt new technologies if they can be quickly integrated into existing technical subsystems. Furthermore, if new technologies allow existing work practices to function more efficiently, firms will seek to exploit these optimisation effects. Overall, firms will thus aim to achieve complementarity between existing and new technologies to stabilise the overall organisation. In other words, because socio-technical systems are characterised by joint optimisation of social and technical subsystems, firms typically would try to avoid radical transformative changes in any one subsystem. He thus pointed out that most empirically studied firms are 'selective digitisers', that is, digital technologies are applied piecemeal to address specific issues.

Overall, research on digitalisation is diverse. On the one hand, there are conceptual visions of networked, autonomously adjusting processes. On the other hand, empirical research highlights that the majority of firms are rather pragmatic and take an experimental stance towards digitalisation. The findings highlight that (digital) technology can be utilised for different ends; technology per se does not prescribe a specific use. Additionally, while it appears rational to expect a selective and step-by-step deployment of digital technologies from the perspective of socio-technical systems, they also leave room for transformative change because social and technical subsystems are adapted not only to each other but also to the external environment of the firm.

3 Methodology

Since the intensive use of digital technologies in the production system is a relatively new phenomenon, we employed a multiple-case research design. The cases include two car manufacturers and five suppliers of parts, three of whom are *keiretsu* suppliers while the remaining are independent ones (Table 1).

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Consistent with theoretical sampling (Eisenhardt, 1989), the cases were selected based on two criteria: lean production and digitalisation. First, the selected firms implement lean production practices to varying degrees. For instance, Firm A executes its production operations through the push and pull principle and delivers its products using just-in-sequence (JIS). Firm B implements pull production, JIS delivery, mixed-model production, set parts supply, and *kaizen* activities. The production systems of Firm C and G are built on just-in-time (JIT) and *jidoka* (autonomation) principles. They both practise pull production, line-balancing, mixed-model production, standard works, *kaizen* activities, suggestion systems, job rotation, and so forth. Firms E and F have introduced the Toyota Production System (TPS) with the aid of TPS specialists. Particularly, Firm F has developed internal *kaizen* experts who take a lead in *kaizen* implementation on the production floor. Although Firm D practises JIT delivery, it has the lowest extent of lean implementation due to the capital-intensive nature of tyre production.

Second, the extent of digital technology introduction varied among the cases. We loosely defined digitalisation as the adoption of digital technologies, such as various types of sensors, radio-frequency identification (RFID), cyber-physical systems (CPS), and artificial intelligence (AI), which potentially contribute to automating data collection and analysis as well as connecting different resources and activities within or across organisations. In this research, we described the digitalisation of the firms based on the interviewees' perceptions. We employed this approach because the use of technologies depends on the cognitive frame of individuals or organisations; novel technologies can be framed and used in an old way and vice versa. As reported in detail in Section 4, Firm F shows the keenest interest in digital technologies, while Firm E barely engages in digitalisation. Other firms (A, B, C, D, and G) are situated between the two ends of the digitalisation spectrum.

Semi-structured interviews with 23 informants were conducted in the seven firms from November 14th to 21st, 2019. Before conducting the interviews, we exchanged views with a contact person of these firms to know the implementation status of digitalisation. In firms with organisation-wide digitalisation initiatives, such as Firm C and Firm G, we selected interviewees from different levels and functions, such as company executives, plant managers, production engineers, and human resources managers. In a firm that barely engaged in digitalisation, we selected a single person who led in a just-convened project related to digitalisation (see Table 1 for further details). Our company visits normally began with an interview about general management and production policies, then moved to a factory tour, and finished with follow-up discussions with all the interviewees. The length of the visits ranged from three to seven hours. We recorded all interviews with permission from the interviewees. Our secondary data sources include company websites, brochures, and business publications (e.g. newspapers, business magazines, and books).

4 Findings

4.1 Background of digitalisation of case firms

The general background is the shrinking labour force in Japan due to the falling birth-rate and the aging population. Thus, a common motivation across the selected firms was to use digital technologies to improve productivity with limited workforce.

The level of clarity in digitalisation motivation varied considerably among the firms. Firm A, for example, has a vison to realise an unmanned factory operating 24 hours for 365 days. The introduction of digital technologies was a natural choice for Firm A. Digitalisation in Firm F was triggered by a *kaizen* suggestion from their primary customer. The customer firm advised Firm F to record the progress of hourly production more accurately to improve the plan-do-check-action cycles. Albeit the importance of recordkeeping, Firm F could not afford an extra workforce only to monitor the production processes. This was why they started studying the potential of digital solutions to achieve real-time data collection while releasing employees from non-value-creating tasks.

The purposes of digitalisation of other firms (except Firm E) were exploratory. For instance, although there were no critical problems in their operations, Firm B introduced digital solutions to visualise production status to support workers' operations (e.g. parts picking, in-line inspection). Firm C experimentally introduced digital technologies in various fields (e.g. machine processing, machine maintenance, logistics, skill training, etc.) to study better ways to utilise new technologies. Firm D introduced digital solutions to automate data collection on production status and inspection. Firm G considered digital technologies as one of the instruments to improve their lean implementation. Firm G further engaged in studying the potential of digital technologies by using them. Their main motivation to introduce IoT technologies was to make workers engage more in solution generation by reducing the workload for *kaizen* preparation (e.g. data collection). Finally, at the time of our interview, although Firm E's informant recognised potential benefits of digital solutions, no explicit digitalisation initiative was implemented due to a lack of consensus among production managers.

4.2 Classification of findings

We classified the selected firms' use of digital technologies into three domains: operations, *kaizen*, and human resource development (HRD). Operations were further categorised into 1) processing, 2) assembly, 3) inspection, 4) inventory and logistics, 5) maintenance, and 6) production planning and control. *Kaizen* activities were distinguished into 1) data collection, 2) analysis, 3) solution generation, and 4) implementation. We sub-categorised the HRD as 1) HRD using digital technologies and 2) HRD for digitalisation. Table 2 is a summary of our case studies.

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4.3 Operations

In the operations domain, the most commonly observed uses of digital technologies were part processing, inspection, and maintenance.

First, we found that real-time monitoring and automated data collection of processing tasks were the typical uses of digital technologies. For example, Firm F found it quite difficult to manually keep accurate records of machine availability because it was unaffordable to assign workers only to monitor the machines. To address this issue, the firm invented simple and low-cost IoT solutions to automatically record abnormal events on the machines. They purchased sensors, radio modules, and single-board computers from an electronics shop and attached them to the existing machine tools to monitor the operation of the machines. Initially, they only collected machine stoppage signals. The types of data collected, however, gradually expanded to include the number of outputs, cycle times, and the length of downtime.

Second, many of the firms (five out of the seven) showed interest in the use of AI to automate inspection. Since inspection is one of the most labour-intensive tasks and does not create (but only assures) customer value, AI could help reduce non-value adding activities and improve accuracy as well as inspection speed. For instance, Firm A experimentally introduced an image diagnosis system to inspect the surface quality of stamped parts. This technology has not yet been put into practical use because it has not reached the level of sensory capability possessed by humans. Firm G implemented experiments to apply AI to inspect stamping parts. This firm has experienced two basic issues with the utilisation of AI: First, the number of non-conforming products is low (around 1/100,000), meaning that creating a sufficiently large training sample for the AI consumes a significant amount of time. Second, while the AI can accurately identify defects, there is currently a problem with over-detection. Firm G also used AI to identify defects in its paint shop. While the AI is currently not good enough to detect all defects, the inspection process is much faster.

Third, we found that preventive maintenance was a typical use of AI. Our sample firms deployed digitalisation at the single process/machine level. Firm C, for example, was experimenting with a predictive maintenance system for a crankshaft pressing machine. The wave profile of pressing loads was measured and analysed by statistical analysis and machine learning. Signs of potential damage were detected one month before a breakdown occurred. A similar project was conducted by Firm G. A machine learning AI was first used to identify spindle damage eight days before failure occurred. This allowed the firm to conduct maintenance work over the weekend to minimise machine downtime. It is noteworthy that Firm G stated that preventive maintenance using AI was a first-aid measure until the root cause could be identified and solved. This case illustrates that the case firm does not consider preventive maintenance to be the final solution but only as a step towards more fundamental problem solving.

Fourth, in the assembly, inventory, and logistics domains, new digital technologies played minor or supplementary roles in the case firms. For example, in Firm

A and Firm F, data on operators' cycle time were collected. The observed deviation from takt time was analysed by *kaizen* events to improve work procedures and the environment. In other cases, we saw more conventional technologies, including (e-)*kanban*, printed instruction bills (manifestos), barcodes and reading devices, LCD monitors, and automated guided vehicles, than new digital tools, including RFID (Firm C) and tablets (Firm G). This may be partly because analogue techniques (e.g. *kanban*) and existing digital technologies (barcodes, for example) have long been used to track the movement of physical goods and information. Since these technologies have already matured and are available at low cost, they would be difficult to replace with new technologies.

Finally, given that production complexity has increased due to growing product variety and expanding production networks, interest has grown for the use of AI in production planning and control tasks. However, we observed few concrete examples of new digital technologies (e.g. IoT and AI) in this domain. For instance, *heijunka* (levelling of production mix sequences) and line-balancing (machine layout and work design aimed at balancing cycle time between processes) tasks were carried out by experienced production managers at Firm C and G. Conventional digital technologies, such as electric data interchange, enterprise resource planning, barcodes, and e-*kanban* played dominant roles in the firms. Firm E, the least interested in digitalisation, engages in robotic process automation (RPA) to automate data input and format conversion in the production control, which is largely a paper-based system that relies on the 1980s IT infrastructure.

4.4 Kaizen

Regarding *kaizen* activities, 1) automated data collection and 2) data analysis (visualisation) were the most commonly implemented uses of digital technologies (six out of the seven cases). In Firm A, for instance, cameras and sensors collect data to monitor the performance of stamping and welding machines (error-related downtime, for example) and operators (cycle time). The collected data were used for visual management. Although the data visualisation techniques are not novel (e.g. error-related machine downtime was recorded as a Pareto chart), the precision and immediacy of data acquisition and the efficiency of data processing have improved.

Digital technologies help shorten the time to gather data. In Firm F, for example, to analyse one production line, four to eight hours were previously needed to collect relatively few data. Then, at least another four hours were required to transform the data into a histogram. Digital technologies allow real-time and automated data processing.

Some experimental cases have used AI to analyse the causes of detected problems and propose solutions. For example, Firm A established a self-adjusting spot-welding system. However, there have been no plans to develop a similar system for other welding methods because they are more difficult to standardise due to factors such as parts positioning, the complex shape of parts, and the sensitivity of the process to minor fluctuations in electric current and voltage. Likewise, Firm C has conducted a study that automatically adjusts the production parameters of a crankshaft production facility. Previously, when any abnormality occurred, the production parameters were modified by operators based on their experience and skills. In this study, big data on production conditions (e.g. temperature, forging load, cycle time, etc.) were statistically analysed by data analysts to calculate new parameters.

Overall, many of the firms regarded digital technologies as a means to enable workers to focus on analysing root causes and generating solutions. In other words, selected firms relied on humans to solve problems. The studied firms also stressed the importance of the location of solution generation. For example, in Firm F, daily meetings (so-called 'line stop meetings') are held on the shop floor. Shop floor managers discuss the potential causes of line stops. They then determine who will take what measures and by when, and they share information about the outcomes of countermeasures and problem recurrences. Similarly, the interviewee from Firm B stressed that they bring the collected real-time data to the shop floor (e.g. by using hand-held devices) to avoid leaving the shop floor.

These examples further suggest that worker autonomy is preserved regarding the question of finding and implementing work process improvement. Simultaneously, Firm A's monitoring of individuals can be regarded as a tool to enforce compliance with standards and undermine individual autonomy. Thus, while firms uphold team autonomy and value team contributions for improvement, individual workers may be more strongly controlled to meet (team) standards.

4.5 Human resource development

Only two case firms used digital technologies for human resource development (HRD). Firm C applied motion capture technologies for skill training in dye polishing. Motion capture suits and eye trackers were used to analyse the movement of workers and create virtual body models. The essential difference between previous direct observation of master craftsmen (*takumi*) and the motion capture technology is that the latter visualises differences between operators (e.g. almost no head motion by *takumi* versus lateral head movement by inexperienced operators). In terms of improving training, it takes 20 years to reach the level of a *takumi* (highest rank out of five). With the use of motion capture technology, the skill development process has accelerated, and several operators reached *the takumi*-level in 12 years. Firm C hopes to shorten this duration to ten years in the near future. Further, visualisation is also used to improve the level of current *takumi* craftsmen. Currently, 45 operators have been trained by this process.

Regarding HRD for digitalisation, many of the firms opted to have existing production engineers or shop-floor managers learn about new technologies. Even in a large enterprise like Firm C, there were no AI specialists in their production departments. Engineers in the production field learn about AI (e.g. a Bayesian network) by themselves. This is even more true for smaller companies. For example, Firm F selected managers from production engineering and manufacturing sections to initiate the digitalisation project. The selected members, who were experts in the Toyota Production System, engaged in inventing IoT systems that were simple and comprehensible for non-specialists. Firm F employed AI specialists only after the firm gained experience in digital technologies.

In Firm G, IT specialists work with the manufacturing section. The interviewee stated that communication between the IT and plant operations staff remains difficult. The firm's IT staff are specialists with (until recently) very little experience with production-related issues. In contrast, its operators lack IT skills. Thus, both sides need to learn each other's 'language' to cooperate in platform creation. The case firm put the IoT project members from different sections in the same large room in the factory to facilitate face-to-face interactions and knowledge exchanges.

5 Implications and future research agenda

5.1 Digitalisation as lean augmentation

Regarding the question of how Japanese firms embrace digitalisation, the studied firms are deliberately seeking ways to enhance their lean capabilities through digitalisation. On the other hand, there are significant differences between the postulated digitalisation concepts and the actual implementation. Our findings generally support previous studies that suggest that digital technologies can assist lean manufacturing (e.g. Bauer et al., 2018; Kolberg et al., 2017; Lugert and Winkler, 2019; Sanders et al., 2016; Wagner et al., 2017). Except for Firm E, all studied firms have selectively introduced digital technologies to support their existing production systems. Various types of sensors are being used to monitor and keep track of production activities such as time-compressing tools for operations control and *kaizen*. LCD *andons*, tablets, and smartphones are being employed to move towards paperless shop floors. Unmanned part delivery systems are being introduced to enhance pull logistics. Some of these technologies are novel to the selected firms but are being used in line with the lean principle. It is likely that these firms regard digitalisation as a means to augment lean production capabilities.[7]

Conversely, we are not convinced that lean production facilitates the introduction of Industry 4.0 or Smart Manufacturing. While we do not deny the logic that lean principles can serve as the underpinnings of Industry 4.0 (Prinz et al., 2018; Rossini et al., 2019; Sony, 2018; Wang et al., 2016), we found no evidence that firms implementing lean practices have a higher willingness to adopt highly automated, autonomously controlled, or self-configuring manufacturing systems. For example, while Firm F exhibits the highest level of IoT implementation, they rely heavily on human efforts to control production operations and implement *kaizen*. This may paradoxically indicate that a firm that practises lean principles and is potentially ready to introduce Industry 4.0-like technologies has fewer motivations to adopt autonomously controlled or self-configuring systems. Similarly, our observations do not indicate that firms seek an integrated vision that relies exclusively on digital data. While firms address aspects of vertical and horizontal integration, they are typically generated to solve concrete operational issues instead of being guided by a concrete vision of seamless, digitally integrated manufacturing. If we compare our cases to the propagated vision of an autonomously adjusting process, we can make the following observation: By and large, Japanese firms focus on the digital shadow, and use data from the digital shadow for *kaizen* by operator teams. Conversely, the German vision[8] aims at self-regulating processes based on digital twin simulation.

5.2 Future research agenda

Additionally, our findings have led us to subsequent research questions.

5.2.1 Digitalisation and *kaizen*

First, will automated data collection (and diagnosis) help improve the effectiveness of solution generation and implementation in the long term? Digitalisation automates data collection (and, to some degree, diagnosis) and allows workers to focus on more creative tasks. Digitalisation may also facilitate a division of tasks between data collection (and analysis) and solution generation and implementation. This may, however, cause an unexpected obstacle for *kaizen*.

Manual data collection is time-consuming but, at the same time, allows workers to gather contextual information and re-examine the situation thoroughly. The current generation of workers at the selected firms have experience in collecting data both manually and automatically. If the next generation of workers come to rely entirely on automated data collection, can they remain creative in problem solving? It is noteworthy that many of our studied firms insisted that *kaizen* activities should be carried out on the shop floor. They know that the critical information needed for problem solving is 'sticky' to where the problem actually occurs (von Hippel, 1994; von Hippel and Tyre, 1995), and it would be problematic to attempt to solve the problem remotely.

Second, even if digital technologies augment lean capabilities, *kaizen* may not happen without organisationally coordinated actions. Problem-solving at a particular shop floor may require cooperation from other sections and suppliers (Fukuzawa et al., 2012; Iwao, 2017; Komatsu, 2006; Tamura, 2011). While introducing digital solutions, the studied firms intentionally secured room for human involvement in *kaizen* implementation. Will digitalised manufacturing reduce the need for human-based coordination?

Regarding this question, a pilot project that explored the relation between lean production and digitalisation has shown a potential conflict (Metternich et al., 2017):

Industry 4.0, especially as promoted in Germany, seeks autonomously self-regulating processes which has led some firms, such as Audi, to experiment with abandoning assembly lines. The study points out that this elimination of interlinked, standardised processes may undermine *kaizen* activity because standardisation is necessary to identify deviations and involve operators in improvement activities. Their argument may be extended by stating that self-regulating processes will be based on current standards and the transformation of these standards into digital models that govern self-regulation. Effectively, current standards will be frozen and self-regulation will only seek Pareto efficiency as defined by these standards. Thus, if processes should indeed be completely self-regulating, this implies that processes would have to be able to perform process improvement activities, such as *kaizen*, by themselves.

This leads to a research question about how digital technologies and humans can complement each other. While digital technologies have many strengths, they are not panaceas. AI will be superior to humans in solving problems in stable and predefined settings (e.g. optimising the paths of forklifts in a warehouse). In ill-defined situations, however, humans can be more flexible in comprehending problems and finding solutions. It appears safe to say that instead of the propagated vision of self-regulating processes, processes that combine the particular strengths of human operators and digital technologies are necessary for *kaizen*.

5.2.2 Lean augmentation versus the lean trap

This brings us to the third question, which is, will Japanese manufacturers go beyond lean augmentation? The digitalisation in the studied firms was implemented bottom-up. Since the interests of implementers (i.e. plant managers, production engineers, and shop-floor engineers) are normally rooted in factory- and/or shop-floor-level production problems, their search for uses for digital technologies will likely be anchored to the existing production paradigm. This gives rise to the possibility that an organisation holds back from adapting itself to develop the potential of new technologies. We frame this potential risk of being competent and persistent in the existing lean practices as a 'lean trap'. There are two streams of work that provide theoretical grounds for our conception.

One of the underlying arguments comes from the behavioural theory of firms (BTF). Levitt and March (1988) argue that an organisation adopts those practices and routines that lead to favourable outcomes as it learns from trial-and-error or organisational search. The so-called 'competence trap' can occur when the organisation ignores other practices/routines that may lead to more favourable outcomes. March (1991) generalises this argument by highlighting a trade-off between exploration and exploitation in organisational learning. When an organisation engages in the exploitation of the existing knowledge base without the exploration of new possibilities, the pace of improvements will be fast in the short term, but the improvements will plateau early. The ability to balance exploration and exploitation—ambidexterity—is essential for the long-term survival of the organisation. Although the majority of the studied firms exhibited the exploration of new digital technologies, they all seemed to frame digitalisation as a means to refine their existing production systems.

Regarding the organisational search, BTF explains that the less a firm is satisfied with its current performance, the more it will engage in searching for new alternatives; the degree of satisfaction will then be affected by a firm's level of aspiration (Argote and Greve, 2007). In the context of the automotive industry, pressures from original equipment manufacturers (OEMs) may serve as a driving force to raise the aspiration levels of suppliers. Olejniczak et al. (2020) found that Japanese subsidiaries whose main customers are German car manufacturers tend to invest more in advanced automation characterised by Industry 4.0 to meet their procurement standards. In our case study, Firms A, B, and F are *keiretsu* suppliers of OEMs (Firm C and G), and they are relatively active in exploring digital technologies. In contrast, Firm E, which is independent of any

OEMs, does not engage in digitalisation in production.

Another reason for the lean trap is our understanding of economic history, especially concerning the so-called productivity paradox. Economic history suggests that industrial revolutions only realise their full impact if they are accompanied by new forms of organisation. David (1990) highlights the time-lag of the macro-economic impact of novel general-purpose technologies and argues that the time lag is caused by the initial use of new technologies within existing organisational patterns. Only when new technology is employed according to novel organisational patterns is superior performance achieved.

If we assume that digitalisation is a novel general-purpose technology, the lean trap means that the firm will employ it within the existing organisational paradigm of lean production. While this may lead to productivity improvement, this improvement is rather modest. Simultaneously, focusing on the current paradigm may cause firms to underutilise the potential that new technologies offer. It is correct that firms search for new practices, but the search is informed by a lean production approach in the sense that new technology is applied to augment existing tools instead of searching for new tools based on novel technology. It should be emphasised that this type of digitalisation relies on bottom-up operator input for problem solving, which is quite different from the propagated visions of a self-regulating manufacturing process that, as a consequence, relies little on operators.

6 Conclusion

The Japanese automotive-related firms investigated in our study selectively adopted digital technologies to achieve paperless shop floors, compress the time needed to grasp the status of operations, and pursue unmanned logistics. Their use of these technologies strengthens the lean principle of existing production systems by compressing the time needed for a task that does not directly add value. We labelled this type of digitalisation use 'lean augmentation'.

Based on our findings, we identified the following research opportunities: 1) long-term impacts of digitalisation (especially the partitioning of data collection and solution generation) on *kaizen*, 2) roles of the human involvement and organisational coordination mechanism in digitalised manufacturing, and 3) the potential risk of lean augmentation being caught by lean trap. The studied firms' digitalisation initiative was predominantly led by practice-based learning rather than theoretical visions (e.g. Industry 4.0 or the Industrial Internet of Things). This approach would allow firms to quickly incorporate digital technologies into existing practices involving human operators in *kaizen*, and prevent black-boxed digitalisation aimed at autonomous production processes. Nonetheless, our theoretical arguments suggest that there is a risk that these new technologies will be underutilised, thus limiting their potential. Japanese manufacturers can be caught in a lean trap if they value exploitation over exploration. To further develop these arguments and collect evidence regarding lean traps, longitudinal studies and international comparative analyses appear to be necessary.

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Table 1 List of firms investigated

Firm	Type	Products	Interviewees	Date
Firm A	Supplier (*keiretsu* of C)	Stamping parts	General manager (Advanced Engineering Centre), deputy general manager (AEC), assistant manager A (AEC), assistant manager B (AEC)	14 Nov. 2019
Firm B	Supplier (*keiretsu* of C)	Meter clusters	President, manager A (production engineering), manager B (purchasing and operations management), manager C (operations management),	14 Nov. 2019
Firm C	OEM	Passenger cars	Executive advisor, deputy general manager (production engineering), manager A (production planning), manager B (industry-academia-government collaboration)	15 Nov. 2019
Firm D	Supplier (independent)	Tyres	Manager A (business planning), manager B (R&D), manager C (production engineering), manager D (production engineering), manager E (technology planning)	18 Nov. 2019
Firm E	Supplier (independent)	Brake parts	Manager (corporate planning, RPA project)	19 Nov. 2019
Firm F	Supplier (*keiretsu* of G)	Metal parts	Chief technology officer, chief consultant	20 Nov. 2019
Firm G	OEM	Passenger cars	Project general manager (assembly division), general manager A (production engineering), general manager B (human resources), group manager (human resources)	21 Nov. 2019

Table 2 Summary of the case studies

		Firm A	Firm B	Firm C	Firm D	Firm E	Firm F	Firm G
		Supplier	Supplier	OEM	Supplier	Supplier	Supplier	OEM
		Stamping parts	Meter clusters	Passenger cars	Tyres	Brake parts	Metal parts	Passenger cars
Operations	1) Processing	X		X	x		X	
	2) Assembly	X		X				
	3) Inspection	x	X	x	X			x
	4) Inventory & logistics		X	x				X
	5) Maintenance	x		x			X	X
	6) Production planning & control					x		
Kaizen	1) Data collection	X	X	X	X		X	X
	2) Analysis	x	x	x	X		x	X
	3) Solution generation			x	x			
	4) Implementation							
Human resource development	1) HRD by digital technologies			X				
	2) HRD for digital technologies			x	x		X	x

[Notes] X: Digital technologies are in use (IoT, CPS, AI, etc.; excluding conventional information and communication technologies, such as barcodes, e-*kanbans*, and LCD *andons*.).
x: Under study or experimentally implemented.

[1] First, we use the term Industry 4.0 as an equivalent to similar terms such as Industrial Internet of Things, Smart Manufacturing, and digitalisation. Second, it should be emphasised that this trigger function is probably more prominent outside Germany. Krzywdzinski's (2020) comparison of automation and digitalisation in the automotive industries of Germany, Japan, and the USA demonstrates that whereas automation, including automation in final assembly, decreased in Japan and the USA, it never truly fell out of favour in Germany. Thus, while there is some continuity between automation and digitalisation in Germany, the Industry 4.0 debate reintroduced automation (as 'smart automation') as a topic in other countries.

[2] We want to highlight two aspects. First, the time lag between the discovery of the potential and the beginning of exploitation suggests that questions about whether technology is inducing incremental or disruptive change can only be answered ex post facto. Second, regarding digital automation, the idealised process is as follows: Various sensor data are aggregated to form a digital, real-time replica of the actual production process, i.e. the digital shadow. The digital shadow is then utilised for real-time simulation of processes, i.e. the digital twin. Finally, the digital twin is the basis for software-controlled self-organisation of processes. Thus, what is different from conventional automation is that the new, 'smart' systems possess the capability to autonomously plan and control decisions about work processes (Hirsch-Kreinsen, 2017, p.172). Simultaneously, our research results highlight that the digital shadow can be used for optimising production through human *kaizen* activity. Thus, regarding the function to 'informate', related questions are who is informed, about what, and for what purpose?

[3] It is noteworthy that the discussion about the compatibility between lean production

and digitalisation is not being conducted in Japan. Reviewed Japanese literature does not engage in this debate at all. A systematic exploration of potential reasons behind the absence of the compatibility argument in Japan will be an interesting question for future research to understand the socio-technical context for digitalisation. See related discussions in sections 5.1 and 5.2.3.

[4] It should be emphasised that while the general principles are unchanging, techniques are constantly evolving. Fujimoto (1999) documented the evolutionary development of the Toyota Production System, including times of crisis and learning. Rother (2010) highlighted that Toyota standardises problem solving patterns but not solutions.

[5]Since *kanban* is a media to carry information, physical cards are replaceable by digital means such as barcodes and RFID. Thus, a paper-based shadow can be substituted by a digital shadow. Toyota started to send kanban for large components such as engines via computers in 1975 and shifted to e-kanban in 1998 (Monden 2012, p. 271f.).

[6] Some researchers from the technical field have even identified Industry 4.0 as a successor of Computer-integrated Manufacturing (CIM), stating the apparent shortcomings of this approach were largely due to the technology not being advanced enough during the 1980s (Jeschke et al. 2017, p. 4f.). Clearly, this technical perspective on digitalisation regards current information technologies as sufficient to implement an updated version of CIM under the label of Industry 4.0.

[7] This maybe also be explained in a different way: Instead of stressing holistic transformation towards a vision, it may be argued that firms purposefully challenge and disrupt routines to stimulate innovation and adaption of parts of the firm (Herrigel, 2017). In this view, organisations may still undergo transformative change, but this change is induced by knock-on effects of endogenous change originating within a distinct part of

the firm.

[8] The gap between vision and actual deployment may also be considerable in Germany: Hirsch-Kreinsen (2019) observes that large German firms are significantly more prone to seek holistic visions of transformative change than SMEs. Remarkably, however, two Japanese OEMs in our sample are rather following an experimental approach to gradually learn how to utilise digital technology.