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Digitalization in lean manufacturing firms: a cumulative capability development perspective

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Abstract

Purpose – The purpose of this paper is to examine the digitalization of operational processes and activities in lean manufacturing firms and explore the associated learning implications through the lens of cumulative capability theory.

Design/methodology/approach – Adopting a multiple-case design, we examine four cases of digitalization initiatives within lean manufacturing firms. We collected data through semi-structured interviews and direct observations during site visits.

Findings – The study uncovers the development of learning capabilities as a result of integrating lean and digitalization. We find that digitalization in lean manufacturing firms contributes to the development of both routinized and evolutionary learning capabilities in a cumulative fashion.

Originality/value – The study adds nuance to the limited theoretical understanding of the integration of lean and digitalization by showing how it cumulatively develops the learning capabilities of lean manufacturing

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firms. As such, the study supports the robustness of cumulative capability theory. We further contribute to research by offering empirical support for the cumulative nature of learning.

Keywords Digitalization, Lean, Cumulative capability development, Industry 4.0, Learning
Paper type Research paper

1. Introduction

Popularized in the 1990s, lean manufacturing remains one of the most successful approaches to business improvement (Jones and Womack, 2016) and continues to be a trending topic in the academic literature, as evidenced by steadily increasing scholarly interest over the past 3 decades (e.g. Furstenau *et al.*, 2021). Nowadays, however, digitalization is gaining greater traction in driving the next wave of industrial improvement, referring to the application of digital technology to "fundamentally revisit intra- and inter-organizational decision making, processes, and architectures" (Holmström *et al.*, 2019, p. 728). This has generated an ongoing discussion regarding the integration of lean and digitalization, particularly, given the backdrop of the fourth industrial revolution – Industry 4.0. To date, there is "much confusion (. . .) about how these two approaches might fit together" (Hines *et al.*, 2023, p. 64).

Nevertheless, the literature on lean and Industry 4.0 has been predominantly optimistic about the integration of lean and digitalization (Cifone *et al.*, 2021; Rosin *et al.*, 2020; Tortorella *et al.*, 2019), with several studies delving into their complementarity (Bittencourt *et al.*, 2021; Chiarini and Kumar, 2021; Ciano *et al.*, 2021). Although the integration of lean and digitalization is essentially a sociotechnical issue, most studies pursue a techno-centric focus, concentrating on technical implementation while neglecting underlying social aspects (Buer *et al.*, 2018). According to Cifone *et al.* (2021), overlooking the social aspects during the integration of lean and digitalization has important consequences. While replacing humans with technology can improve performance, it might hinder sustained improvement by constraining empowerment and limiting the capability of humans to reflect, learn and act. Furthermore, integrating lean and digitalization depends critically on learning (Saabye and Powell, 2022).

We, therefore, suggest that digitalization requires lean manufacturing firms to embrace multiple capabilities simultaneously – pointing to the importance of cumulative capability development. Cumulative capabilities are referred to as behavior modes of a firm that build upon and mutually reinforce each other (Flynn and Flynn, 2004; Größler and Grübner, 2006). As such, developing cumulative capabilities is crucial to obtaining synergies (Ferdows and De Meyer, 1990). Thus, there is a need to better understand capability development and how established capabilities are affected by new capabilities and vice versa (Wiengarten *et al.*, 2023). Research also highlights learning as essential in developing cumulative capabilities (Rosenzweig and Roth, 2004).

Whereas the interconnections between lean and learning on one hand and digitalization and learning on the other have been acknowledged independently in the literature (Åhlström *et al.*, 2021; Powell and Coughlan, 2020; Tortorella *et al.*, 2020), the learning implications associated with the integration of lean and digitalization lack sufficient conceptual elaboration and empirical evidence (Cifone *et al.*, 2021). Furthermore, the development of cumulative capabilities underpinning the integration of lean and digitalization remains poorly scrutinized in extant literature, requiring scholarly attention (Belinski *et al.*, 2020; Saabye *et al.*, 2021).

Responding to the identified practical challenges and the presented research gaps, this study aims to examine the learning implications associated with the integration of lean and digitalization from a cumulative capability development perspective. Addressing this research objective, we pose the following research question: *How does digitalization in lean manufacturing firms relate to cumulative capability development?*

To answer the research question, we adopt a qualitative research approach, conducting a multiple-case study (Eisenhardt, 1989) that investigates digitalization initiatives across four lean manufacturing firms. Our findings highlight that digitalization in lean manufacturing firms contributes to the cumulative development of multiple capabilities. We develop a theoretical model of cumulative capability development in digitally enhanced lean manufacturing. Offering a response to our research question, the model interrelates the core components of cumulative capability development. Identifying the importance of cumulative learning, we add insights on how to effectively integrate lean and digitalization, responding to calls for research on the topic and providing empirical evidence to advance its theorization (Meindl *et al.*, 2021; Mora *et al.*, 2017; Powell *et al.*, 2018).

The remainder of the manuscript is organized as follows. Section 2 establishes the conceptual background of the study. In Section 3, we outline the research design. We then present the empirical findings derived from within-case analysis (Section 4) and cross-case analysis (Section 5). In Section 6, we discuss contributions and implications as well as the study's limitations and future research avenues.

2. Conceptual background

2.1 Lean and digitalization

The term lean manufacturing was first coined by Krafcik (1988) and later popularized by Womack *et al.* (1990). From a phenomenon-based perspective, lean manifests itself in distinct "lean" practices, principles, strategies, behaviors and mindsets that can be observed in firms (Cusumano *et al.*, 2021). Seeking improvement, many manufacturing firms turned toward lean manufacturing which is a multifaceted concept that lacks a unifying and commonly accepted definition (Åhlström *et al.*, 2021). In this study, we conceive of lean manufacturing as an integrated learning system, composed of interrelated elements such as lean thinking and lean practices (Jones and Womack, 2016). Lean manufacturing aims at creating customer value, reducing waste and being cost-efficient. Firms that have successfully adopted lean manufacturing have witnessed productivity soar, defects cut in half and development times slashed (Netland and Powell, 2017). Oriented toward continuous improvement, learning has been identified as a core element of lean success (Powell and Coughlan, 2020; Saabye *et al.*, 2023).

With the onset of Industry 4.0, digitalization has shifted to the forefront in both practice and academia. Digitalization refers to the application of digital technology to "fundamentally revisit intra- and inter-organizational decision making, processes, and architectures" (Holmström *et al.*, 2019, p. 728). A prerequisite for digitalization is digitization, referred to as the straightforward conversion of analog information to a digital format (Gobble, 2018; Holmström *et al.*, 2019). Essentially, whereas digitization does not change the business in itself, digitalization does (Gobble, 2018). Two fundamental digital technologies which are cornerstones of digitalization are cloud solutions and industrial Internet of things (IIoT) (Frank *et al.*, 2019; Koh *et al.*, 2019; Liu *et al.*, 2021).

Cloud solutions such as cloud-based collaboration and communication platforms provide a real-time environment for multiple persons to access, share and store information, communicate, work together and coordinate activities (Frank *et al.*, 2019; Thoben *et al.*, 2017). IIoT refers to a "network of intelligent and highly connected industrial components that are deployed to achieve high production rate with reduced operational costs through real-time monitoring, efficient management and controlling of industrial processes, assets and operational time" (Khan *et al.*, 2020, p. 2).

Digitalization in manufacturing aims at increasing the efficiency and flexibility of manufacturing operations (Lorenz *et al.*, 2019) and is considered a primary enabler of competitive advantage (Buer *et al.*, 2018). Digitalization has been shown to enhance both firms' operational (Hautala-Kankaanpää, 2022) and financial (Abou-Foul *et al.*, 2021) performance. However, realizing digitalization's potential requires firms to go beyond the mere use of digital technologies and requires a systematic integration within the established manufacturing landscape (Angelopoulos *et al.*, 2023). This raises the question about the relationship between lean and digitalization, whereby lean continues to be the dominant approach to industrial improvement (Ashrafian *et al.*, 2019).

Discussions around the combination of lean and digitalization are ongoing in scholarly literature, where diverse arguments have been presented. While few researchers have argued that lean and digitalization may need to be traded off against each other (Sartal *et al.*, 2022), the majority of research adopts an optimistic view, proposing a complementary relationship (Buer *et al.*, 2018). For example, setting out to investigate the contradictory or complementary nature of lean and digitalization, Lorenz *et al.* (2019) indicate a positive correlation between the digital and lean maturity of firms and the respective impact on operational performance. The authors suggest that digitalization can support lean, and lean can support digitalization. Similarly, Cifone *et al.* (2021) present examples of how digital technologies can support lean practices, for example, by providing greater visibility of processes and fostering greater employee engagement in problem-solving activities. Although most studies suggest a positive link between the two, some authors (e.g. Tortorella *et al.*, 2019) advise about unexpected negative implications on operational performance, particularly, when one of the approaches is ill-structured or misguidedly implemented. However, only a few studies have explored approaches to synergistically integrate digitalization efforts in lean manufacturing firms (Deuse *et al.*, 2020).

Prior research has largely explored the digitalization of processes (Lorenz *et al.*, 2020) emphasizing technological aspects (Dalenogare *et al.*, 2018), implementation patterns (Frank *et al.*, 2019) or strategies to capture digitalization benefits (Stark *et al.*, 2023). More recently, studies approach digitalization from a sociotechnical point of view (Laubengaier *et al.*, 2022), offering preliminary steps to our research. For example, Romero *et al.* (2020) explored Operator 4.0, placing workers at the center of digitalization efforts, while Marcon *et al.* (2022) evaluated the contribution of various sociotechnical factors (such as the practices exhibited by lean manufacturers), on the implementation of Industry 4.0 technologies. Furthermore, Dornelles *et al.* (2022) indicated how different digital technologies are linked to the "smart working" dimension of Industry 4.0, while Cagliano *et al.* (2019) investigated the human aspects of "smart working" in manufacturing, such as worker autonomy and social interaction, finding that when firms adopt technology they must also adapt work organization. Investigating the application of collaborative robots, Dornelles *et al.* (2023) indicated how digital technologies can affect workers' skills, including upskilling, reskilling or even deskilling. Though such studies converge on approaching digitalization from a more balanced sociotechnical perspective, they poorly address learning aspects, which presents itself as a major shortcoming in the extant literature.

Thus, most research still tends to view workers as "static recipients of tools and technologies" (Hines *et al.*, 2023, p. 77), while learning implications of digitalization initiatives remain poorly scrutinized (Angelopoulos *et al.*, 2023; Tortorella *et al.*, 2022). Though Tortorella *et al.* (2020) suggested that learning mediates the effect of digitalization on performance, the authors do not explore the development of learning capabilities. Moreover, the implications of digitalization on a firm's ability to learn are quite unknown (Bittencourt *et al.*, 2021). Reflecting on this challenge, Saabye and Powell (2022) investigated how manufacturers can foster insights and improvements from real-time data among shop-floor workers. They identified the development of organizational "learning-to-learn" capabilities, based on the lean principle of learning through problem-solving, as essential for advancing a firm's digitalization initiatives.

2.2 A cumulative capability development perspective on digitalization in lean manufacturing firms

Given the importance of learning in both lean and digitalization initiatives and drawing on previous research pointing to the need to account for cumulative capability aspects in lean manufacturing (Powell and Coughlan, 2020), we adopt a cumulative capability development perspective to uncover learning implications associated with the integration of lean and digitalization. We propose cumulative capability theory as a suitable lens to analyze how firms can embrace multiple capabilities simultaneously when integrating lean and digitalization.

In operations management (OM) literature, capabilities are referred to as "behavior modes of a plant with which it can support and shape corporate strategy and which help it succeed in the marketplace" (Größler and Grübner, 2006, p. 458). The concept of cumulative capability development indicates capabilities that build upon and mutually reinforce each other, implying "high performance in multiple capabilities simultaneously" (Flynn and Flynn, 2004, p. 440). Cumulative capability theory assumes that cumulative capabilities are more likely to lead to lasting improvements than capabilities that are established at the expense of others (Ferdows and De Meyer, 1990).

Most studies dealing with cumulative capabilities examine the cumulative nature of strategic or competitive capabilities (Rosenzweig and Roth, 2004) composed of quality, delivery, cost and flexibility (Amoako-Gyampah and Meredith, 2007; Flynn and Flynn, 2004; Narasimhan and Schoenherr, 2013). Though the cumulative nature of lean practices has also been explored (Bortolotti *et al.*, 2015), systematic examinations of digitalization efforts in lean contexts to analyze associated cumulative capability development are lacking.

Cumulative capability theory suggests that learning is central to developing cumulative capabilities (Rosenzweig and Roth, 2004). For example, Tamayo-Torres *et al.* (2017) identify learning as an enabler for cumulative capability development. Learning has further been established as an integral part of lean (e.g. Powell and Reke, 2019), while digitalization has also been shown to lead to learning (Sunder *et al.*, 2023; Tortorella *et al.*, 2022). Though the significance of learning has been established for both lean and digitalization in isolation, learning mechanisms associated with the integration of lean and digitalization are unexplored (Belinski *et al.*, 2020).

Accounting for learning, Fujimoto (1999) presents an evolutionary perspective of capability development to explain the long-term success of Toyota Motor Company and offers a three-level model consisting of routinized manufacturing capability, routinized learning capability and evolutionary learning capability. Whereas routinized manufacturing capability refers to the ability to maintain a steady state with stable performance, routinized learning capability refers to the ability to change the manufacturing system to improve functionality. Evolutionary learning capability is defined as a firm's ability to cope with a complex process of capability building and affects the other capabilities themselves. This capability is of the highest importance as it allows a firm to outperform its rivals in dynamic conditions characterized by high uncertainty. Although Roehl (2000) stressed the "important conceptual contribution that Fujimoto makes" (p. 439), the conceptual model remains largely neglected in the scholarly literature and lacks empirical substantiation.

Drawing on cumulative capability theory (Ferdows and De Meyer, 1990; Flynn and Flynn, 2004), we propose that the three levels of capability development presented by Fujimoto (1999), may be three cumulative levels that a lean firm must further embrace in the digital era. Possessing evolutionary learning capability is pivotal to realizing growth opportunities but the limited understanding of how or what "enables a firm to develop such a capability" causes the need for corresponding investigations (Heller, 2002, p. 37).

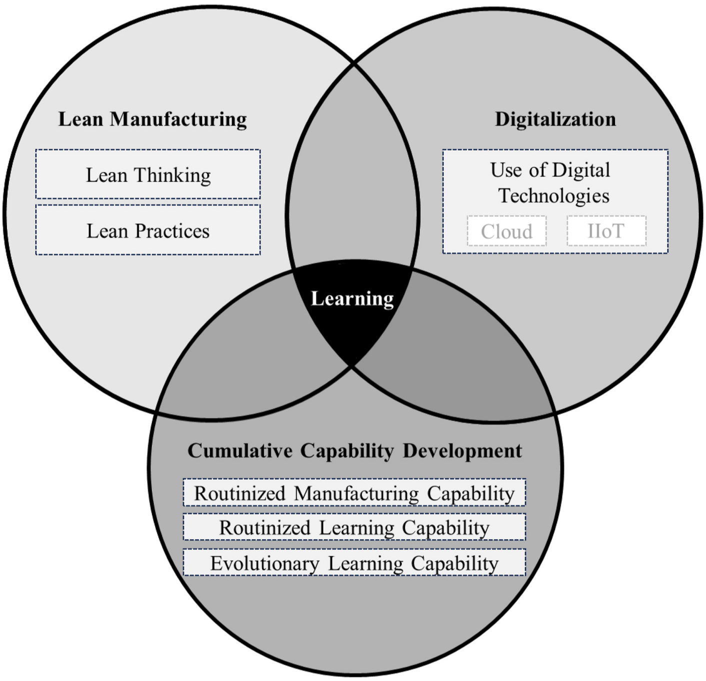
In summary, there is a lack of research into digitalization in lean manufacturing firms from the angle of cumulative capability development. In line with these identified research gaps, we pose the following research question (RQ): *How does digitalization in lean manufacturing firms relate to cumulative capability development?* The conceptual framework guiding our study is shown in Figure 1.

3. Research design

Owing to the exploratory nature of our research question, we applied a qualitative, multiple-case design (Eisenhardt, 1989, 2021). Case research allows for examining phenomena in their real-life context and understanding complexities and dynamics (Eisenhardt, 2021), making it appropriate to explore digitalization in lean manufacturing firms. We engaged in a qualitative inquiry as it is particularly suitable when little is known about the phenomenon under study (Miles and Huberman, 1994). Relying on multiple cases enables inter-case comparison and fosters external validity (Eisenhardt, 1989). Multiple-case research allows to build and elaborate theory (Gehman *et al.*, 2018). In this study, we attempt to elaborate theory as the integration of lean and digitalization is at an early stage of knowledge creation. For example, though digitalization, lean and learning have been studied separately, only a few studies consider them collectively (e.g. Saabye *et al.*, 2023).

3.1 Case selection

Case research requires "choosing cases where the focal phenomenon is likely to occur, and (. . .) where similarities and differences across cases are likely to improve theory building" (Eisenhardt, 2021, p. 149). Although multiple-case research "is *not* about a specific number of



Source(s): Author's own work

Figure 1.
Conceptual framework

cases," a workable amount ranges between 4 and 10 (Eisenhardt, 2021, p. 153). We carefully selected four cases following theoretical logic to support the content validity and generalizability of our study (Eisenhardt, 1989, 2021). Informed by the key concepts of our investigation (Figure 1), our case selection was based on the following key criteria:

Manufacturing firms with a formal lean program were selected to ensure comparable and mature adoption of lean throughout the firms. Encountering the narrow focus on singular countries in many studies which has been claimed for instance by Szász *et al.* (2021), we selected lean manufacturing firms across different sectors and located in different countries. We do so to offer a more generalizable empirical examination and increase the robustness of the theoretical insights derived from the empirical findings. Considering the integration of lean and digitalization as a sociotechnical phenomenon, we selected two countries strongly oriented toward sociotechnical manufacturing systems and which place particular emphasis on social concerns – namely, Denmark (Marcon *et al.*, 2022) and Norway (Hekneby *et al.*, 2021); and two countries that have a prevailing techno-centric orientation guiding manufacturing – namely, Brazil and Germany (Brunheroto *et al.*, 2021).

Given that our unit of analysis is the digitalization initiative in each of the firms, we selected firms that were engaging in digitalization initiatives, involving the use of digital technologies that were new to the firms. Each firm's digitalization efforts comprised an array of different digital technologies (see Table 1), such that their digitalization breadth (defined as the number of types of digital technologies adopted (Yang *et al.*, 2023)) went beyond a singular digital technology. The digitalization intensity [referred to as the degree of use of a type of digital technology (Yang *et al.*, 2023)] was another important aspect to consider. We deemed it crucial to focus on specific digital technologies exhibiting digitalization intensity to ensure in-depth use and continued entrenchment of the technology within the firm (Yang *et al.*, 2023). Correspondingly, we refrained from examining diverse digital technologies that were merely in the trial stage or used sporadically. In the interest of digitalization intensity, we determined cloud solutions and IIoT to be appropriate because of their fundamental importance for digitalization (Frank *et al.*, 2019; Koh *et al.*, 2019; Neumann *et al.*, 2021). Moreover, these technologies are highly relevant in practice and research alike (Frank *et al.*, 2019). Therefore, for selection purposes, firms should exhibit high digitalization intensity in cloud-based solutions and/or IIoT. Concentrating on these two specific digital technologies enabled meaningful comparison across cases.

In line with the notion of matched pairs (Eisenhardt, 2021), we selected two firms using cloud-based collaboration and communication platforms and two firms using IIoT. Comprised in their digitalization initiatives, these digital technologies were new to the firms and used committedly (i.e. digitalization intensity). We also opted for an array of two pairs of similar case features as prior multiple-case studies demonstrated it to be appropriate for achieving a satisfactory level of theoretical saturation (e.g. Jia *et al.*, 2021). As Germany, Brazil, Norway and Denmark are the home countries of select authors of this study, we used our local industrial networks and talked to industry experts in the respective countries to help identify potential case firms. Direct contact with firm representatives was carried out to confirm fulfillment of the selection criteria.

Finally, in line with recent OM studies (e.g. Al Hasan and Micheli, 2022), we purposely focused on a different focal area within each firm with the aim of replicating emerging insights across settings. The focal areas considered were product development, production, shopfloor management and maintenance – covering the main aspects of the manufacturing value chain. Corresponding with the collaborative nature of product development and shopfloor management, we examined cloud-based solutions in these two focal areas. Production and maintenance typically involve machinery and equipment, making the study of IIoT appropriate in these two focal areas. The four lean manufacturing firms are described in Table 1.

Table 1.
Case overview

Case company	Industry	Country	Digitalization breadth (select technologies)	Principle technology examined	Focal area of investigation	Interviewees
DENTAL Co.	Healthcare	Germany	Artificial intelligence, 3D-printing, cloud-based services and solutions	Cloud-based collaboration and communication platform	Product development	1 director process engineering and production, 4 managers (parts manufacturing, process engineering parts manufacturing, process engineering assembly, process support parts manufacturing), 2 process engineers (manufacturing, IT)
ELECTRO Co.	Electronics	Brazil	Industrial Internet of Things (IIoT), Cloud computing, big data analytics, wireless sensors, remote monitoring	Industrial Internet of Things (IIoT)	Production	1 manufacturing manager, 1 maintenance coordinator, 2 maintenance analysts, 3 maintenance technicians, 1 production supervisor
BUILD Co.	Building material	Denmark	Industrial Internet of Things (IIoT), Cloud computing, Digital twins, simulation and modelling, autonomous-guided vehicles (AGVs)	Industrial Internet of Things (IIoT)	Maintenance	1 factory manager, 2 directors, 1 department manager, 1 general manager, 1 technical manager, 3 project managers
MARITIME Co.	Maritime technology	Norway	Cloud-based services and solutions, 3D printing, Remote monitoring solutions	Cloud-based collaboration and communication platform	Shopfloor management	1 production manager, 1 lean program manager, 1 quality manager, 1 production planner, 2 production team leaders, 3 operators

3.2 Data collection

The bulk of data originates from semi-structured interviews with a total of 33 employees ranging from directors to operators. We established a key contact person per firm who assisted us in identifying suitable interviewees (Longoni and Cagliano, 2015). The selection criteria were as follows: each interviewee should be directly involved in or knowledgeable about the firm's lean and digital initiatives, should have been applying lean practices as part of the daily business and should be subjected to using digital technology.

The semi-structured interviews (of approximately 1-h duration) followed an interview guide (see Appendix 1) and were recorded upon approval by interviewees. We developed open-ended questions based on a literature review (e.g. Saabye *et al.*, 2023), which covered several main topics, including lean implementation, digitalization efforts and learning implications. The interview guide was shared with interviewees beforehand for familiarization purposes. Interviews were conducted in a hybrid mode, with at least one researcher physically present and others participating online. Interviews were conducted in English and transcribed verbatim. Transcriptions were quality assured by the interviewees.

Triangulating the interview data, we conducted direct observations through site visits at each firm. Doing so, we follow previous lean studies that argue for the use of "direct observation of the operations in order to get a thorough and comprehensive understanding of the degree of adoption of the various lean practices together with an appreciation of the overall level of maturity of the lean production system in place" (Camuffo and Gerli, 2018, p. 407). Site visits lasted at least one day and were conducted by different members of the research team depending on their home country. The visits involved gemba walks to observe the production operations, lean practices and technologies, as well as to identify indications of problem-solving and learning. During the direct observations, we were also able to obtain specific insights into how the digital technologies adopted related to the firms' lean efforts.

3.3 Data analysis

The analytic process consisted of iterations of constant comparison and replication logic to identify patterns within and across cases (Eisenhardt, 2021). First, descriptions of each case were developed. Being our main source of evidence, interview transcripts were read several times allowing the researchers to immerse themselves in the topic. We complemented the interview data with notes taken during and after site visits to create the descriptions. As part of the within-case analysis, we identified the principal technology adopted and we coded and assessed if and how it related to the firm's lean initiatives. Using open coding (Gioia *et al.*, 2013), the authors independently coded the cases and checked the reliability of the coding through check-coding and comparison, allowing us to reach inter-coder agreement (Goffin *et al.*, 2019; Miles and Huberman, 1994).

We then engaged in cross-case analysis to identify dominant patterns across cases. Eisenhardt (2021) refers to cross-case analysis as "various approaches to improve the creativity and reliability of the analysis" (p. 152). A major component of the cross-case analysis is the development of theoretical arguments that explain the patterns observed in the data (Eisenhardt, 2021). We grouped and connected first-order codes into second-order themes and abstracted these to aggregate dimensions (see Appendix 2). Representative data supporting each first-order code and second-order theme are displayed in Appendix 3.

To achieve conceptual abstraction within the a priori determined case settings (i.e. matched pairs of digital technologies in diverse focal areas), we proceeded iteratively through repeated steps of data collection and analysis until a sufficient level of saturation was reached. Theoretical saturation denotes the point where "the researcher has continued collecting and analyzing data until no new concepts appear and, thus, no additional data is needed" (Ketchen *et al.*, 2014, p. 8). In line with Eisenhardt (1989), we inferred saturation "at the point where the continuation of data collection provided no new conceptual insights" (Chakuu *et al.*, 2020, p. 1234). We stopped collecting and analyzing data once insights obtained in the last iterations were minimal and no new themes were identified. Therefore, the four cases were enough to reach a sufficient level of saturation. Data collection ended when we concluded that additional data would neither add new insights to theory construction nor increase our understanding of the research question (Eisenhardt, 2021). Theoretical relationships among constructs were established both within and across cases (i.e. replication logic) and with no more emergent patterns in the data, we were able to reach consensus on the resultant theoretical model.

4. Within-case analysis

This section presents findings from the within-case analyses. Following Pratt (2008), we integrate "power quotes" in the text to support arguments and provide supplementary "proof quotes" and observations in a separate Data Table (Appendix 3).

4.1 Digitally enhanced product development

DENTAL Co. is a producer of dental equipment and consumables with factories in 21 countries. The German plant is the largest production location and is considered the innovation center, as it features the firm's R&D and establishes the processes that are the fundament of the entire firm's product development in the equipment business area. As highlighted by the director of process engineering and production, the firm has "a very complex product and production structure".

The firm began its lean journey 20 years ago and not only adopted lean practices but also internalized the lean philosophy over time. The overall ambition is continuous improvement. The conventional innovation mode was to improve products incrementally but in 2022, the scope expanded to pursuing more radical innovations: "For about 15 years, we made smaller improvements or changes, but we did not redevelop completely. And now, we are on our way to making a complete change in our whole product" (manager – process engineering assembly).

Given its recent merger with an overseas corporation, the firm began to move toward a greater level of digitalization in 2018, adopting a cloud-based digital communication and collaboration platform (Microsoft Teams) for remote connectivity and virtual mobility of personnel to enable tighter integration with its US owners and employees at other overseas plants. The production manager said "before, we would send emails to each other and not know if people had even seen the emails. Now we meet every day at 7:30 am [on Microsoft Teams], to look at delivery dates and discuss delivery problems." Operators and shopfloor managers have also recently been equipped with wearable headsets such that they are "continuously connected as part of the network" (process engineer). The interviewees highlighted that the novel work approach required people to adjust their behavioral patterns (e.g. by embracing remote communication). Especially, operators had to get used to the new practices as part of their daily business, making learning among blue-collar workers fundamental.

DENTAL Co. has been accelerating its product innovation process through remote collaboration, where geographically distributed product development teams were able to meet more frequently, albeit online. People located in different countries worked intensively together, shared ideas to a higher extent and supported each other in ongoing projects. Such connectivity has also enabled product development teams to break down large development projects into smaller, sub-projects and distribute ownership and responsibility worldwide, which has enabled faster learning cycles and greater sharing of "lessons learned" in the product development and industrialization process. Work in smaller sub-projects also enabled “to pre-develop some critical situations and parts and get them back together to the main project” (process manager).

Though the firm’s online meetings were structured around “technical product- and production issues” as well as “leadership topics”, the production manager reported that “although after some months the technical part works better and better, it remains difficult to talk to people and [gauge] their feelings on MS Teams. [. . .] When we are talking about technical points, it’s really easy with digital tools. When we’re talking about human topics, it’s very difficult.” The reason for this was that “the personal direct contact is missing” (process engineer). In product development, the “big problem also here is not the technical background but more the social organization. (. . .) This is more important than the technical background” (production manager). The “human” aspects appeared to be of the highest importance also for remote collaboration because many workers did not want to work online and showed high skepticism, fear and insecurities: “We had to solve a lot of tensions in the beginning and people were afraid of what was coming. [There was] a lot of work and talk about this point. Quite a tough time for me. Quite a tough time for everybody” (manufacturing manager). These issues were addressed and resolved in a communicative and collaborative approach. The improved collaboration from Microsoft Teams enabled employees to solve issues and support each other. A process engineer underlined “we learn together, either in discussion directly or remotely”. The future aspiration was to “find a good mix to learn together where we have to be in discussion directly or by a remote function” (production manager) to properly address the “technical” and the “human” aspects of new product development.

4.2 Digital total productive maintenance

ELECTRO Co. is a large electronics manufacturer located in Brazil that started its lean implementation in 2000. A multinational firm, its approach to lean has been standardized across sites, resulting in the prioritized adoption of certain lean practices. Among these, total productive maintenance (TPM) has been emphasized due to its benefits to process stability, which is still a point of concern. The firm has developed a systematic approach for TPM implementation, encompassing training and kaizen activities with all shopfloor operators and support employees, such as engineering, maintenance and quality. This has yielded significant improvements in overall equipment effectiveness (OEE), particularly in the first five years of its implementation. However, managers began to notice stagnation in the improvement of performance resulting from TPM, which raised the need for formulating new approaches.

In 2016, management decided to embark on a digital transformation, which saw the firm integrate digital technologies into its critical business processes. Given the previous focus on TPM, maintenance was selected as a pilot for the digital transformation initiative. Bottleneck operations across the manufacturing units, which already had many TPM practices implemented were the focus of an IIoT initiative. As there were different machines from various suppliers with distinct control systems, the challenge relied in understanding the feasibility of technology integration in each bottleneck operation. The manufacturing manager outlined that “the goal for this pilot was to integrate new technologies to allow the collection, sharing, and processing of data related to the conditions of the bottleneck operations (e.g. machine stoppages and critical components’ performance) in real-time. These data would be used to revise preventive and predictive maintenance activities, favoring the development of more assertive routines that could reduce maintenance costs while increasing OEE”.

With the significant increase in the amount of information, the maintenance crew became overwhelmed, raising barriers regarding technology acceptance. For example, despite the availability of information, "the process for conducting preventive and predictive maintenance activities based on [such] information was ill-structured, leading to confusion and skepticism from team members" (maintenance technician). However, personnel began to create new routines and new standards for preventive and predictive maintenance based on real-time data. As stated by the maintenance coordinator, "frequencies of preventive activities were tailored according to the wear of critical components observed from the data, allowing for smart resource optimization". Before the availability of these data, thresholds were based on the machine supplier specification, which may not always be optimal for the actual condition of use of the equipment. Overall, the incorporation of digital technologies into TPM practices helped this firm to reduce maintenance costs by 15% over a three-year period and improve the average OEE of the bottleneck operations from 72% to 80% during the same period. Additionally, the firm shared the lessons learned by disseminating the benefits throughout the global organization (i.e. yokoten which is the practice of and strategic focus on knowledge creation and sharing for increasing competitive advantage).

Over this process of digitalization, two distinct but interrelated types of learning were observed in the firm. First, when these technologies were introduced, employees struggled to understand the function of new technologies as stated by one of the maintenance analysts: "employees had to learn how to properly adjust, repair, or reset the wireless sensors installed on the components following a corrective or preventive maintenance activity." These issues were the main concern during the first few months following implementation. However, the production supervisor pointed out that "as this knowledge gap was mainly technical, it was easily addressed with technical assistance from the technology providers."

As the technical doubts were solved, a second learning process began, which was related to the actual integration of the information collected, shared and processed into TPM practices. The production supervisor suggested that "at the beginning, the exact benefits that would be observed from such technology integration were not entirely clear to operative and technical personnel." In fact, there was even a certain level of skepticism with the incorporation of digital technologies as pointed out by one of the operators: "I believe these new technologies provide very little value for money. I believe we have many more important issues that these technologies cannot address. So, I understand the company should be prioritizing other initiatives."

Such skepticism was also observed in the maintenance and engineering teams, as informed by a maintenance technician: "we believed our TPM practices were consistent enough and not much could be done differently to yield significantly superior OEE results." To address these issues and facilitate the second learning process, leadership played a key role in fostering the improvement of TPM practices based on the new, real-time information. In this sense, the maintenance coordinator together with the production supervisor organized meetings with their teams to explain the benefits of the digital technologies' integration into existing TPM practices. The production supervisor mentioned "during our daily management routine, we were fostering the utilization of the new information provided to challenge the existing assumptions about components' endurance and failure modes, for example. This critical-thinking development was mainly done by constantly questioning team members, although there were some situations where we had to be more directive with our employees to push the utilization of the new information provided by digital technologies." As this learning process occurred, team members started to realize their knowledge gaps, identifying new opportunities to revise predictive and preventive activities (e.g. frequencies, thresholds, etc.). Combining the action-learning approach from lean with digital enhancement of TPM practices using real-time information allowed the further improvement of the average OEE at bottleneck operations from 80% to 86% one year later.

4.3 Human-centric IIoT-based production

BUILD Co. is a large Danish building material firm. In 2005, the firm started implementing different lean practices. In 2019, it decided to introduce an IIoT system in its production line, the purpose of which was to digitalize the measurement of OEE and make real-time data accessible to operators. According to the project manager: “we assumed that once real-time data were available for the operators, they would engage in problem-solving, leading to improved production performance.” However, after several months, the factory manager concluded that “the initiative didn’t yield the intended result, and the production line was not performing any better, nor had the operators engaged in problem-solving efforts.”

The firm sought to understand the reasons for failure, identifying several factors all relating to human aspects. First, there was a widespread belief among shopfloor workers that their role was simply to identify problems and generate ideas. They believed it was the job of maintenance specialists or managers to solve problems and implement ideas. Second, utilizing real-time data generated by the IIoT system required a systematic problem-solving method, but the firm’s general approach to problem-solving was “at best be characterized as firefighting” (factory manager). Third, inquiries into the shopfloor workers’ perception of the new IIoT system revealed that they experienced the adoption as coercive, such that their acceptance of the new digital technology was rather low. When asked what they thought about the new system, the operators replied: “it is not our system. It is the leader’s or maintenance technician’s system. We know what is wrong with the production line and do not need this system to tell us this.” As such, operators did not see how this new system could enable them to improve performance. Although managers expressed a strong willingness to experiment and try new approaches, they themselves lacked the ability and capacity to foster experimentation and reflection due to the short-term focus on efficiency. Finally, despite all good intentions, managers neither facilitated learning, promoted empowerment, nor developed operators to become problem-solvers, despite the existence of real-time data.

Regardless of the failed implementation, the IIoT implementation led BUILD Co. to identify several impediments to the firm’s digital (and indeed lean) transformation. The newly introduced technology not only enabled the firm to detect these deficiencies but also evoked the pursuit of an extensive learning and development journey for employees across all hierarchical levels. Managers became more proficient in finding and framing problems in a systematic manner, facilitating a learning process to enable and empower subordinates to solve problems. Moreover, managers obtained higher awareness and a deeper understanding of digital technologies and the related adoption challenges. As part of the learning journey, managers were trained to become learning facilitators with the aim of cascading learning throughout the firm. One shopfloor manager stated, “we have managed to develop and empower operators to drive problem-solving activities themselves. Our role as managers is to ask questions instead of giving answers.” With respect to the learning path of operators, the shopfloor workers were empowered to find, face, frame and solve problems systematically using digital data. They were also able to learn where and how to set up further IIoT sensors.

Overall, the digitalization initiative allowed the firm to create a supportive learning environment. One of the operators said, “the [digital] screens prevent us from assuming what the problems and solutions and help us locate and remove the root causes of unplanned stops more effectively.” Another operator added, “the digital data we have access to has provided us with information of where to intervene in order to remove waste in our processes.” As such, the firm’s management has re-oriented its views on adopting and utilizing new digital technologies as “a learning process and developmental path,” where the implementation of technology is rather a means of finding and solving problems and not the end in itself.

4.4 Digitalized shopfloor management

MARITIME Co. produces technological products for the maritime industry and is headquartered in Norway. The firm began implementing its lean program in 2014 using a mixture of expert-led lean training for managers and operators, as well as implementing whiteboards and post-it notes to gather and promote improvement (kaizen) suggestions in the co-located factory teams. The program was rolled out globally across the firm's 12 production sites in Scandinavia, Europe, North America and China from 2015 onwards, first focusing on the adoption of lean best practices and from 2017 focusing more on lean leadership development and problem-solving capabilities. In 2018, the firm transitioned its suggestion system from an analog to a digital form throughout the entire firm, migrating its kaizen platform to a digital, cloud-based solution using Microsoft Teams and Planner and replacing wall-mounted whiteboards with digital screens.

With the new system, employees could enter improvement suggestions using their personal computers or smartphones rather than having to physically visit the whiteboard and fill out a post-it note. This gave much more reliable and real-time visibility of the system and digital kaizen cards were able to be transferred from team to team without the risk of losing paper cards, for example: "we did not know what happened to the note once we handed it over to another team . . . now we can see it online" (production operator). Moving also toward digital shopfloor management, the structure of departmental meetings was also later converted to a digital format, using Planner buckets for each production team. Moreover, Planner was also used for Health, Safety and Environment (HSE), daily management, reporting the progress of strategic actions, status with current and planned new product introductions and risk management. There was even a bucket for "good news" where employees could upload pictures and text to celebrate achievements and successes. In addition, there was a business intelligence app for performance management (PowerBI) in the suite of cloud-based solutions.

Though employees were generally neither for nor against such digitalization – "I don't care whether I write it manually or on the screen – this doesn't affect my suggestions" (operator) – the firm registered a significant increase in the number of improvement suggestions raised and implemented when transitioning from the analog tothe digital system (20–50% across most teams, and over 100% increase in one case in particular). The lean program manager suggested this was due to several factors, including "improved vertical escalation functionality, as well as the optimization of workflows and reduced administrative time required to enter, evaluate and review suggestions in the system." Second, the daily production management meetings became much more effective, with participants gathering around digital screens on the shopfloor (or joining remotely) rather than meeting around the desk of the production manager. The production manager suggested that "the better cross-functional coordination capability created by this hybrid approach improved horizontal collaboration opportunities and has increased productivity." The lean manager added that "our continuous improvement practices are now digitally connected, enabling increased transparency and a greater level of cross-functional continuous improvement and learning."

To summarize, Table 2 provides a comparison of the within-case findings.

5. Cross-case analysis

This section presents and elaborates on the main findings from the cross-case analysis. We refer the reader to Appendix 3 for further examples of evidence collected.

5.1 Routinized manufacturing capability: implementation of lean as base capability and improvement aspirations

Though the lean journeys of the firms began at different points in time, all firms exhibited the deployment of a formal lean program, which we refer to as the *implementation of lean as base*

Case	Introduction of lean	Digitalization initiative	Exemplary lean manifestations	Exemplary digitalization manifestations	Exemplary learning manifestations
DENTAL Co.	From 2000	From 2018	Formal lean program 5S audits Value stream mapping (VSM) Standardized work instructions Whiteboards/ Kaizen boards Daily meetings Formal training Kaizen events	Online daily meetings Wearable headsets	Discussing (delivery) problems daily Remote collaboration for product innovation process Sharing of improvement success stories across plants (yokoten) Worldwide distribution of ownership and responsibility of PD sub-projects
ELECTRO Co.	From 2000	From 2016	Formal lean program 5S audits TPM/OEE Standardized work instructions Whiteboards/ Kaizen boards Formal training Kaizen events PDCA Problem-solving	Digitalization of TPM practices Use of real-time data Smart resource optimization (using data)	Development and sharing of new standards based on the availability of real-time data Sharing lessons learned throughout the organization (yokoten)
BUILD Co.	From 2005	From 2019	Formal lean program 5S audits VSM TPM/OEE Standardized work instructions Whiteboards/ Kaizen boards Daily meetings Formal training	Digitalization of OEE measurement and visualization process (IIoT)	Facilitation of a learning process to enable and empower subordinates to solve problems Establishment of a learning process and development path using digitalization Training managers in learning facilitation to cascade learning throughout the firm
MARITIME Co.	FWithirom 2014	From 2018	Formal lean program Suggestion system 5S audits VSM Whiteboards/ Kaizen boards Daily meetings Formal training PDCA Problem-solving	Digital kaizen platform Digital screens MS Teams/ Planner PowerBI	Hybrid daily meetings for problem-resolution Digital shop floor management for problem identification Online connectivity of value stream allows for improved horizontal collaboration and provides the basis for productivity improvement through cross-functional, organization-wide continuous improvement and learning (yokoten)

Table 2. Comparison of within-case findings

capability. Base capability is a firm’s basic behavior mode that needs to be in place and continuously fostered to enable the establishment of further capabilities. Whereas DENTAL Co., ELECTRO Co. and BUILD Co. had more than 15 years of experience with lean, MARITIME Co. started using it sometime later but had already been awarded a national lean prize in 2017. Lean practices were used widely throughout the firms, including value stream mapping, 5S, standardized work and visual management. Soft lean practices such as teamwork and close communication were also evident in each case. Similarly, a lean mindset was a commonality across cases, as, for example, the manufacturing manager at DENTAL Co. stated, “we live the lean philosophy.” Thus, lean represented the firms’ base capability as it was deeply embedded within the firms’ beliefs and actions, guiding their daily business.

Common across all firms was that they initially introduced lean with the *aspiration for improvement*. For example, the production director at DENTAL Co. commented that “there is always room for improvement,” while managers at BUILD Co. “wanted to improve production performance.” Improving remained a central concern that developed into firms’ enduring emphasis on continuous improvement, pointing to lean thinking. The implementation of lean as base capability and the presence of improvement aspirations over time in all firms indicate the existence of routinized manufacturing capability, as the firms were able to maintain a steady state of manufacturing by following static routines to create a stable environment.

5.2 Routinized learning capability: problem-finding, problem-solving and adaptation of the status quo through digitalization

Having developed into lean manufacturing firms that aspired to continuously improve enabled them to routinely identify improvement opportunities and challenges in their manufacturing system that triggered them to take further action. In other words, *problem-finding* became a core activity that traces back to the firms’ aspirations to improve and indicated a desire to understand causes rather than operate in firefighting mode. Intertwined with finding problems, *problem-solving* among the workforce emerged as a common theme, manifesting in daily meetings during which pressing issues were discussed, as well as the frequent occurrence of the structured problem-solving approach “kaizen events” (i.e. “a structured project performed by a multidisciplinary group with the aim of improving a targeted work area or process in a given timeframe,” Bortolotti *et al.*, 2018, p. 555). For example, a manager at ELECTRO Co. reported that “the employees frequently participate in training and kaizen events”.

The firms’ digitalization initiatives were largely driven by their improvement aspirations, which provided impetus to consider digitalization in the first place. Indicating a progression from an analog form of problem-finding and problem-solving, the firms’ deliberations to digitalize represented intentions of enhancing the problem-solving task. Consequently, the firms’ digitalization efforts developed based on their routinized manufacturing capability and can be considered as measures to enhance problem-finding and problem-solving. As the digitalization efforts were carried out to reach internal advancements (DENTAL Co., BUILD Co., MARITIME Co.) or eliminate shortcomings (ELECTRO Co.), the digitalization initiatives themselves can be considered problem-solving measures.

In carrying out the digitalization initiatives, firms acquired digital technologies that were new to them – implying a departure from the existing technological landscape, adapting the firms’ ways of doing business by adopting new technologies. For instance, collaboration that used to be on-site shifted to online (DENTAL Co.) or hybrid modes (MARITIME Co.). BUILD Co. and ELECTRO Co. were also able to deploy IIoT devices to enhance their problem-solving skills. Interestingly, in contrast to the firms’ lean journeys which had temporal differences, the digitalization initiatives commenced at similar points in time. In addition to problem-finding and problem-solving, we also highlight the *adaptation of the status quo through digitalization* as an indication of the existence of routinized learning capability.

The firms, however, differed in their routinized learning capabilities. DENTAL Co., ELECTRO Co. and MARITIME Co. possessed routinized learning capability before the digitalization initiatives began, as expressed by the fact they actively identified problems and engaged in problem-solving cycles prior to their digitalization. BUILD Co., on the other hand, had a lower routinized learning capability before digitalization as underlined by the fact that problems were addressed ad hoc in firefighting mode ("we tended to fix problems through rapid response and corrective action" (technology manager); "We didn't really use data in the start and didn't really focus so much on it" (department manager)). Yet, the digitalization initiative contributed to developing BUILD Co.'s routinized learning capability as it caused the firm to engage to a greater extent in problem-finding (i.e. actively engaged in learning to understand why the digitalization efforts were not delivering expected results) and problem-solving (i.e. located causes and took action in the form of training for digital skills that led to the retention of the solution and the willingness to use it).

5.3 Evolutionary learning capability: knowledge sharing and deliberate progression

The firms' digitalization journeys also contributed to what we label *knowledge sharing* and *deliberate progression*, indicating the development of evolutionary learning capability.

The firms' *knowledge sharing* was facilitated by digitalization in different ways. On the one hand, information was digitally available which made it easier for the firms to circulate information internally. For instance, in MARITIME Co., digital kaizen cards were transferred from team to team online. On the other hand, firms shared knowledge related to their digitalization efforts and beyond, spreading lessons learned. BUILD Co. cascaded learnings throughout the firm and ELECTRO Co. disseminated the benefits of using IIoT throughout the global firm. In addition to sharing lessons learned, members of the product development teams at DENTAL Co. shared their ideas with each other to a greater extent. In each firm, the practice of yokoten further substantiated knowledge sharing.

Deliberate progression was a further indication of evolutionary learning capability inside the firms that we identified along five different dimensions:

First, *enhanced collaboration* was evident in DENTAL Co., ELECTRO Co. and MARITIME Co. In DENTAL Co., enhanced collaboration surfaced particularly horizontally with employees solving issues together and working more intensely across countries. In ELECTRO Co. and MARITIME Co., vertical collaboration increased as managers started to interact with employees to strengthen technology acceptance.

Second, in all firms, digitalization initiatives evoked *improved communication*. In DENTAL Co. and MARITIME Co., the way of communicating went from asynchronous to synchronous modes. DENTAL Co. understood the need to increase communication ("You have to talk to people", manager). In DENTAL Co., ELECTRO Co. and BUILD Co., open communication about difficult topics such as employees' fears, insecurities and skepticism regarding the technology took place ("Reach out to colleagues in order to say I have a problem", BUILD Co., general manager).

Third, deliberate progression manifested in *new work practices and new digital tools* being introduced. Firms, however, differed in doing so. DENTAL Co. introduced both new work approaches (e.g. subdividing projects) and new digital tools (e.g. wearables). MARITIME Co. did not introduce additional practices beyond those that were deployed during the digitalization initiative but expanded the use of digital tools to other activities (i.e. started to use planner also for daily management and reporting) and introduced additional digital tools (e.g. PowerBI). In ELECTRO Co., new standards for preventive and predictive maintenance based on real-time data were introduced but no further technological innovations happened.

In both DENTAL Co. and ELECTRO Co., new work practices emerged bottom-up as employees proactively and autonomously set them up. BUILD Co. introduced neither new work practices nor additional digital tools.

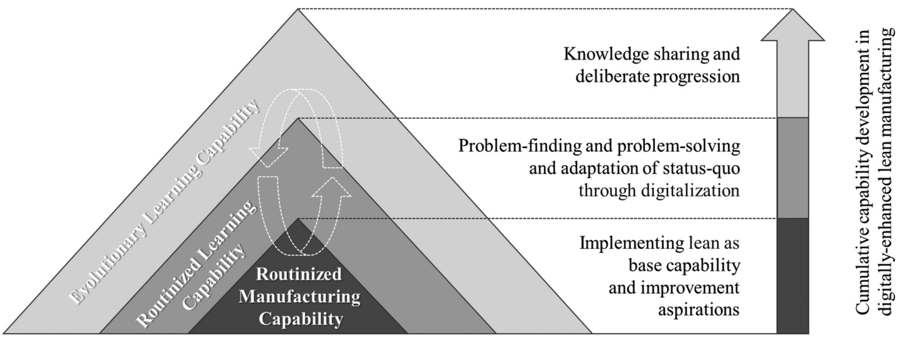
Fourth, the cross-case analysis revealed that *recognizing developmental needs or opportunities* constituted deliberate progression. However, this was evidenced in DENTAL Co. and MARITIME Co. only. DENTAL Co. became aware of the importance of addressing the "human" factor that used to be largely underestimated and neglected, as the focus was always on "technical" aspects. Similarly, based on its digitalization initiative, MARITIME Co. came to fundamentally rethink and revise its notion of lean: "We realized that learning lean must be seen as a process of deep thinking, reflection, and improvement rather than simply learning and implementing lean practices" (MARITIME Co., lean manager). ELECTRO Co. and BUILD Co. did not come to such "transcending" insights.

Fifth, *envisioning and taking new paths* emerged as a constituent of deliberate progression that only DENTAL Co. displayed. Having recognized the "human" factor as a developmental need, DENTAL Co. shifted to a human-oriented approach to advance not only digitalization but the business as a whole. With this shift, DENTAL Co. was able to pursue a new innovation mode that allowed the firm to completely change its products.

Overall, the firms exhibit different degrees of evolutionary learning capability. DENTAL Co. shows itself to possess the highest evolutionary learning capability followed by MARITIME Co., then ELECTRO Co. and then BUILD Co. Digitalization contributed particularly to the development of evolutionary learning capability in DENTAL Co., ELECTRO Co. and MARITIME Co. In BUILD Co., digitalization mainly improved routinized learning capability, although it also helped to establish an early stage of evolutionary learning capability.

5.4 Toward a model of cumulative capability development in digitally enhanced lean manufacturing

Consolidating our findings from the cross-case analysis, we develop a model of cumulative capability development in digitally enhanced lean manufacturing (see Figure 2). The model illustrates a cumulative and mutually reinforcing progression from routinized manufacturing capability, to routinized learning capability, to evolutionary learning capability in the context of digitalization in lean manufacturing firms. This makes digitalization a mode of developing both routinized and evolutionary learning capabilities in lean manufacturing firms, as well as being a capability in itself. Echoing Powell and Coughlan (2020), our model resonates with



Source(s): Author's own work

Figure 2. Model of cumulative capability development in digitally enhanced lean manufacturing

Ferdows and De Meyer's (1990) "sand cone" model that proposes that capabilities are cumulative and exhibit a progression sequence (Rosenzweig and Roth, 2004).

Our model suggests that the establishment of lean as base capability and improvement aspirations (i.e. routinized manufacturing capability) is crucial for developing further capabilities. In this respect, simply implementing lean practices may be considered necessary but not sufficient, and as such, digitalization initiatives in lean manufacturing firms enable the subsequent development of routinized learning capabilities that pave the way toward evolutionary learning capability. Developing evolutionary learning capability is pivotal as it affects and contributes to the development of other capabilities. Such evolutionary learning capabilities enable a firm to dynamically shift its focus to address and exploit new and emerging, otherwise unknown opportunities. Importantly, however, our model shows that developing new capabilities does not necessarily involve the abandonment or neglect of already-established capabilities. Rather they are mutually reinforcing (as indicated by the cyclical arrows in Figure 2), which suggests the continuous advancement of established capabilities.

6. Conclusion and implications

Drawing on cumulative capability theory, we posit that digitalization contributes to the development of cumulative learning in lean manufacturing firms. More specifically, our investigation of four lean manufacturing firms' digitalization initiatives shows that digitalization fostered the development of both routinized and evolutionary learning capabilities.

6.1 Theoretical contributions

Our study contributes to research on lean and digitalization by examining digitalization initiatives in lean manufacturing firms. In particular, we respond to the need for research on the integration of lean and digitalization to provide empirical evidence and advance its theorization (Meindl *et al.*, 2021; Mora *et al.*, 2017; Powell *et al.*, 2018). Our findings suggest the combinative and synergistic nature of lean and digitalization, whereby we confirm studies that have proposed an optimistic view on their integration (Cifone *et al.*, 2021; Rosin *et al.*, 2020). Moreover, we provide empirical evidence on effective integrations as requested by Frank *et al.* (2022). In identifying that cumulative learning is central, we add insights on how to effectively integrate lean and digitalization. Our findings are in line with competitive progression theory (Rosenzweig and Roth, 2004), according to which manufacturing plants gain knowledge to support multiple capabilities simultaneously as they engage with novel technologies and improvement activities. We also respond to Saad *et al.* (2023) who identified a need for researching the impact of Industry 4.0 on TPM specifically (see ELECTRO Co. and BUILD Co.); while our model also presents a new perspective on lean implementation frameworks in the digital era, a gap pointed out by Buer *et al.* (2018).

Furthermore, the work contributes to cumulative capability research in different ways. First and foremost, we respond to the call that "additional studies on cumulative capabilities theory are worthwhile" (Amoako-Gyampah and Meredith, 2007, p. 929) and that cumulative capability development necessitates scholarly attention (Flynn and Flynn, 2004). In adopting a cumulative capability development perspective, we respond to Angelopoulos *et al.*'s (2023) claim that "to carefully study such a novel phenomenon [i.e. digitalization in lean manufacturing firms], we need to approach it with new perspectives" (p. 11). Whereas prior cumulative capability studies focused on quality, delivery, flexibility and cost and dealt with the sequence of capability development (Amoako-Gyampah and Meredith, 2007; Ehie and Schoenherr, 2021; Größler and Grübner, 2006; Schroeder *et al.*, 2011; Tamayo-Torres *et al.*, 2017), we adopt a cumulative capability perspective to examine the integration of lean and digitalization, paying specific attention to the associated learning.

Although cumulative capability theory points to the relevance of learning and assumes it to be an enabler in the sense that each progressive step requires more learning than the previous (Boon-Itt and Wong, 2016; Rosenzweig and Roth, 2004), extant cumulative capability research largely neglects learning in an explicit way. Our study considers learning and identifies its development in a cumulative fashion, providing insights into how digitalization contributes to the development of learning capabilities. In contrast to Rosenzweig and Roth (2004) who propose that capability progression accelerates learning, our insights suggest that learning accumulates.

Based on our findings, we argue that learning is both an enabler and a consequence of capability progression and is facilitated by digitalization. Thereby, we add nuance to the understanding of learning and contribute to the robustness of cumulative capability theory. We maintain that enhancements in certain capabilities facilitate improvements in other capabilities, as argued by Schmenner and Swink (1998). Lastly, we contribute to cumulative capability research by progressing the work of Fujimoto (1999) and providing empirical evidence for his conceptual framework. We add to the scarce OM research using Fujimoto and reinforce Roehl (2000) who stressed the importance of this largely neglected conceptualization of capability development.

6.2 Practical implications

Practitioners should understand that digitalization is not only an end in itself but a means. Although digitalization can serve as a means for achieving several different objectives, our study shows specifically that it can be used to build cumulative capabilities in the context of lean manufacturing, providing practitioners with learning opportunities. As such, digitalization in a lean context should be framed as a learning journey.

Cumulative capabilities allow firms to simultaneously thrive on different capabilities. For example, in the case of lean manufacturing firms that have already achieved routinized manufacturing capability through the implementation of lean practices, digitalization is shown to contribute toward the further development of both routinized and evolutionary learning capabilities. Thus, we suggest that an awareness of the three different levels of cumulative capability development in digitally enhanced lean manufacturing is critical for managers and workers participating in digital initiatives in lean manufacturing firms and advocate that the mere implementation of lean and digital technologies alone will not deliver the expected benefits. In the absence of developing learning capabilities (both routinized and evolutionary), we suggest that firms are unlikely to realize significant levels of improvement and competitive advantage. Lean manufacturing firms are therefore advised to purposefully design digitalization strategies to foster the creation of a learning organization.

6.3 Limitations and future research

In terms of limitations, one shortcoming of this study is not capturing the performance implications of cumulative capability development. As such, future research might investigate the effects of the various levels of cumulative capability development on a firm's performance outcomes. As we relied mostly on subjective data retrieved from interviews, future research is recommended to collect more objective data and operationalize cumulative learning capabilities, especially for performance evaluation.

Furthermore, our focus on digitalization in lean manufacturing firms specifically places boundary conditions on our insights (e.g. in support of lean activities only), which future research could expand upon by examining new ventures and management concepts other than lean (e.g. agile). Further work might also consider investigating firms that possess digitalization as a base capability and thereafter strive for cumulative development of other capabilities.

One further limitation of this study is the case selection and our focus on two specific digital technologies. Though the adoption of cloud-based solutions on one hand and IIoT on the other may seem like simple digitalization initiatives, in reality, the initiatives presented sociotechnical challenges for the firms involved and required significant levels of learning in all cases. Future research should, however, investigate other, more advanced digital technologies like digital twins, collaborative robots and artificial intelligence which are sometimes presented as substitutes for workers and may change the way lean practices are used (Hines *et al.*, 2023).

Finally, our research considers intra-firm learning only. Future research could explore cumulative learning in an inter-firm (or network) setting, using longitudinal designs that pay specific attention to a wider range of digital technologies. This would also support policymakers and business leaders in prioritizing efforts toward realizing the next industrial revolution.

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Appendix 1
Case study protocol

This outline describes the field procedures we determined in preparation for our study and that we followed in executing the case studies.

Preparation

Upon initial contact with the companies, the researchers should identify a key contact person that should serve as the main coordinating link between the researchers and the company. The key informant should be well-connected inside the firm and hold a managerial position to ensure the person is knowledgeable about corporate activities regarding lean and digitalization initiatives and help identify interviewees. A general description of the study including the research objectives, topic areas and research activities intended to be carried out as part of the research should be sent to the contact person.

Data collection

Each case study should consist of interviews and one or more visits to the plant.

Opening	Introduction of interviewer(s) Objectives of the study Confidentiality and anonymity Agreement to record the interview
Interviewee background	Introduction of interviewee - tenure - function - position - other relevant aspects
Lean implementation and use of novel work/ management practices	Determine lean practices in use Describe the lean journey Discuss further work/management practices that are newly introduced
Adoption of digital technologies	Describe the plant's digitalization efforts Determine the major/most important novel digital technology/technologies that has/have been introduced
Integration of lean and digital	Elaborate on the relationship of the new digital technology to lean manufacturing How has the combination of lean and digitalization affected day-to-day business? Discuss learning implications
Implications, influential factors, consequences and outcomes of lean and digitalization	Reflect on what the new digital technology means for the work Reflect on the implications of digital technologies and if and how digitalization has brought changes in lean manufacturing? What implications/impacts/changes did you experience or observe?
Last comments	Have we missed an important aspect in our discussion? Do you have additional comments on what we have talked about?
Closure	Follow-up Thank you

Table A1. Interview guide

Interviews

The key informant should provide assistance in identifying suitable interviewees and facilitate contact with them. Per case, multiple people from different hierarchical levels should be interviewed. Interviews should be semi-structured following an interview protocol covering topics and questions that are relevant to our research interest (see interview protocol below).

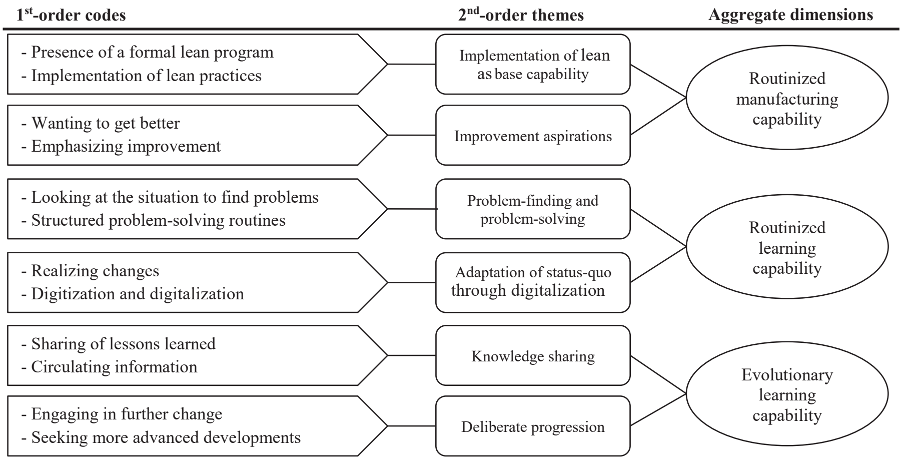
The interviews should have the character of open dialogue and conversation as we aspire to retrieve the interviewees' personal opinions, behaviors and experiences. Interviews should elapse around 60 min and should be recorded for later analysis in strictly anonymized form.

Site visits

In each case company, direct observations through site visits should be conducted. Site visits should involve a guided gemba walk through the plant. During the direct observations, researchers should inquire about and take notes on the lean implementation, the use of technology and the learning implications reported/experienced by the workforce.

Source(s): Author's own work

Appendix 2



Source(s): Author's own work

Figure A1.
Data structure

Appendix 3

Second-order theme	Representative first-order data (interview quotes and observations)
Implementing lean as base capability	*Interview quotes* We are really working on lean and continuous improvement for a lot of years. (DENTAL Co., Production Manager) We have implemented and standardized TPM practices for several years. (ELECTRO Co., Manufacturing Manager) We implemented all the lean tools nearly 20 years ago. (BUILD Co., Director) We started lean just like anybody else . . . by implementing 5S. (MARITIME Co., Lean Manager) *Direct observations* Company-specific lean program (xPS) 5S audits displayed on shopfloor Standardized work instructions hung up at workstations Whiteboards/Kaizen boards Colored tape/marking on the floor (5S)
Improvement aspirations	*Interview quotes* They aim to do their work more effectively and efficiently. (DENTAL Co., Director) Although we noticed significant improvement during the first years of TPM implementation, OEE performance stagnated after those and wanted to push forward with more improvement. (ELECTRO Co., Production Supervisor) We shifted focus from resource efficiency to flow efficiency. (BUILD Co., Project Manager) We use the suggestion system to drive improvement on the shopfloor. (MARITIME Co., Operator) *Direct observations* TPM standards and/or standard work instructions visible on shopfloor Whiteboards/Kaizen boards/suggestion system People in the workplace openly discuss improvement activities
Problem-finding and problem-solving	*Interview quotes* Many reactions are necessary to solve the problem and we have to go to the machine and talk with the workers to find and solve the problem and give them the necessary support. (DENTAL Co., Process Engineer) Bottleneck operations with a high level of TPM adoption are the focus of our IoT initiatives. We collect, share and process real-time data about the conditions of the equipment. (ELECTRO Co., Maintenance Coordinator) Operators are much more interested in IoT and now we create a team that could work on the problems where we have maintenance and operators and ourselves. Instead of taking the phone and calling them [maintenance guys] now they are analyzing so they can say to the maintenance guys it's in this area. (BUILD Co., Department Manager) Management teams began conducting regular Gemba walks to proactively discover technical problems and support problem-solving and learning. (MARITIME Co., Lean Program Manager) *Direct observations* Kaizen/Kata boards for problem-solving Active use of tablets and digital screens for problem-finding Real-time information displays for identifying improvement areas A3 problem-solving forms displayed Discussions among employees centered around issues or problems during breaks/lunch

(*continued*)

Table A2.
Data table

Second-order theme	Representative first-order data (interview quotes and observations)
Adaptation of status-quo through digitalization	*Interview quotes* We improve with (the) tools. (DENTAL Co., Process Engineer) We have been revising both preventive and predictive maintenance activities based on the new data collected in real-time. This led to more accurate standards, entailing maintenance cost reduction. (ELECTRO Co., Maintenance Analyst) You are trained to solve problems ASAP [. . .] now I am more aware of taking a step back and looking at the actual problem. (BUILD Co., Department Manager) Don't focus on implementing tools rather use them as accelerators for improvement. (MARITIME Co., Team Leader) *Direct observations* Improvement boards regularly in use Revision dates on standard operating procedures updated regularly Demonstration of the digital suggestion system in use Use of tablets
Knowledge sharing	*Interview quotes* Knowledge transfer from and to each other. (DENTAL Co., Manager) We used our daily meetings to promote the use of new technologies and share learning lessons among the team. (ELECTRO Co., Production Supervisor) Before, the production guys, the quality guys and the maintenance guys would sit in their own corners. Now they meet together around the (digital) data to collaborate and learn (to succeed) together. (BUILD Co., Senior Operator) We have a corporate-wide initiative to share learnings from each side by documenting success stories and sharing them in feedback reports via an online platform. (MARITIME Co., Quality Manager) *Direct observations* A3 problem-solving forms displayed to share information Yokoten practices demonstrated in real-time (sharing of lessons learned) Dedicated meeting points in place for knowledge sharing (e.g. obeya rooms, whiteboards, etc.) Use of SharePoints and Intranet sites for collecting and sharing information, clarifying questions and seeking insights
Deliberate progression	*Interview quotes* Knowledge extraction to keep (employees) in a continuous learning process. (DENTAL Co., Manager) As people understood the benefits of technology integration and learned how to use it, they identified opportunities in other production areas and maintenance issues, hence, actively involving more people in the activities. (ELECTRO Co., Manufacturing Manager) Our new way of working first transferred from one production line to the neighboring line and then further on to the other departments and factories. Like a ripple effect. (BUILD Co., Production Manager) We established an industrialization department specifically to develop a greater level of value stream management. (MARITIME Co., Production Manager) *Direct observations* Employees solving issues together Cross-functional leadership interactions Horizontal and vertical collaboration

Source(s): Author's own work

Table A2.

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