# Enabling the Twin Transitions: Digital Technologies Support Environmental Sustainability through Lean Principles



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# Enabling the twin transitions: Digital technologies support environmental sustainability through lean principles

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ABSTRACT

Manufacturing companies seek innovative approaches to achieve successful Green and Digital transitions, where adopting lean production is one alternative. However, further investigation is required to formulate the strategy with practical inputs and identify what digital technologies could be applied with which lean principles for environmental benefits. Therefore, this study first conducted a case study in three companies to collect practice-based data. A complementary literature review was then carried out, investigating the existing frameworks and complementing practices of digitalized lean implementations and the resulting environmental impact. Consequently, the Internet of Things and related connection-level technologies were identified as the key facilitators in lean implementations, specifically in visualization, communication, and poka-yoke, leading to environmental benefits. Furthermore, a framework of **DI**gitalization **S**upports **E**nvironmental sustainability through **L**ean principles (DISEL) was proposed to help manufacturing companies identify the opportunities of digitalizing lean principles for Environmental sustainability, thus enabling the twin transitions and being resilient.


## 1. Introduction

Manufacturing companies face increasing pressure to be profitable and environmentally sustainable, thus, approaches such as decarbonization and dematerialization are increasingly applied (Beier et al., 2022). Furthermore, companies aim to improve environmental performance by integrating new technologies and re-evaluating the production processes, leading by example in the green transition (European Commission, 2021). Therefore, effectively managing the Green and Digital twin transitions is a cornerstone of achieving sustainability (Muench et al., 2022).

Aiming for successful twin transitions is pushing manufacturing companies to be innovative. Exploitative innovation, or incremental innovation "kaizen," maximizes gains with minimum changes and reduces uncertainties (Dixit et al., 2022; Kurdve et al., 2016). Integrating digital technologies with lean production to achieve sustainability is an exploitative innovation approach. In a previous study, Chen et al. (2020) claimed that green-lean integration could encourage and support practitioners to apply digital technologies for environmental sustainability. Furthermore, lean production has been recognized as a world-class manufacturing philosophy to improve operational or economic performance (Henao et al., 2019) and build resources and capabilities that support environmental performance (Galeazzo et al., 2014).

Digitalization, or Industry 4.0 (I4.0) (Lee et al., 2015), has been adopted to accelerate sustainable manufacturing, often supporting economic opportunities (Brozzi et al., 2020). An I4.0-based manufacturing system is structured with a cyber-physical system comprising five levels, the 5C architecture: connection, conversion, cyber, cognition, and configuration levels (Lee et al., 2015). The rapid and evident changes in economic profits from digital technologies, such as increased productivity and quality, encourage manufacturing companies to prioritize the application of digitalization for economic growth over their environmental benefit. Hence, the potential of using digitalization to improve environmental performance in manufacturing needs to be addressed to reach sustainability goals (Chen et al., 2020; Despeisse et al., 2022).

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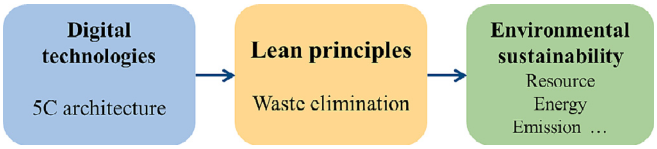


**Fig. 1.** Theoretical framework built upon existing research.

The integration of digitalization and lean production has excellent potential for developing eco-efficient products (Dahmani et al., 2021), improving operational performance (Liao and Wang, 2021; Tripathi et al., 2021), and supporting environmental sustainability (Lobo Mesquita et al., 2021; Touriki et al., 2021). Adopting lean production and I4.0 technologies helps the transition toward a circular economy (Ciliberto et al., 2021; Guaita Martínez et al., 2022), such as integrating value stream mapping to achieve better circularity (Nascimento et al., 2022). Digitalization can support operational and environmental performance improvements by integrating lean production with frameworks (Amjad et al., 2020; Leong et al., 2020; Touriki et al., 2021). The form of framework gives an overview that "describes and/or guides the process of translating research into practice" (Nilsen, 2015). Amjad et al. (2021a) proposed a step-by-step approach to combine lean and green manufacturing concepts with I4.0 technologies, to reduce environmental impacts. Leong et al.'s (2020) lean and green framework consists of seven steps to identify the best process improvement pathway supported by machine learning. Touriki et al. (2021) proposed a framework to illustrate the drivers, barriers, and critical success factors of integrating smart manufacturing to promote lean and resilient manufacturing while enhancing green performance. As a result, the existing studies build a theoretical framework (Fig. 1) that digitalized lean implementations improve environmental sustainability.

In framework development, Tabak et al. (2012) advise researchers to be aware of the substantial overlap between existing and new frameworks to ensure the new framework fills a gap in the body of knowledge. Hence, frameworks illustrating the relationship between digitalization, lean, and ES were reviewed and summarized to identify the remaining gaps as vital inputs to the new framework development.

a) Lack of practice-based frameworks. Liao and Wang developed the framework *h*[1] (2021) based on a case study in the chemical industry focusing on pairwise relationships of digitalization, lean and environmental sustainability. However, they do not provide operational and implementation guidelines.
b) The bridging mechanisms between digitalization, lean, and green require more investigation.
c) Very few studies targeted environmental benefits.

Moreover, coinciding with the identified gap b), further clarity is needed on which digital technologies could be integrated with which lean implementations (Buer et al., 2018; Lobo Mesquita et al., 2021; Varela et al., 2019) for environmental sustainability. Therefore, this paper presents an empirical framework based on practices that address digitalized lean implementations to benefit environmental sustainability.

Accordingly, two research questions were formulated:

1. Which digital technologies are used to facilitate the implementation of lean principles to improve environmental sustainability?
2. How can the identified digital technologies facilitate lean principles to improve environmental performance?

[1] A more detailed analysis of the existing frameworks is available in Appendix A.

To answer these two questions, we conducted a case study and a literature review using the theoretical framework (Fig. 1) as a basis. The case study was carried out in three companies to explore their use of digital technologies, the applications in lean principles, and reflected changes in environmental performance. Meanwhile, we investigated existing frameworks to learn digitalized lean implementations and environmental implications.

Our findings indicate that the Internet of Things and related connection-level technologies were identified as the key facilitators in lean implementations, specifically in visualization, communication, and poka-yoke, leading to environmental benefits. Based on the observations, an updated framework was proposed to illustrate that **DI**gitalization **S**upports **E**nvironmental sustainability through **L**ean principles (DISEL). DISEL can support industrial decision-makers in identifying opportunities to digitalize lean principles for environmental benefits, such as in digital technology investment, environmental performance improvement, and lean implementations,

The remainder of this paper is structured as follows. Section 2 introduces the digitalization, lean, and environmental sustainability paradigms. Section 3 presents the methodology for developing the framework, including a case study and literature review. The empirical data and literature review findings contributing to developing the framework are shown in Section 4, as well as the DISEL framework. Section 5 discusses the theoretical and practical implications, limitations, and future research directions. At last, Section 6 concludes briefly.

## 2. Background

The three topics that consist of the theoretical framework (Fig. 1) are explained in this section, providing the definitions adopted by this study.

### 2.1. Digitalization

I4.0 is a trending technological paradigm that has redefined the way of manufacturing through digital technologies, such as cyber-physical systems (CPS), internet of things (IoT), cloud computing, big data analytics, virtual reality (VR), augmented reality (AR), intelligent robotics, industrial artificial intelligence (IAI) and additive manufacturing (AM) (Chen et al., 2020; Nascimento et al., 2019; Oláh et al., 2020; Sony, 2018). These technologies enable a digitalized, integrated, automated, and optimized manufacturing system that increases productivity, promotes revenue growth, and attracts investors and employees. The 5C architecture and the related digital technologies, as adapted from Lee et al. (2015), structures an I4.0-based manufacturing system described in detail as shown in Table 1.

As the fundamental level of the 5C architecture, the Internet of Things (IoT) is a "global infrastructure for the information society, enabling advanced services by interconnecting (physical and virtual) things based on existing and evolving interoperable information and communication technologies" (ITU, 2012). IoT connects machines with sensors and actuators to the internet, thus enabling the devices to generate, process, and communicate data in real-time to humans or machines (Tilson et al., 2010). As a subset of IoT, Industrial IoT (IIoT) covers the domains of machine-to-machine (M2M) and industrial communication technologies with automation applications (Sisinni et al., 2018). According to Lee et al. (2015), an I4.0-based manufacturing system is structured with a cyber-physical system comprising five levels, of which IIoT coincides with the *connection* level. It is described as condition-based monitoring, sensor network, controller, or enterprise manufacturing systems (e.g., ERP, MES), a seamless and tether-free method to manage, acquire and transfer data to the central server, plug and play, etc. (Lee et al., 2015).

**Table 1**
Digitalization associated with each level of the 5C architecture and technology categories used in this paper.
Adapted from Chen et al. (2020) and Lee et al. (2015).

| 5C architecture | Description of each level | Example of technologies |
|---|---|---|
| Connection level | Condition-based monitoring using sensor network, controller, or enterprise manufacturing systems (e.g., ERP, MES) to seamlessly and tether-freely manage, acquire and transfer data to the central server, plug & play, etc. | (Industrial) Internet of Things (IoT) |
| Conversion level | Meaningful information inferred from data, self-aware, self-predict, smart analytics, algorithms for prognostics and health management applications, degradation, performance prediction, etc. | Intelligent robotics Additive manufacturing |
| Cyber level | Central information hub, information pushed to form machine network, self-compare among the fleet, twin model for components and machines, clustering for similarity in data mining, managing, and analyzing information, etc. | Big data analytics Cloud computing |
| Cognition level | Prioritize and optimize decisions, integrate simulation and synthesis, collaborative diagnostics and decision making, remote visualization of the acquired knowledge to expert users, etc. | Virtual/augmented reality (VR/AR) |
| Configuration level | Feedback from cyber space to physical space, acts as supervisory control to enable self-configure, self-adjust, self-optimize, and to apply corrective and preventive decisions by resilient control systems, etc. | Industrial artificial intelligence (IAI) |

### *2.2. Lean production*

Lean production (or lean manufacturing) brings manufacturers significant benefits by reducing cost, improving productivity and quality, and improving operational performance (Bhamu and Sangwan, 2014; Hines et al., 2004; Shah and Ward, 2007). However, since *The Machine that Changed the World* (Womack et al., 1990), lean production has evolved much (Hines et al., 2004), and the concept is still developing (Zekhnini et al., 2021). Strategically, lean production may be a philosophy (Liker, 1997; Shah and Ward, 2007), a set of principles (Womack et al., 1990), a system (Liker, 2021), or a manufacturing paradigm (Seth and Gupta, 2007) that sought to perceive or enhance value to customers by eliminating wasteful activities (Hines et al., 2004). Waste (lean waste), or waste of time, here is defined as activities that add no value to customers, and the customer ultimately decides what comprises Muda (waste) (Hines et al., 2004; Liker, 2021). The seven commonly recognized wastes in lean production are overproduction, waiting, transport, overprocessing, unnecessary inventory, unnecessary motion, and defects (Hines and Rich, 1997). Operationally, lean production may be a set of tools and techniques (Bicheno and Holweg, 2000), a process (Womack et al., 1990), or a practice (Simpson and Power, 2005) that aligns with the company's value, including value stream mapping (VSM), Kanban/pull system, total productive maintenance (TPM), just-in-time (JIT), continuous improvement/Kaizen, smoothing production/Heijunka (including SMED: Single Minute Exchange of Die), total quality management (TQM), visualization (including 5S), poka-yoke, standardized work, automation, communication, etc. (Bhamu and Sangwan, 2014; Netland, 2013).

### *2.3. Environmental sustainability*

Environmental sustainability (ES) is the development of "meeting the resource and service needs of current and future generations without compromising the health of the ecosystems that provide them" (Keeble, 1987; Morelli, 2011). ES in production systems involves stabilizing the balance between manufacturing activities and their impact on the natural environment. The 2030 agenda for sustainable development is urging the industry to reduce the environmental impact of manufacturing activities to meet the UN Sustainable Development Goals (UN, 2015). The links between activities in production systems and the natural environment are becoming recognized (Rosen and Kishawy, 2012), which motivates manufacturers to prioritize ES in their operational strategy.

As defined by the U.S. Department of Commerce, sustainable production is the creation of manufactured products through processes that "minimize negative environmental impact, preserve natural resources and energy, are safe to employees, consumers, and communities, and are economically sound" (Haapala et al., 2013). According to the National Institute of Standards and Technology (NIST) (Joung et al., 2013), environmental impact indicators may be categorized by resource consumption, emissions, pollution, and natural habitat protection.

Green is here used as a set of activities designed to manage environmental performance, such as energy efficiency, waste reduction of natural resources, and elimination of pollution. The green paradigm is a concept that focuses on the environmental impact of production (Baumer-Cardoso et al., 2020). Green manufacturing practices help minimize the negative impact of manufacturing activities and protect the environment (Zekhnini et al., 2021). Therefore, green manufacturing is interchangeable with the ES of production systems in this study.

## 3. Methodology

This study was carried out through an iterative process in three stages: case study, complementary literature review, and framework development. First, based on the theoretical framework illustrated in Fig. 1, a case study with three companies was conducted to use multiple sources to ensure construct validity (Yin, 2003). Then an integrative literature review was carried out, specifically investigating the existing frameworks, complementing with digitalized lean implementations and the resulting environmental impacts. Finally, a new framework was developed to elaborate on the theoretical framework with practices and complementary literature findings.

### *3.1. Case study*

#### *3.1.1. Case company introduction*

Interviews and onsite observations were used to collect and address the same phenomenon to provide more convincing and accurate findings through data triangulation (Yin, 2009). Case companies A, B, and C were three small and medium enterprises (SMEs) participating in a collaborative research project with academic and research institutions. The companies were chosen because they implement lean production principles, intend to improve their ES, and are keen to apply digital technologies. The interviewees from companies A and B were Chief Executive Officers (CEOs) with knowledge of technology, lean implementation, and environmental performance. The interviewees at company C were chosen because of their expertise in lean and technology implementation. The factory tours were accompanied by the production leader (company A), CEO (company B), and lean manager (company C) to observe the onsite practices. Table 2 briefly introduces the case companies, the interviewees, and the people accompanied in onsite observations.

#### *3.1.2. Interviews*

An interview protocol was designed and developed following the protocol framework that Castillo-Montoya (2016) advised. At first, the research question was broken down into three categories, and the interview questions were designed and mapped onto the three categories through a matrix to ensure alignment with the purpose of the study. The interview questions were listed in rows, and the research questions

**Table 2**
Information about the case companies.

| # | Business focus | Size | Interviewee | Onsite guides |
|---|---|---|---|---|
| A | Packaging | <50 employees | CEO | Production leader |
| B | Machining | <150 employees | CEO | CEO |
| C | OEM manufacturing | <250 employees | Lean, logistics, and production managers | Lean manager |

were in columns. Examples of interview questions included the use of digital technologies, the use of lean principles, and corresponding environmental performances. The crossing cells were marked to indicate that the interview questions could stimulate information relevant to the particular research questions (Castillo-Montoya, 2016). Creating this matrix helped display whether any gaps existed in the interview questions, and the number of questions was evenly distributed to cover each research question. Secondly, the interview questions were further developed and adjusted to be understandable and accessible as the everyday language of the interviewees (Kvale and Brinkmann, 2015). Finally, the manufacturing background of the interviewees was considered to adjust the language of the interview questions. At last, the research group provided feedback on the interview protocol on how well the interview questions were understood. The interview protocol is attached in Appendix B.

Four interviews were conducted in total. An outline including interview purpose, topics to be covered, and estimated time was sent out before the interviews. However, the authors did not send the exact interview questions to avoid the risk of over-preparation. Each interview took 1 h and was recorded and transcribed by the online meeting tool (Microsoft Teams).

#### 3.1.3. Observations

Observational data often provides additional and supplementary information about the studied topic (Yin, 2009). In this study, onsite observations added dimensions for understanding the context of the three companies and enhanced the understanding of implementing technologies and lean principles. The authors visited all three companies and started the observations with a field tour on the shopfloor with accompanies to observe the practices of using technologies and lean principles. Then the group discussed the remaining questions regarding the study topic in a meeting room. During the tour, other personnel was consulted for questions and discussions, including the environmental managers, warehouse workers, logistic workers, operators, and process managers. Before leaving the company, the authors summarized the key points to align and enhance the understanding. Notes were documented and categorized into digital technologies, lean principles, and ES, following the theoretical framework shown in Fig. 1. In addition, a master thesis (Chandrasekaran and Ternström, 2022) supervised by one of the authors provided input on understanding the ES at company B.

#### 3.1.4. Analysis

Data collected during the interviews (transcriptions) and observations from all three companies were extracted and categorized into the type of digital technologies, use of lean principles, digitalized lean implementations, and the reflected change of environmental impact. Moreover, explicit descriptions were generated, including how the technologies facilitate lean implementations, how they affect the environment, and with which impact.

The data was analyzed through the lens of strategic and operational perspectives for two reasons: the simultaneous distinction between lean production from strategic and operational levels is crucial for applying the right strategies and tools (Bhamu and Sangwan, 2014), and both strategic and operational levels were focused in the three companies,

### 3.2. Literature review

An integrative review approach promotes the emergence of new theoretical frameworks and perspectives by reviewing, critiquing, and synthesizing representative literature on the subject (Snyder, 2019; Torraco, 2005). The literature review was done iteratively. Initially, it investigated the existing frameworks to identify the key learnings and remaining gaps. After that, the practices of digitalized lean implementations for environmental benefits were summarized as complementary to the case findings. Finally, the search and analysis followed Snyder's (2019) and Torracos (2005) recommendations, covering the relevant literature on digitalization, lean, and ES.

With the study goal of investigating digitalized lean implementations toward ES performance, keywords were selected to cover the three topics: *green*, *sustainab**, *lean*, *digital**, and *Industr* 4.0*. The context of production or manufacturing and the focus on environmental sustainability was not specified in the selected keywords but were included in the screening process. Also, papers that slightly touched on the three topics but did not focus on the correlation or integration among them were excluded.

Literature analysis consists of descriptive information, framework analysis, and integration practices. The descriptive information categorized the lean principles, type of digital technologies, and type of environmental impacts. The framework analysis explicitly focused on critical takeaways of the existing frameworks. Finally, the integration practices investigated the application of digital technologies in lean principles, and through which paths the integration happened.

Although objectivity is greatly sought, the qualitative analysis was somewhat affected (researcher bias) by the authors' pre-existing conceptions of lean production and sustainable production. Therefore, some subjectivity is recognized in the findings. However, to evaluate the results and provide a new angle for the support of digital technologies toward more sustainable manufacturing, previous knowledge of lean and sustainability (expertise) was required.

### 3.3. Framework development

The framework development consists of three parts, key learnings from the literature analysis, case practices, and complementary literature practices.

The key learnings from the framework analysis are summarized as follows.

- Digitalization (I4.0 technologies) can function as an accelerator, strengthening lean and green implementation. It may include other paradigms, e.g., resilience (Amjad et al., 2021b; Reyes et al., 2021; Touriki et al., 2021), agile (Amjad et al., 2021b, 2020), and circular economy (Ciliberto et al., 2021; Dahmani et al., 2021), to support improving the environmental and overall operational performance.
- The integration of digitalization and lean green can be from a general or strategic level (Ciliberto et al., 2021; Dahmani et al., 2021; John et al., 2021; Liao and Wang, 2021; Lobo Mesquita et al., 2021; Muñoz-Villamizar et al., 2021; Reyes et al., 2021; Touriki et al., 2021; Vinodh et al., 2021) and an operational level (Amjad et al., 2021a, 2021b, 2020; Leong et al., 2020; Tripathi et al., 2021). General-level frameworks address digitalization, lean, and green integration

opportunities based on their features, allowing greater flexibility to be applied in various contexts. On the other hand, operational frameworks provide orderly and detailed instructions for the implementation processes.

- In the lean paradigm, value creation and waste elimination are adopted in lean implementation. Monitoring, tracking, analysis, and control can strengthen lean implementations in the digitalization paradigm. In the green paradigm, resource and energy consumption recurrently appear as the focus of environmental impact reduction. Emission reduction is a vital concern. Nevertheless, it is often achieved by saving resources, energy consumption, and direct emission reduction.

Therefore, using the theoretical framework as a basis, the developed framework adopts the attributes of digitalization functions as an accelerator to facilitate lean principles from a strategic and operational level. The strategic level is supported by the paradigm of digitalization, lean, and ES, with respective values.

Furthermore, observed practices of digitalized lean implementations and the resulting environmental benefit were filled in the framework to enrich the content. The practices summarized from the literature were added as complementary. The patterns were identified based on 1) the applied digital technologies in lean principles and 2) the paths that digital technologies facilitate lean principles.

## 4. Results

This section presents findings from the case study and literature review. It starts with case study findings, including the adoption of digital technologies, lean principles, and ES at the strategic level. Then, it shows the practices of digitalized lean implementations and the resulting environmental impact at the operational level (Section 4.1). Next, the findings in the same manner from the literature review are presented with digitalized lean principles for ES (Section 4.2). Finally, it introduces the proposed framework DISEL (**DI**gitalization **S**upports **E**nvironmental sustainability through **L**ean principles) in Section 4.3.

### *4.1. Digitalized lean and ES: case study findings*

#### *4.1.1. Strategies*

*4.1.1.1. "**Lean** is like a culture.".* Similarities can be easily identified in all three companies regarding the motivation for implementing the lean principle. Firstly, the lean principle is a *culture* in all three companies. The culture here is defined as a shared set of values and practices within a group formed over a relatively long period, as Taras et al. (2009) defined. All three companies have been working with lean production: 1) for many years, 2) daily, 3) on everything possible, 4) doing without noticing. Secondly, *adding value* works as a guiding thread of lean implementation, meaning lean equals adding value into the process with minimum cost. Table 3 illustrates quotes from the interview corresponding to *culture* and *value-adding*.

**Table 3**
Representative quotes from the interviews: Lean production.

| Strategies | Quotes | # |
|---|---|---|
| Culture | - "With me, I think we had **everything** we tried to go lean. Lean is basically do it smartly." | A |
| | - "Lean is like a **culture**." | B |
| | - "We have a production system in place, and we have been working for **many, many, many years**." | |
| | - "In general, for us, we are not talking about so much of lean because, in general, lean is something that you are doing in the **daily work,** so it is not anything special about lean." | B |
| | - "But if you ask operators just today in the factory, what kind of lean tools are you using? They could hardly say it because they are working **with all the tools."** | B |
| | - "We have been working with all what you talk about the lean tools, but mainly it is about the **philosophy**." | C |
| | - "We have, like, we do not talk about lean; we **just do it**. It is more like how we work it." | C |
| | - "You need to work with **whatever you do;** you should have a sort of lean aspect to do it." | C |
| Value adding | - "Yeah, **high output**, happy customers, help profit. Everything is the same. If you aim for a happy customer and always produce the things, you earn money. You would get more customers and more recent customers. A happy customer creates a good company." | A |
| | - "If it is not lean, it is not **effective**. Not effective, is not **profitable**. It is dumb not to use lean." | A |
| | - "Make sure that the whole chain of **value-adding** is considered. In that words, quality, productivity, and safety are the backbone of all the work in the projects." | C |

*4.1.1.2. "We try everything we can to **reduce the environmental impact** in our factory.".* Environmental care is adopted among the three companies. Environmental key performance indicators (KPIs) are adopted in companies B, and C. Motivations of caring for environmental performance are mainly from their customer's requests and the pressure of reducing costs. Customers start to add environmental performance as one assessment when choosing suppliers. Meanwhile, lower energy and resource consumption in manufacturing is pushed by higher production efficiency. The environmental KPIs are followed to track the consumption of energy and resources, including emissions, material (raw material, packaging material, etc.), liquid (water, lubrication, cutting fluid, etc.), and wastes (water, liquid, raw material, packaging material, etc.). Table 4 illustrates quotes from the interview corresponding to environmental care and KPI tracking.

*4.1.1.3. Digitalization: "we use **MONITOR** for everything.".* Monitoring/tracking, communication, and automation are the three main functions of digitalization that companies are adopting. Machines' working status, safety stock level, and products' status are tracked to respond faster to machine breakdowns and stock level adjustments, as well as enable products' traceability. Meanwhile, digital signals allow efficient communications with suppliers for material and machine supply, and with customers for delivery planning. Finally, automation enables higher machining, assembly, and employee training efficiency. Table 5 illustrates

**Table 4**
Representative quotes from the interview: ES.

| Strategies | Quotes | # |
|---|---|---|
| Environmental care | - "I **do not choose anyone** to work with when it does not (go with environmentally friendly)." | A |
| | - "We **try everything** we can to reduce the environmental impact in our factory." | B |
| | - "We are looking into in what way we could and should act to make our little **contribution to the planet** working in the right direction." | C |
| Environmental KPI | - "We all have **KPIs** for how much **electricity** we are consuming. Divided by machining hours that we are using. So, if you run the production more efficiently, we have a better **KPI**." | B |
| | - "We also have a **KPI** of how many **cutting liquids** we use. And how we could improve that, for example." | |
| | - "We also have some other small **KPIs**, that we are not using any environmentally unfriendly material like this is a **hazard** material painting and this kind of stuff. You could call it the blocklist." | |
| | - "We also have a **KPI** of how many **cutting liquids** we use. And how we could improve that, for example." | |
| | - "We follow **all our water consumption**, electricity, lubrication, cutting fluid, and all that. And we also have goals, how to decrease that and so." | C |

**Table 5**
Representative quotes from the interview: Digitalization.

| Strategies | Quotes | # |
|---|---|---|
| Monitoring/tracking | - "We use **MONITOR** for everything." | A |
| | - "It is a system that shows if the machines are running or standing still." | B |
| | - "But if the volumes go up and we are consuming more tools, then the system will **calculate and say,** hey, we maybe need to have third drills now in the safety stock because we have higher volumes." | |
| | - "We have an ERP; we have our system for **keeping track** of every single part in our factory." | C |
| Connection | - "All the machines are **connected** to the suppliers so that they can get remote services and also read out problems for the machines." | A |
| | - "So, they are digitalized directly **from our customer**, directly into our system, and we try to optimize how we do our planning from that data into our system." | B |
| | - "We have **digital communication** to our suppliers where they have these plans that we think we require." | C |
| | - "The individual with the headset, the headset **communicates** with this device." | C |
| Automation | - "So, we train **16 persons every four hours** with voluntary personnel." | A |
| | - "That system also automatically calculates how many cutting tools we are consuming." | B |
| | - "It is not a code that the operator is punching in; it is **automatically** done." | |
| | - "You get all the information instead of reading the paper or reading from the screen; you get all the **information in your ears**." | C |
| | - "A manufacturing machine where we have all the measurements completed directly in the machine so that we **reduce the manual need** of measuring that saves us a lot of time." | |

quotes from the interview corresponding to digitalization's use in monitoring, communication, and automation.

Additionally, digital technologies could help to build an attractive working place, especially for young people, as specified by Company C: "*you can learn this new stuff that you probably would have good use in your private life as well. And you can learn that when you get paid*."

#### 4.1.2. Operational best practices

*4.1.2.1. Applied digital technologies.* The observed implementations in the case companies were grouped into the categories of applied technologies, integrated lean principles, and impact on ES, with the source of data marked in the last column, as shown in Table 6.

The applied digital technologies were categorized according to the definition of 5C architecture, as described in Section 2. ERP (enterprise resource planning), MONITOR, MindSphere, and smart sensors belong to the *connection level* because of the enabled functions of condition-based monitoring, sensor network, controller, or enterprise manufacturing systems (Lee et al., 2015). ERP system is a centralized online platform within the information and communication technology system of a company that seeks to "integrate the complete range of business processes and functions to present a holistic view of the business from a single information and IT architecture" (Klaus et al., 2000; Polivka and Dvorakova, 2021). MONITOR is an ERP system developed by the Swedish company MONITOR ERP System AB. MindSphere is part of the Industrial IoT (IIoT) system developed by Siemens. IIoT is a subset of IoT; it connects machines with sensors and actuators to the internet. It enables machines to generate, process, and communicate data in real-time to machines (Sisinni et al., 2018; Tilson et al., 2010). The pick-by-voice system assists in picking objects with audio and voice commands, following orders placed through the headset, where data is exchanged in real-time (Sheriff and Aravindhar, 2022). Intelligent robotics and automated machines are in the *conversion* level based on its

**Table 6**
Digital technologies integrate lean principles and the corresponding environmental impact.

| 5C/digital technologies | Integrated lean principles | Impact on ES | # |
|---|---|---|---|
| *Connection level* | | | |
| ERP (MONITOR) | Visualization | RE, EN | A |
| | Waste elimination: *defects* | RE, EN | |
| | Visualization | | |
| | Communication | EM | |
| | Waste elimination: *Transport* | | |
| | Communication | RE, EN | |
| ERP | Visualization: *Kanban* | RE, EN | B |
| | Poka-yoke | RE, EN | |
| | Visualization | EN | C |
| | Waste elimination: *Transport* | | |
| Smart sensors | Visualization | EN | |
| | Visualization: *standardization* | RE, EN | |
| | Waste elimination: *defects*, *waiting* | RE, EN | |
| MindSphere | Visualization | RE, EN | B |
| | Communication | | |
| | Communication: *Transportation* | EM | |
| Digital screen | Standardization | RE, EN | A |
| | Visualization | | |
| Animated instruction SOPs | Waste elimination | RE, EN | |
| | Standardization | | |
| | Poka-yoke | | |
| *Conversion level* | | | |
| Automated machine with intelligent robotics | Kaizen | RE, EN | C |
| Automation | Waste elimination: *unnecessary motions* | RE, EN | |
| *Cyber level* | | | |
| ERP and cloud computing | Communication | RE, EN | B |
| | Poka-yoke | | |
| *Cognition level* | | | |
| Pick-by-voice (Audio AR) | Waste elimination | RE, EN | C |
| | Standardization | | |
| | Poka-yoke | | |

AR: augmented reality. EM: emission. EN: energy. RE: resource. SOP: standard operating procedure.

characteristic of self-aware and smart analytics; audio augmented reality is grouped in the *cognition level* due to the enabled functions of collaborative diagnostics and remote virtualization (Lee et al., 2015). There were no configuration-level applications observed.

The primary digital technologies used in the case companies are the IoT-related connection level technologies, such as the ERP system, MONITOR, smart sensors, MindSphere, and digital screen, as shown in Table 6. The lean principles that are supported by digital technologies are visualization (8 practices, e.g., Kanban, VSM), waste elimination (transports, defects, motion, waiting), poka-yoke (4 practices), communication (5 practices), and standardization (4 practices).

*4.1.2.2. Supporting paths (IoT-related technologies support lean principles).* The main paths that the IoT-related connection level technologies support are visualization, communication, standardization, and lean waste elimination. Visualization is enhanced by visualizing the production data, such as the consumption of material, cutting tool, tooling, waste material, scrap rate, generated heat, machine status, and air quality, supported by real-time updates enabled by the IoT platform.

Communication is strengthened owing to the instant feedback loop enabled by the systems; for example, at company C, the generation of metal chips is constantly updated to the recycling company so that they can plan their pick-ups with milk runs. Another example is to update the number of containers on the customer side, so company A can plan when to return the containers for re-use.

Standardization is supported by using IoT-related technologies to minimize deviations. For example, as observed in company A, the air quality is measured and compared to the required standard. Once there is a deviation, the system will send an alarm and request action. Another example observed at company B was the ERP system-supported poka-yoke. The previous tooling storage tried to visualize the number of tools with a Kanban system so that the operators could come and fetch the new cutting tools when they wore out in the machine. However, there was a risk that the wrong type of tool could be taken, and unnecessary stock may be required because the operator took extra sets to the workstation. With an ERP-supported tooling poka-yoke control, as shown in Fig. 2, the operator needs to enter the product type and machine number to get the right tool, eliminating the risk of fetching the wrong tool. Besides, the system would only allow one set of tools to be taken and immediately update the information to ensure sufficient stock. Accordingly, extra stock can be reduced, and the stock information could prepare the system with the right amount.

Lean waste elimination is observed when avoiding the generation of defects and waiting time by monitoring equipment conditions, such as the spindle monitoring at company C. The spindle's condition is crucial to smooth and continuous production because its unplanned maintenance could cause the whole line to stop, and operators will have to wait until the spindle is repaired or replaced. Furthermore, the vibration caused by the spindle failure could produce defective workpieces. The risks can be avoided with the support of smart sensors to notify the time to change or maintain the spindles.

The environmental impact reduced through digitalized lean implementations is mainly attributed to resource and energy consumption reduction and waste and emission generation. The main contributors are the increased visibility enabled by production data monitoring, increased efficiency by avoiding unplanned breakdowns and eliminating wastes brought by stock control, and error/scrap/defects prevention. In addition, reduced resources and energy consumption could also be attributed to prolonged material/product lifetime by reusing the material/product through advanced real-time monitoring and communication. It therefore leads to less generation of carbon emissions. Moreover, carbon emission is also reduced by optimized transport enabled by IoT-related technologies.

In summary, IoT enables a smart connection system that enhances visualization, communication, standardization (poka-yoke), and waste elimination, thus contributing to ES through efficient production and increased quality. Furthermore, IoT-enabled visualization also provides a basis for operational and environmental performance optimization.

### 4.2. Digitalized lean and ES: the literature findings

This section presents digitalized lean implementations and the corresponding environmental impact from the literature's best practices. Hence, the practices only focus on digitalization and lean, or lean and ES were excluded. The practices were summarized in the same structure as in the case study to provide input for the framework development, as shown in Table 7.

#### 4.2.1. Applied digital technologies

IoT-related connection-level digital technologies (including IoT, smart sensors, ERP, and simulation) were widely applied in facilitating lean implementations, accounting for 80 % (25 out of 31) of the total applications. Simulation is categorized into the connection level because it tracks the operational status and collects data to provide the basis for improvement. However, no practices of cognition-level technologies were observed in the reviewed literature.

The other levels' technologies, such as conversion, cyber and configuration levels, are more advanced and usually enabled by the IoT platform. For example, the big data analysis was based on the data collected through IoT and analyzed for further improvement. Moreover, the cloud-based system was connected to IoT, where real-time data is collected and analyzed. Hence, IoT and related digital technologies are primarily used to facilitate lean principles.

#### 4.2.2. Supporting paths (IoT-related technologies support lean principles)

IoT and connection-level digital technologies facilitate the implementations of visualization (VSM, Kanban), standardization (poka-yoke, FIFO (first-in-first-out)), lean waste elimination, and communication. Visualization was enhanced by monitoring material (Yilmaz et al., 2022) water (Phuong and Guidat, 2018) and energy consumption (Kabzhassarova et al., 2021; Yilmaz et al., 2022), production efficiency (Lobo Mesquita et al., 2021), waste generation (Duarte and Cruz-Machado, 2017; Kurdve, 2018), the stock level of raw materials (Lobo Mesquita et al., 2021), machine status (Dixit et al., 2022), etc. The enabled real-time visibility of resource and energy consumption leads to a more significant opportunity to identify areas for improvement, thus reducing the consumption of resources (material, water, tools) and energy. The simulation based VSM uses real-time updates to provide more accurate data to identify the real bottlenecks, optimizes milk runs and stock levels (lean waste reduction), and compares performances for a more cost-effective alternative. As a result, carbon emissions are reduced by less processing time, optimized traveling routes, and eliminated wastes (Amjad et al., 2021a; Yilmaz et al., 2022).

Communication became smarter because a more efficient interaction system was enabled by IoT, providing smoother information exchange for remanufacturing and recycling processes (Tseng et al., 2021). Furthermore, the visualized material, waste, and information flow enhanced by IoT lead to more efficient integration of processes and people, which ultimately supports achieving green goals with less resource and energy consumption and less emission produced (Dixit et al., 2022).

IoT and connection level technologies supported standardization with transparent production data. It could be achieved by using

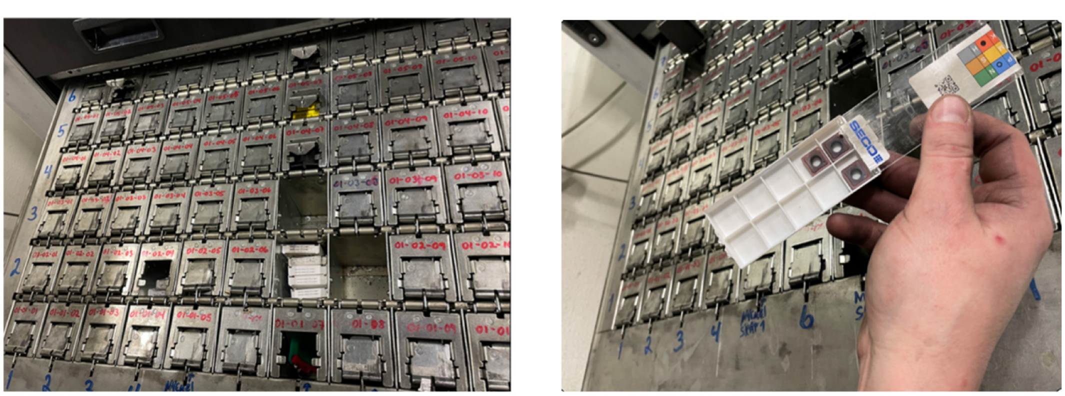

**Fig. 2.** The ERP-supported tooling poka-yoke control.

**Table 7**
Digital technologies integrate lean principles and the corresponding environmental impact (literature findings).

| 5C/digital technologies | Integrated with lean | Impact on ES | References |
|---|---|---|---|
| *Connection level* | | | |
| IoT | FIFO, TPM | EM | (Amjad et al., 2021a) |
| | FIFO | EN | |
| | Visualization and communication | RE, EN | (Dixit et al., 2022) |
| | Visualization | RE, EN | (Duarte and Cruz-Machado, 2017) |
| | Visualization: *VSM* | RE, EN | (Ferrera et al., 2017) |
| | | EN | (Kabzhassarova et al., 2021) |
| | Visualization: *Kanban* | RE, EN | |
| | Visualization: *VSM* | RE, EN | (Lobo Mesquita et al., 2021) |
| | Visualization | RE, EN | (Kabzhassarova et al., 2021; Yilmaz et al., 2022) |
| Smart sensors | Visualization: *VSM* | RE, EN, WS | (Phuong and Guidat, 2018) |
| | Visualization | EN, WS | (Lobo Mesquita et al., 2021) |
| Digital instruction | Visualization; standardization | RE, EN, WS | (Kurdve, 2018) |
| Simulation | Visualization: *VSM* | EM | (Amjad et al., 2021a) |
| | | EN, EM | (Heilala et al., 2008) |
| | | EM | (Heilala et al., 2010) |
| | | RE, EN | (Yilmaz et al., 2022) |
| | | EM | |
| | Waste elimination: *Kanban and milk-run* | EM | |
| | Poka-Yoke and Jidoka | EM | |
| *Connection ➔ Conversion* | | | |
| IoT and big data | Visualization and monitoring | RE, EM | (Amjad et al., 2020) |
| | | RE, EN, EM | (Bittencourt et al., 2019) |
| | Visualization | RE, EN, EM | (Lobo Mesquita et al., 2021) |
| | Visualization and monitoring | EN, WA, EM | (Santos et al., 2019) |
| | Communication | RE, EN, WS | (Tseng et al., 2021) |
| IIoT and Cloud computing | Visualization | RE (SCA) | (Khanzode et al., 2021) |
| *Conversion level* | | | |
| AM | Inventory reduction | RE, EN | (Lobo Mesquita et al., 2021) |
| Automation | Poka-Yoke | RE, EN, WS | (Amjad et al., 2020) |
| *Cyber level* | | | |
| Big data | Visualization and monitoring: *VSM* | RE, EN, WS | (Castiglione et al., 2022) |
| | Continuous improvement | EN, EM, POL, WS | (Lobo Mesquita et al., 2021) |
| Cloud-based system and big data analytics | Visualization | EM | (Amjad et al., 2021a) |
| *Configuration level* | | | |
| Machine learning | Waste elimination | RE, EN, EM | (Leong et al., 2020) |

AM: additive manufacturing. EM: emission. EN: energy. FIFO: first in, first out. Jidoka: automation. POL: pollution. RE: resource. SCA: scarce resource. TPM: total productive maintenance. VSM: value stream mapping. WS: waste. WA: water.

automated and integrated scheduling to reach FIFO (Amjad et al., 2021a), applying smart sensors to predict an optimal time for TPM and ensure quality (Amjad et al., 2021a), exploiting simulation to prevent deviations from standard consumption of fuel (Yilmaz et al., 2022). Consequently, reduced lead-time, increased quality level, and less consumption of fuels lead to reducing energy consumption and emission generation.

To summarize the practices from the literature, the connection level of digitalization accounts for the most significant share of integrating with lean implementations, including IoT, ERP, smart sensors, and simulation. The primary role of smart connection is to monitor and track the operational and environmental performance, mainly through increased visibility of production data and resource and energy consumption, thus leading to direct and indirect reduction of resource and energy consumption.

### 4.3. The DISEL framework

Based on the theoretical framework, the findings led to the development of the framework of **DI**gitalization **S**upport **E**nvironmental Sustainability through **L**ean principles (DISEL), as shown in Fig. 3.

Both strategic and operational levels of digitalization, lean production, and ES are described in the DISEL framework.

Strategically, the three paradigms are all involved in the companies' sustainable development. Digitalization mainly serves the functions of monitoring and tracking data, connecting through transferring data and information, analyzing data to support decision-making, and executing control commands based on self-awareness, corresponding to Lee et al.'s (2015) 5C architecture. Lean production mainly focuses on value-driven and waste-elimination principles, where the customers ultimately decide what value is and what comprises waste (Hines et al., 2004; Liker, 2021). Finally, ES in manufacturing involves minimizing environmental impact and prioritizes emission elimination due to the pressure of climate change (European Union, 2021), which also appears as the focus of the studied companies.

Operationally, IoT and related connection-level technologies offer enormous opportunities to facilitate lean principles' implementation. However, the support of other levels' technologies in lean principles is not yet fully discovered, given that too few practices were observed in the case study and literature. Therefore, the patterns were identified in IoT-related digital technologies in the DISEL framework.

The facilitation paths include enhancing visualization and connection, minimizing deviations, and monitoring lean waste. Enhanced visualization can be achieved by increasing the visibility of production data, including the machines' running states, productivity, the consumption of resources (material, water/lubrication/cooling liquid) and energy, and the generation of waste and emissions. Kanban or VSM may be used as tools to visualize specific areas or tasks. Enhanced connection means using real-time data to connect and integrate operations, production activities, and people to increase communication efficiency. Standardization can be enhanced by identifying and minimizing deviations with the support of connection technologies, such as ensuring working procedures (poka-yoke), safety stock level (raw materials, package materials, tooling), and material handling sequence (FIFO).

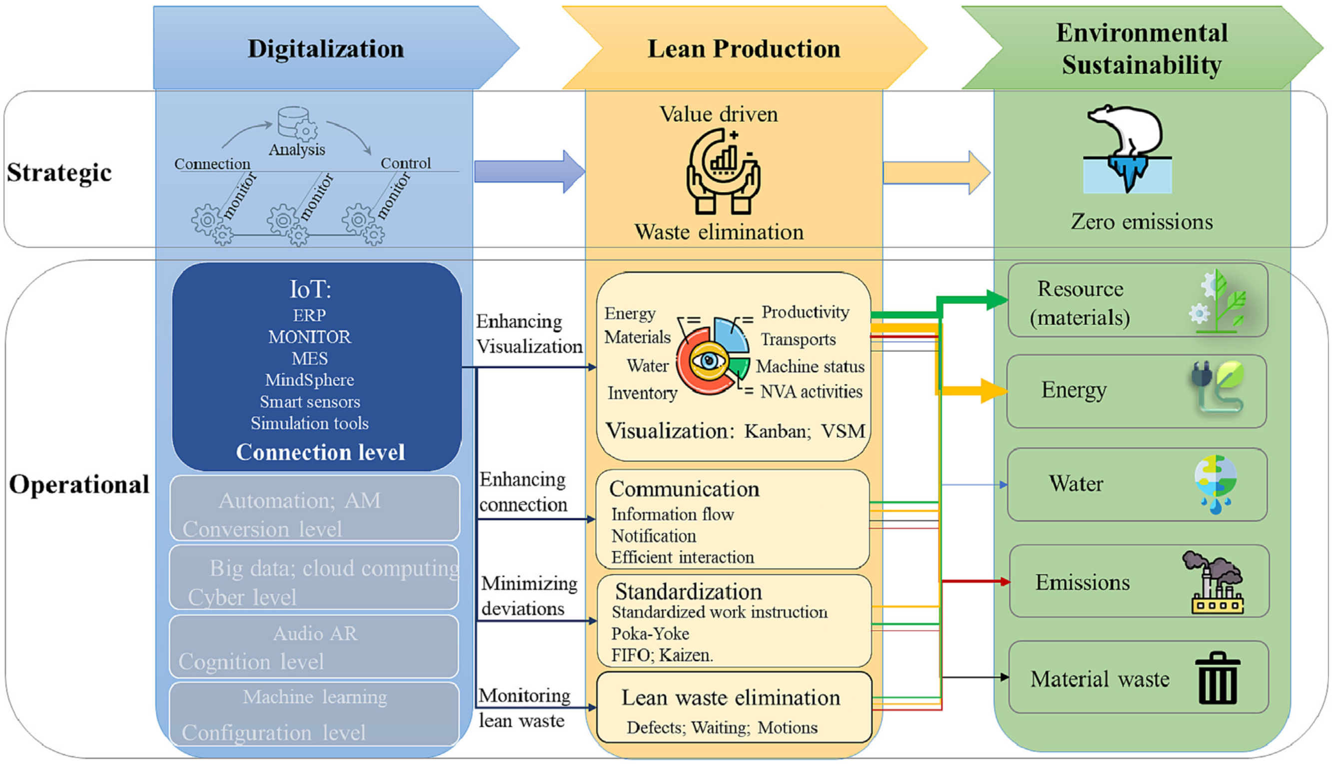


**Fig. 3.** Framework of **DI**gitalization **S**upports **E**S through **L**ean principles (DISEL).

Finally, lean waste elimination/reduction can be advanced through tracking and monitoring product quality status, motions, machine running, etc.

IoT-supported visualization, communication, standardization, and lean waste elimination reduce environmental impact, including the consumption of resources (materials and water) and energy, and the generation of emissions and industrial waste. Compared to the other lean principles, enhanced visualization has a relatively high possibility of contributing to reducing resources and energy consumption, and emissions production.

To use DISEL to promote ES, a company can start by focusing on and relating the three paradigms in its strategies. Specifically, smart connections enhance the performance of value-adding and waste elimination in operations, contributing to zero emissions. Alignment at the strategic level can help build organizational commitments, raise people's awareness, and accelerate implementation. It follows with identifying opportunities for IoT-related connection technologies to enhance visualization. The enhanced visualization provides a foundation for increasing communication and operational efficiency, offers a basis for improving standardization and leading to continuous improvement, and supports waste elimination through visualizing non-value-added activities.

## 5. Discussion

Manufacturing companies seek innovative approaches to create a seamless transition to digital and green, with lean production being one option. Digitalized lean solutions can enhance production environmental performance. However, through the literature analysis, integrating digital technologies and lean production requires more practice-based research, especially when targeting the improvement of ES. Moreover, more clarity is required on which digital technologies may be combined with which lean principles for a better ES.

To fill the gaps, we conducted a practice-based study at three case companies to investigate their digitalized lean implementations and the resulting environmental changes. Meanwhile, a literature review was conducted to complement the case findings. Consequently, Tables 3, 4, and 5 show the strategies for adopting digitalization, lean, and ES, and Tables 6 and 7 describe the application of digital technologies in lean principles and the reduced environmental impact. The observed case findings and practices indicate that IoT and the related connection level technologies were widely used to integrate with visualization, communication, standardization, and waste elimination, as illustrated in the DISEL framework (Fig. 3). The integration paths include enhanced visualization, enhanced connection, minimized deviations, and monitoring, leading to a reduction of material, water, and energy consumption, and emission and waste generation.

Based on the findings, we will discuss 1) the DISEL framework, 2) theoretical and practical implications, and 3) the limitations and future work. Regarding the DISEL framework, four aspects will be covered: the accelerators' role of IoT and related connection level digital technologies, the bridging role of lean principles, the paths that strengthen lean principles and ES, and the reduced environmental impact.

### 5.1. The DISEL framework

This study showed improved environmental performance through enhanced lean principles implementations with IoT-based digital technologies. In other words, ES is improved because of digital technologies' role as accelerators and lean principles' role as bridges, as shown in Fig. 3. Furthermore, the DISEL framework illustrated the integrating paths that accelerate and enhance the implementation of lean principles, and the reduced environmental impacts.

#### 5.1.1. Accelerators: IoT-based digital technologies

As observed in the case study and the literature practices, IoT-related digital technologies from the connection level of the 5C architecture were most widely applied in supporting lean principles. IoT and related digital technologies, including ERP, MONITOR, MES, MindSphere, and smart sensors, were widely used in the case companies. Similarly, IoT, smart sensors, and simulation practices were observed as broadly applied digital technologies in the literature. This finding strengthens that IoT is highly important among the other I4.0 technologies in manufacturing (Chen et al., 2020; Ghaithan et al., 2021).

The DISEL framework indicates that IoT-enabled data tracking and monitoring connect different business functions and support efficient visualization and communication. Visualization accounts for the biggest share because it is easy to implement and can be extensively integrated with digital technologies. According to Liker and Meier (2006), visual management is a cornerstone of lean production. In this study, digitalized visualization enhances the visibility of material flow, finished goods, tools inventory, energy consumption, machine status, scrap rate, and waste generation (packaging material, cutting chips, etc.), mainly through the exchange and communication of real-time data and information. Based on this, big data analytics and cloud computing could suggest eliminating or minimizing deviations and improving operational performance. Furthermore, the enhanced transparency of the material and information flow ensures more robust capabilities to adapt to changes and be flexible when responding to customers' needs.

Moreover, the observations from the case studies indicate IoT-based higher level applications, for example, intelligent robotics at company C and cloud computing at company B. It coincides with Lobo Mesquita et al.'s (2021) claim that IoT generates big data and provides a basis for optimizing operational performance, including machine running status, productivity, failure rate, etc. It also confirms the conclusions from the previous research (Chen et al., 2020; Reyes et al., 2021) that manufacturers' digital transformation could start with implementing IoT and CPS technologies, especially for SMEs challenged with limited financial support and incentives (Leong et al., 2020).

*5.1.2. The bridging role: lean principles*

It was observed that lean principles are implemented as a culture at all three companies from the strategic level to engage people throughout the organization. This alignment is crucial for any change management initiative, including digital and green transformations. As Bittencourt et al. (2019) and Kamble et al. (2020) claimed, the successful implementation of lean production enables manufacturing companies to prepare for digital and green transitions.

The enhanced visualization increases the visibility of production data, such as the consumption of material, cutting tool, tooling, waste material, scrap rate, generated heat, machine status, and air quality, at all three companies. The increased visibility provides greater opportunities to improve the efficiency of using resources and energy through smarter stock control (company B), error/scrap/defects prevention (companies A, B, and C), and reusing material/product (companies A and C). It therefore also leads to less generation of carbon emissions. In the presence of lean, the effect of digitalization on sustainability is enhanced. This conclusion corresponds with previous studies that lean is meant to be a significant bridging factor (Ghaithan et al., 2021), a prerequisite (Schumacher et al., 2020), or an enabler (Yilmaz et al., 2022). As observed in the companies, they could have used the technologies to improve their environmental performance directly, but they did not. It verified what Bittencourt et al. (2019) claimed: if digitalization is developed as a standalone application, it may not contribute directly to ES. Our findings indicate that the odds of contributing to sustainability can be increased if we use lean as a bridge to guide the application of digital technologies.

*5.1.3. The paths that strengthen lean principles and ES*

*5.1.3.1. Digitalized lean implementations.* Applying digital technologies on lean principles could accelerate and enhance the value-adding and waste-elimination process, allowing better performance improvements than using either lean or digitalization solely. From our observations, IoT is the leading digital technology that could be integrated with lean principles to contribute to the environment, strengthening Lobo Mesquita et al.'s (2021) conclusion. The strengthening paths can be categorized into enhanced visualization, enhanced connection, minimized deviations, and monitored lean waste enabled by IoT-related technologies (MONITOR, ERP, smart sensors). The affecting mechanism is mainly enabled by tracking and monitoring the operational status, such as machines' running status, stock level, defects, air quality, spindle condition, etc. The increased transparency of operational data aligns with the visual management principle, providing a basis to increase communication efficiency, deviation visualization, and lean waste monitoring. Lean waste refers to the seven types: overproduction, waiting, transport, overprocessing, unnecessary inventory, unnecessary motion, and defects (Hines and Rich, 1997).

Tracking and monitoring can enhance the connection between machines, systems, and people. For example, as observed in company A, the real-time update of the raw material consumption and finished products provides suppliers and customers with more accurate information, thus increasing communication efficiency. Similarly, in company B, the real-time update of machine status reduces the response time to machine failures, smoothening the communication between production and maintenance.

*5.1.3.2. Digitalized lean pull green.* In this study, the environmental benefits are mainly attributed to the real-time interaction enhanced information visibility, including machine status, productivity, material flow, inventory (products and tools), resource and energy consumption, scrap, and waste. Consequently, these actions increase resource and energy utilization, thus contributing to ES with less depletion of resources and emissions. It aligns with Kamble et al.'s (2020) claim that digitalized lean enhances the ES of production systems.

All three companies advocate lean and ES by their belief of “lean benefits green” and that lean's value-driven and waste elimination principles contribute to ES performance. Operational practices also show a tight connection between digitalized lean implementations and reduced environmental impact (Table 6). It coincides with the claim from previous research (Baumer-Cardoso et al., 2020; Dieste et al., 2019; Garza-Reyes et al., 2018) that the lean waste-elimination principle includes green wastes, such as excessive consumption of materials, energy, water, etc. Moreover, some of the waste elimination goals of lean “naturally” coincide with sound green practices. As observed in the case study and from the literature practices, the excessive transportation of raw materials or finished goods is one of the seven wastes defined in lean. This type of waste minimizes operational expenses and the unnecessary consumption of natural resources, energy, and emissions (Garza-Reyes et al., 2018). Many more examples can be identified from this study, including the long processing time, overproduction, excessive inventory, defects, etc.

Furthermore, it is argued that the successful implementation of lean is a prerequisite for the successful adoption of green (Amjad et al., 2021a) because the focus on waste elimination creates a better atmosphere for initiating green practices. Moreover, using lean principles could support identifying the potential to reduce environmental impacts (Baumer-Cardoso et al., 2020; Garza-Reyes et al., 2018). Similarly, as observed in this study, visual management (VSM, Kanban, 5S), SMED, pull production (FIFO), Poka-yoke, standardization, etc., enhance environmental performance.

*5.1.4. Reduced environmental impacts*

The DISEL framework shows that reduced resources (materials: raw materials, work-in-process, finished goods) and energy consumption are the main contributors toward ES. The reduced consumptions were mainly attributed to enhanced visualization by IoT-based platforms enabling real-time visibility of the consumption of resources and energy, eventually leading to less emission and waste. The increased visibility could also urge people to take immediate action to eliminate unnecessary resources (dematerialization) and energy consumption, as well as reduce waste and emission generation.

Furthermore, higher production efficiency could be achieved through increased visibility of cycle time/lead-time, quality level (defects), and machine status, which leads to a higher resource and energy consumption efficiency, as Khanzode et al. (2021) claimed. Moreover, the increased visibility of wastes, such as inventory level, non-value-added activities (e.g., training time), human errors in assembly, and resource consumption, indirectly increase the efficiency of resource and energy consumption. Additionally, the increased communication efficiency between different stakeholders, such as production, planning/scheduling, suppliers, and customers, could also increase production efficiency and reduce transport. Hence, the affecting approaches (increased efficiency, de-materialization, detection and monitoring of changes, and transports) coincide with the four approaches that digitalization benefits ES, as Berkhout and Hertin (2004) proposed. Hence, it strengthened the finding that digitalized lean implementations could support ES through similar approaches.

### 5.2. Practical and theoretical implications

#### 5.2.1. Practical implications

The DISEL framework (Fig. 3) provides an overview of integrating digitalization and Lean implementation to improve the environmental performance of production systems. The observed improvements could encourage practitioners to expand the application of digital technologies to improve environmental performance. Specifically, IoT-related digital technologies have great potential to facilitate lean principles. Lean production focuses on value-driven and waste elimination, providing principles to enable transparency and standardization and acting as the guidance for effective operational management. As a recent revolution, I4.0 entails new opportunities with new technologies and cannot be captured without such "guidance" (Kabzhassarova et al., 2021). Hence, applying digital technologies to improve ES does not necessarily involve sacrificing operational performance when we use lean as the bridge. Being both economically and environmentally sound strengthened the interconnection of the sustainability pillars (Chen et al., 2020); it also showed a synergistic effect on developing the company's sustainability culture.

Moreover, digitalized lean principles are usually executed after waste is identified, visualized, and removed. Therefore, it could minimize the risk of automating non-value-adding activities or accelerate waste generation while unlocking the full potential of I4.0 (Bittencourt et al., 2019; Chiarini et al., 2020). Additionally, accepting digitalized lean principles could be easier than a brand-new technology, as shown in our case companies. The streamlined and waste-free process and standardized procedure realized through lean implementations could smooth the application of digital technologies in production systems (Buer et al., 2018; Chiarini et al., 2020).

IoT-enabled data tracking and monitoring provide real-time updates and support efficient visualization and communication, as shown in Tables 6 and 7. Specifically, the practices indicate that visualization is easier to implement and can be extensively integrated with digital technologies. The observed primary application of IoT-related connection level technologies could be due to limited financial support and incentives at the studied SMEs, as Leong et al. (2020) claimed. On the other hand, it could also be because IoT is often chosen as an initial step to enhance connectivity and obtain data for further analysis and improvement (Chen et al., 2020; Ghaithan et al., 2021). Either way, the summarized practices could inspire practitioners to implement possible applications in their companies and provide insights into the "easily attainable goals," such as the application of IoT-related connection level technologies and the enhanced transparency enabled by visualization.

#### 5.2.2. Theoretical implications

The DISEL framework was oriented by studying the use of digital technologies, lean implementations, and the resulting environmental impacts at the case companies, which fulfills the gap of seldom considering empirical implications in framework development (Leong et al., 2020; Touriki et al., 2021; Tripathi et al., 2021).

Furthermore, this framework focuses on improving ES in the production system, attempting to reshape the situation of digital applications by prioritizing the environmental benefits (Chiarini et al., 2020). Moreover, the common goal of value-driven and waste elimination shared by lean, digitalization, and green could help manufacturing companies reduce costs, improve operational performance, and reduce environmental impacts. Additionally, DISEL addresses lean's intermediary role of bridging digitalization and ES, acting as a foundation for commencing digital and green transition (Amjad et al., 2021a; Beier et al., 2022). Finally, by utilizing available resources, embracing changes, and pursuing sustainability, DISEL shows the positive synergy between paradigms and allows companies to become profitable, sustainable, and resilient.

This study provides further clarity on topics that remain unclear in the literature. For example, Tables 6 and 7 provided answers to "which digital technologies could be integrated with which lean implementations" (Buer et al., 2018; Lobo Mesquita et al., 2021; Varela et al., 2019). Moreover, the DISEL framework enriches the theoretical framework with integration paths linking identified digital technologies and lean principles, leading to specified environmental impacts (Buer et al., 2018; Varela et al., 2019). Furthermore, the tables and DISEL framework also reply "which green performance could be improved" (Kamble et al., 2020; Lobo Mesquita et al., 2021) with observed practices.

### 5.3. Limitations of the study and future work

This study conducted a case study at three SME companies and drew conclusions based on the observed practices. The three SMEs are from the Swedish manufacturing industry and have different products and operations. Thus, the conclusions may not apply to other industrial companies that vary considerably. However, although the study was performed in SME companies, the conclusion could be generalized to other manufacturing companies. For example, IoT-related connection level technologies applications were also observed in previous research (Dixit et al., 2022; Yilmaz et al., 2022).

The DISEL framework identified that IoT and related digital technologies are widely applied and integrated with lean principles, especially with visualization, communication, standardization, and lean waste elimination. However, the findings did not provide enough data to identify the other levels' digital lean implementations. The potential of other levels of digital technologies awaits further studies to identify integration opportunities. Moreover, the reflected environmental impacts could vary depending on the newly identified integration possibilities, which would be interesting and valuable to explore. Also, the actual environmental impact of applying digital technologies was not quantified in this study, which indicates a further step to measure the environmental impact from a holistic perspective.

Furthermore, this study aimed to ensure construct validity by collecting data 1) using multiple sources of evidence, including interviews and observations at three companies, and 2) establishing the chain of evidence as shown in Table 6 (Yin, 2003). Meanwhile, the report review of key informants is still in progress. Hence, further studies are encouraged to extend the internal validity with more in-depth case studies and increase the generalizability and external validity by conducting survey studies.

## 6. Conclusion

Manufacturing companies seek an innovative approach to achieve successful digital and green "twin" transitions in their existing production systems. The production systems need to be digitalized toward I4.0, becoming efficient in production and consumption, sustainable and resilient.

This paper identified an exploitative innovation approach to use lean as a bridge leading toward the twin transitions. It proposed a DISEL framework to integrate digitalized lean principles for environmental sustainability. The practices summarized from the case study and literature review were essential in developing the framework, providing a solid basis to use it in practice.

IoT and its related connectivity level technologies were identified as the most widely applied digital technologies from the observations made. They can be widely integrated with lean principles through tracking, monitoring, connecting, and analyzing the collected data to enhance visual management, standardization, poka-yoke, and inventory reduction. Hence, resource and energy consumption could be reduced attributed to more efficient consumption, eliminated excessive usage (dematerialization), reduced transports, and increased optimization opportunities.

The proposed DISEL framework fulfills the identified research gap by answering "which digital technologies could be integrated with which lean implementations" to improve "which green performance." The identified IoT and related digital technologies can facilitate lean principles to reach environmental impact reduction. Moreover, it provides practitioners with implications to promote environmental sustainability through digitalized lean principles, thus achieving sustainable production systems and smooth twin transitions.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Key takeaways from the reviewed frameworks

| # | Objective & method | Key takeaways |
|---|---|---|
| a | (Amjad et al., 2021a)<br>Economic and environmental performance.<br>Developed from literature review and implemented in a case study. | A step-by-step implementation of Lean and Green manufacturing concepts, adopting I4.0 technologies. Starting with Lean preparation, implementation, and completion, then following Green preparation and implementation. The opportunities for implementing I4.0 are identified in the implementation phases, adopting smart production control, cyber-physical systems, and energy monitoring. |
| b | (Amjad et al., 2021b)<br>Operational excellence by applying Lean, agile, Resilience, and Green manufacturing concepts with I4.0.<br>Literature review | It entails a step-by-step implementation that starts with Lean manufacturing principles, then agile manufacturing, resilient paradigm, and green manufacturing. Each of the four principles goes through three phases: planning, analysis and improvement, and control. This framework has eleven phases and thirty-one steps to successfully implement Lean, agile, resilient, and Green through the support of I4.0. |
| c | (Amjad et al., 2020)<br>Operational, economic, and green benefits by integrating I4.0 technologies with LARG (Lean, Agile, Resilient, Green).<br>Systematic literature review | The conceptual LARG implementation framework integrates with I4.0 technologies to simultaneously support the implementation of Lean, agile, Resilience, and Green manufacturing. The integration with Lean is through smart production control and manufacturing, and the integration with Green is mainly through IoT, big data, and smart grids. |
| d | (Ciliberto et al., 2021)<br>Achieve digital, sustainable products and processes by integrating I4.0, Lean, and circular economy principles.<br>Literature review | This conceptual framework illustrates that the Lean strategy promotes circular principles with waste elimination principle, and with the support of digital applications, to de-materializing and de-energizing production and products and reintroduce waste into the production cycles as a raw material to create regenerative and circular systems. |
| e | (Dahmani et al., 2021)<br>Design eco-efficient products by exploring the relationship between Lean, eco-design, and I4.0 strategies.<br>Literature review | It illustrates how I4.0 technologies facilitate the integration of Lean eco-design approaches. Circular strategies are adopted in the smart circular design by supporting cyber-physical interaction to connect elements throughout the product lifecycle, thus creating value from disposed waste and leading to smart and eco-efficient design solutions. |
| f | (John et al., 2021)<br>Operational and sustainable performance by implementing Lean & Green in an I4.0 environment.<br>Literature review | It uses I4.0 technologies to accelerate and promote the integration of Lean and Green. For example, I4.0 technologies can specify Lean and Green value through data analytics, identify Lean and Green value streams, create a Lean and Green flow through data visualization, create a Lean and Green pull system, and reach continuous performance improvement. |
| g | (Leong et al., 2020)<br>Operation performance. Prepare for the I4.0 transition through Lean and Green, supported by machine learning.<br>Theory & methods dev., implemented in a case study. | The Lean and Green framework, supported by machine learning, optimizes operational performance. The framework consists of seven steps of action to identify the best process improvement pathway and to improve the current operational performance toward the benchmark outcome based on algorithm-processed experts' input and operation data. |
| h | (Liao and Wang, 2021)<br>Operational performance of the triple bottom line of sustainability in the chemical industry through integrating Lean, digitalization, and sustainability.<br>Developed through a case study. | A Lean enterprise architecture framework and a Lean model are developed. The Lean enterprise architecture framework presents the mission, driver, strategy, goal, architecture, and principle for all three sustainability aspects. The Lean enterprise model presents the operational practices of Lean, digitalization, and sustainability, of which the overlap between every two principles represents profit, planet, and profit. |
| i | (Lobo Mesquita et al., 2021)<br>Operational and environmental benefits through an integrated framework of I4.0 and Lean practices, supporting ES.<br>A systematic literature review. | It indicates the integrations of Lean, I4.0, and ES at the level of constructs and variables, and the level of constructs and components, mainly illustrating the integration of technologies with Lean practices supporting ES. The integration of I4.0 and ES to support Lean practices is also identified. The level of integration is represented through the number of citations in the literature. |
| j | (Muñoz-Villamizar et al., 2021)<br>Production and environmental efficiency using toolkit with integrated Lean, I4.0, & Green.<br>Dev. Model from Lean manufacturing. | The model adds ES to the objective of Lean house. The entailed toolkit includes training and commitment on the management level, OEE, and VSM to measure the Greenness and identify environmental wastes and plug&green to track productivity and environmental performance data. |
| k | (Reyes et al., 2021)<br>Supply chain performance through structured Lean, agile, sustainable, resilient, and flexible paradigms implementing I4.0.<br>The literature review and the model were validated through interviews. | The conceptual model presents integrating Lean practices, I4.0 technologies, risk management, and supply chain structure to improve supply chain management performance. Implementing I4.0 is separately integrated with risk management, Lean production, and supply chain flows. These integrations together enhance the supply chain performance. |

(*continued*)

| # | Objective & method | Key takeaways |
|---|---|---|
| l | (Touriki et al., 2021)<br>Using combined smart, Green, resilient, and lean paradigms, environmental and operational performance.<br>Literature review. | Two frameworks are proposed, of which one framework illustrates the drivers, barriers, and critical success factors of integrating smart manufacturing to promote Lean and resilient manufacturing while enhancing Green performance, and the other framework summarizes the present tendencies and future research avenues in the field of smart Green resilient Lean manufacturing paradigms. |
| m | (Tripathi et al., 2021)<br>Operational performance model using Lean, Green, and innovative approaches.<br>Dev. from literature study, validated by case studies. | It includes five steps for implementing smart, Lean, and Green concepts: *examine* the current performance and identify the issues, *demonstrate* the planning of production management, *standardize* the production flow, *optimize* production performance, and *validate* the improvement actions. |
| n | (Vinodh et al., 2021)<br>Maximize operational performance, enhance productivity, and improve sustainability.<br>A systematic literature review. | It integrates continuous improvement strategies (including Lean principles, six sigma, Kaizen, and sustainability) and I4.0 technologies (including four concepts and thirteen technologies) in eleven operational application areas, such as product development, transportation, manufacturing, quality control, environmental control, industrial communication, etc. |
| o | (Zekhnini et al., 2021)<br>Improve supply chain performance by integrating digitalization, Lean, Green, and sustainability.<br>Literature review. | The viable, sustainable digital supply chain model (viability means "the capacity to preserve system identity in a changing environment") entails two decomposed frameworks, one for sustainability improvement that includes practices of Lean and Green, and one for digital supply chain management, key performances of digitalization, Green and Lean. |

## Appendix B. Interview protocol used in the case study

Objective:

To understand the **role of digitalization in implementing lean and green strategies and practices** toward sustainable manufacturing (environmentally sound without compromising economic and/or social sustainability).

Research question:

How can digitalization support the implementation of lean and green strategies and practices toward more sustainable manufacturing?

RQ breakdown to Interview questions:

1) Use of digital technologies and where and how they are used.
2) Use of lean and green strategies and tools, and where and how they are used.
   2A. Use of lean strategies and tools
   2B. Use of green strategies and practices

3) Operational performance change because of the use of digitalization in lean and green (what have you seen and what are you expecting to see)

| # | Interview questions | Research question breakdown | | | | | |
|---|---|---|---|---|---|---|---|
| | | Background information | Use of digitalisation | Use of lean strategies and tools | Use of green strategies and tools | Operational performance change | Overall perception |
| 1 | To begin this interview, could you please introduce your role in the company? | X | | | | | |
| 2 | Do you work with lean?<br>How do you use these tools? | | | X | | | |
| 3 | Which lean tools have you used the most? | | | X | | | |
| 4 | What is your main objective in using the lean tools? | | | X | | | |
| 5 | Where in manufacturing, and how do you apply these lean tools? | | | X | | | |
| 6 | Do you work with environmental performance improvement? | | | | X | | |
| 7 | Which tools/methods have you used to improve environmental performance? | | | | X | | |
| 8 | What is your main objective in using the tools? | | | | X | | |
| 9 | Which tools have you used the most to improve environmental performance? | | | | X | | |
| 10 | Where in manufacturing, and how do you apply these tools? | | | | X | | |
| 11 | Which digital technologies do you have/plan to use? Which do you use the most? | | X | | | | |
| 12 | What is the main objective of using these digital technologies? | | X | | | | |
| 13 | Where in manufacturing, and how do you apply these digital technologies? | | X | | | | |
| 14 | Do you think the use of digital technologies could affect the implementation of lean tools? | | X | | | | |
| 15 | Do you think the use of digital technologies could affect environmental performance? What impact could it be? | | X | | | | |
| 16 | Do you think using lean tools/principles could affect environmental performance? What impact could it be? | | | | | X | |
| 17 | From your experience, do you see any changes in operational performance by using digital technologies? | | | | | X | |
| 18 | Do you see any changes in operational performance by using lean tools? | | | | | X | |
| 19 | Before we close, do you may have something to add up or comment on? | | | | | | X |

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