THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Strengthening the Environmental Sustainability of Production Systems through Digitalization

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ABSTRACT

Industrial companies are facing incremental pressure to strive for environmentally sustainable development. This can be attributed to their increased contribution to energy consumption and carbon emissions and the growing international attention focused on global warming. Meanwhile, digitalization has been a promising approach to improving overall operational performance and has profoundly impacted the environment of production systems. However, digitalization has been prioritized for its economic opportunities over environmental benefits and needs to be studied to expand upon its implications for environmental sustainability.

Hence, this thesis aims to reveal the potential of digital technologies for production systems' environmental sustainability by focusing on: 1) identifying the potential environmental benefits of using digital technologies and 2) identifying the mechanisms for using digital technologies to generate environmental benefits. These aims were achieved by adopting a practical manner and conducting four studies that mixed qualitative and quantitative methods and involved industrial partners. The data collection methods included interviews, onsite observation, questionnaires, focus groups and literature reviews.

The results consist of two parts. First, the main benefit shows that the application of digital technologies can generate environmental benefits primarily through greater resource and information efficiency in the production stage of a product life cycle. Furthermore, the IoT-related connection-level technologies have a relatively high degree of application throughout the manufacturing value chain. The application of VR is also identified as enhancing remote technical communication, thus reducing physical meetings and travel. Moreover, digitalized lean implementations can lead to reduced environmental impact, mainly through integrating IoT and related technologies with lean principles by improving visualization and communication, reducing deviations and monitoring waste generation.

Secondly, the mechanisms by which digital technologies generate the benefits consist of three elements, technological functions, enabled operations and impact pathways. Specifically, the technological functions include *tracking and monitoring status*, *increased efficiency* (production and communication), *dematerialization* and reduced *transport* (with *reduced transport* as a subordinate function compared to the first three). Enabled operations involve context-based examples which could be linked to the operational performance factors and be environmentally performance-driven. The impact pathways comprise prevention, reduction, optimization, reuse and substitution. From the observations in this research, the generation of environmental benefits using digital technologies usually starts with technological functions, which enable operations to reduce environmental impact through impact pathways.

Taken as a whole, this thesis deepens the understanding of using digital technologies to improve the environmental performance of production systems, thus contributing to sustainable manufacturing.

Keywords: environmental sustainability, digitalization, environmental benefits, digital technology, mechanisms, Industry 4.0, production system, manufacturing

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Xiaoxia Chen

Göteborg, 2023

APPENDED PAPERS

PAPER I	Chen, X.; Despeisse, M.; Johansson, B. Environmental sustainability of digitalization in manufacturing: a review. *Sustainability*, 2020, 12, 10298; https://doi.org/10.3390/su122410298
CONTRIBUTION	Principal author. Xiaoxia conducted the literature review, analyzed the collected data, and wrote the paper, considering her co-authors' comments.
PAPER II	Chen, X.; Despeisse, M.; Dahlman, P.; Dietl, P.; Johansson, B. The environmental implications of digitalization in manufacturing: a case study. Presented at *EcoDesign 2019 conference*, Yokohama, Japan. Published in: Kishita Y., Matsumoto M., Inoue M., Fukushige S. (eds) EcoDesign and Sustainability I. Sustainable Production, Life Cycle Engineering and Management. Springer, Singapore. https://doi.org/10.1007/978-981-15-6779-7_18
CONTRIBUTION	Principal author. With Patrik and Paul, Xiaoxia conducted the interviews and onsite observations. Xiaoxia also analyzed the empirical data and wrote the paper, considering her co-authors' comments.
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PAPER IV	Chen, X; Kurdve, M.; Johansson, B.; Despeisse, M. Enabling the twin transitions: digital technologies support environmental sustainability through lean principles. *Sustainable Production and Consumption.* Volume 38, 2023, Pages 13-27, ISSN 2352-5509, https://doi.org/10.1016/j.spc.2023.03.020
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ADDITIONAL PUBLICATIONS

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Abubakar, A.S.; Evans, S.; Margherita, E.G; Chen, X. 2022, August. The role of people and digitalization as an enabler of resource efficiency in manufacturing. In *8th International Workshop on Socio-technical Perspective in IS development* (STPIS'22).

Despeisse, M.; Chari, A.; González Chávez, C.A.; Chen, X.; Johansson, B.; Igelmo Garcia, V.; Syberfeldt, A.; Abdulfatah, T; Polukeev, A. 2021, August. Achieving circular and efficient production systems: emerging challenges from industrial cases. In Advances in Production Management Systems. Artificial Intelligence for Sustainable and Resilient Production Systems: IFIP WG 5.7 International Conference, APMS 2021, Nantes, France, 5-9 September, 2021, Proceedings, Part IV (pp. 523-533). Cham: Springer International Publishing.

Chen, X. Impact of digitalization on environmental sustainability in manufacturing systems. *Licentiate thesis*, 2021. Chalmers University of Technology: IMS-2021-5

Fang, Q.; Despeisse, M.; Chen, X. 2020. Environmental impact assessment of boatbuilding process with ocean plastic. *Procedia CIRP*, 90, pp.274-279.

Gong, L.; Söderlund, H.; Bogojevic, L.; Chen, X.; Berce, A.; Fast-Berglund, Å.; Johansson, B., 2020. Interaction design for multi-user virtual reality systems: an automotive case study. *Procedia CIRP, 93*, pp.1259-1264.

Chen, X.; Despeisse, M.; Johansson, B. Environmental impact assessment in manufacturing industry: a literature review. Presented at *the 6th International EurOMA Sustainable Operations and Supply Chains Forum*, Gothenburg, Sweden, 18-19 March, 2019.

Kurdve, M.; Hanarp, P.; Chen, X.; Qiu, X.; Zhang, Y.; Stahre, J. and Laring, J., 2011, May. Use of environmental value stream mapping and environmental loss analysis in lean manufacturing work at Volvo. In Proceedings of *the 4th Swedish Production Symposium* (SPS11) (pp. 3-5).

Chen, X. & Qiu, X. 2009, Dec. Evaluation of the Environmental Impacts from Implementing Lean in Production Processes of Manufacturing Industry. Presented at *the 3rd Swedish Production Symposium* (SPS09), Göteborg, Sweden.

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1

INTRODUCTION

This chapter introduces the background to the research topic and positions this thesis within it. It then presents the vision, aim, research questions and delimitations and concludes with an outline of the thesis.

1.1 BACKGROUND

Sustainability and Industry 4.0 are key themes in today’s production system. In the context of Industry 4.0, digitalization has been a promising approach to improving overall operational and environmental performance by integrating with manufacturing and business processes (de Sousa Jabbour et al., 2018; Nascimento et al., 2019) which lead towards sustainable manufacturing. By capitalizing upon digital technologies, manufacturing companies attempt to reduce their environmental impacts by implementing more sustainable practices. For example, digital technologies enable companies to improve eco-design by incorporating information from manufacturing, use and recycling (Zhang et al., 2019). In manufacturing processes, digital technologies enable real-time monitoring and collect resource and energy consumption data to provide opportunities for optimizing and reducing consumption (Oláh et al., 2020). Regarding material handling, digital technologies promote autonomous vehicles to optimize transportation routes and frequencies (Bechtsis et al., 2017).

The potential environmental benefits of using digital technologies are presented either on a general level by, say, discussing the integration of Industry 4.0 and operation scenarios (Oláh et al., 2020), or the critical success factors (de Sousa Jabbour et al., 2018) or by discussing one particular technology implementation (Kiel et al., 2017; Santos et al., 2019). Moreover, few studies have examined and summarized industrial practices for improving environmental performance throughout manufacturing value chains, aided by technological advancement.

Furthermore, the mechanism that enables the realization of desired benefits (illustrated in Figure 1) awaits further investigation.

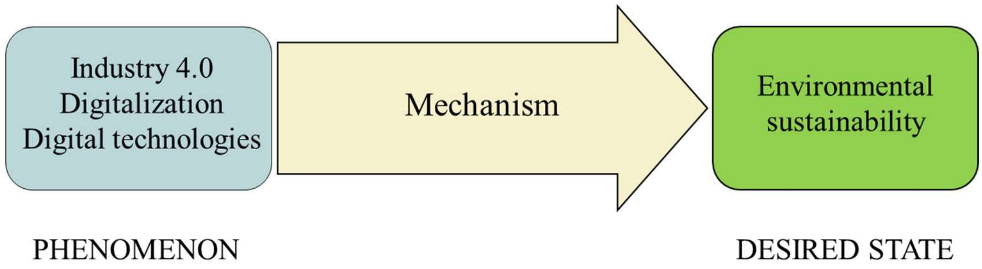

Figure 1. Conceptual mechanism.

Berkhout and Hertin (2004) attempted to draw the relationship between information technologies and environmental sustainability, by such means as segregating them into direct and indirect, positive and negative. Specifically, the positive impacts may relate to improved efficiency, dematerialization and virtualization, detecting and monitoring changes in environmental impact and reducing transport (Berkhout and Hertin, 2004). This classification details the support of the technology functions. However, it refers to information and communication technologies in general, rather than the manufacturing context. Also, the resulting types of environmental impact remain unclear. More recent research from Liu et al. (2022) conducted a systematic literature review to explore the appropriate digital functions for circular economy strategies. The proposed framework identified seven mechanisms between the three main digital functions (collection and integration, analysis, and automation) and the 9R circularity strategies (from refuse to recover) throughout the manufacturing value chain. This study uses some operational practices to elaborate on the relationship between digital technology and environmental sustainability. Nonetheless, the mechanism linking digital functions, the enabled operations and resulting environmental impact changes await further explanation through empirical practice.

Therefore, this thesis aims to study the phenomenon of digitalization in strengthening the environmental sustainability of production systems. Moreover, this thesis aims to provide insights for manufacturing companies to learn how to generate environmental benefits by explaining the mechanisms by which digital technologies improve environmental performance. By doing so, manufacturing companies can harness digital technologies to more effectively and efficiently achieve environmentally sustainable manufacturing.

1.2 VISION AND AIM

The thesis envisages an environmentally harm-free production system in the context of digitalization. Such a production system generates no harmful waste and emissions to our living environment through optimal use of resources and energy and by incorporating new technological advancements.

As a step towards realizing its vision, this thesis aims to identify the potential for applying digital technologies to improve the environmental sustainability of production systems and understand the improvement mechanisms.

1.3 RESEARCH QUESTIONS

The rapid development and deployment of digitalization in manufacturing has a substantial impact on the environment. To get a clear picture of the impact, this thesis started by clarifying the *benefits* of using digital technologies to improve the environmental performance of production systems. Furthermore, knowing *how* the benefits happen deepens the understanding of using digital technologies to improve environmental sustainability.

Manufacturing companies tend to prioritize using digital technology to improve economic growth over environmental performance, although research has shown that digital technologies can improve environmental performance (de Sousa Jabbour et al., 2018; Nascimento et al., 2019). The benefits need to be studied by further investigating industrial practices to reveal the potential of digital technologies in sustainable manufacturing.

Two research questions have been formulated to fulfill the research aim:

RQ1: What are the potential **benefits** of using digital technologies to improve the environmental performance of production systems?

Given the identified benefits, it is important (as a further step) to understand the mechanisms that enable digital technologies to improve environmental performance. Hence, the second research question is formulated as follows:

RQ2: What **mechanisms** can generate environmental benefits from using digital technologies in production?

The generation mechanisms illustrate the pathways to improving environmental performance by applying digital technologies. It thus provides a better understanding of *how* to use digital technology to strengthen the environmental sustainability of production systems.

1.4 SCOPE AND DELIMITATIONS

This thesis focuses on the application of digital technologies in improving the environmental sustainability of production systems and aims to provide practitioners with the knowledge to use digital technologies to become more environmentally sustainable. "Practitioners" here primarily refers to: 1) decision-makers investing in digital technologies, 2) operational managers and engineers applying digital technologies and 3) environmental managers and engineers working on improving the environmental performance of production systems.

Moreover, this thesis focuses on the application of digital technologies to improve the environmental performance of production systems. Economic and social sustainability are equally vital to production systems but are not the focus of this thesis. Additionally, the thesis focuses on applying digital technologies rather than developing those technologies.

1.5 THESIS STRUCTURE

Following this introductory chapter, the rest of the thesis is structured into the following five chapters.

Chapter 2, **Frame of Reference**, presents the theoretical foundation of the thesis. It includes the concepts of sustainable manufacturing, digitalization (Industry 4.0 technologies) and previous research into the relationship between digitalization and environmental sustainability in production systems.

Chapter 3, **Research Methodology**, presents the author's perspective on research and introduces the methods and techniques for conducting the research activities.

Chapter 4, **Results**, presents the results of the four studies conducted in this research, summarizing them according to the research questions.

Chapter 5, **Discussion**, discusses the contributions of the key findings with reference to the research questions, positions this work within the research field and suggests future research. The research quality and its limitations are also reflected upon.

Chapter 6, **Conclusion**, summarizes the research and highlights its major points of interest.

2

FRAME OF REFERENCE

This chapter presents the theoretical framework of this thesis, including sustainable production systems, digitalization and the applications of digital technologies for sustainable production systems, as illustrated below in Figure 2.

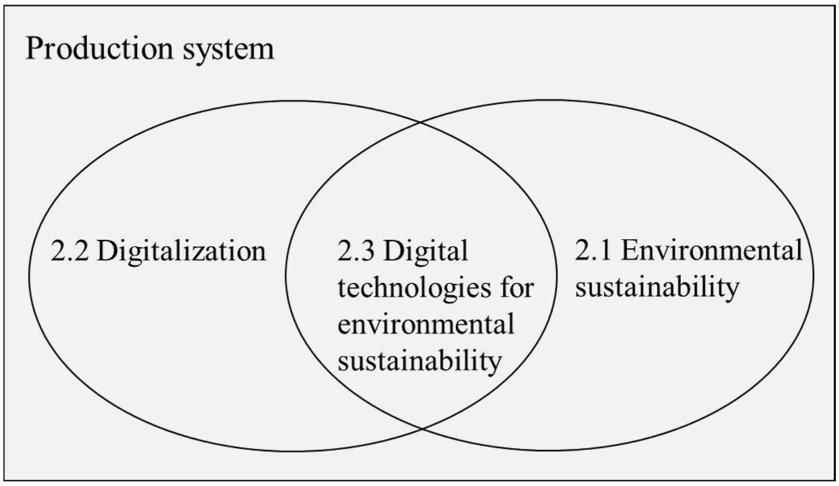

Figure 2. Research framework.

The research framework consists of three sections corresponding to the two research questions. Specifically, the first section introduces the background of environmental sustainability and its development in production systems. Next, it follows digitalization, its emerging technologies and their development and application in production systems. Finally, it introduces the development of applying digital technologies to environmentally sustainable production systems. Table 1 illustrates the structure of the theoretical framework.

Table 1. Structure of the theoretical framework and corresponding research questions.

Section	**Corresponding RQ**
2.1 Sustainability in production systems	
2.1.1 Sustainable development	RQ1, RQ2
2.1.2 Environmental sustainability	RQ1, RQ2
2.1.3 Sustainable production systems	RQ1, RQ2
2.2 Digitalization in production systems	
2.2.1 Digital technologies	RQ1, RQ2
2.2.2 Technological functions	RQ2
2.3 Digital technologies for sustainable production systems	RQ1, RQ2
2.3.1 Technological functions for environmental sustainability	RQ2

2.1 SUSTAINABILITY IN PRODUCTION SYSTEMS

Environmental sustainability is a core topic of this thesis and has evolved alongside sustainable development. Hence, this section begins by introducing the concept of sustainable development, then presents environmental sustainability. The context of production systems is provided on the basis of these two concepts.

2.1.1 Sustainable development

According to the Brundtland Report, sustainable development is “the development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (Brundtland, 1987). Based on this definition, Lozano (2008) highlights the time perspective; that the long-term effects of today’s decisions must be considered. Another focus of this definition is continuity; sustainable development is development that continues (Ciegis et al., 2009). As a general concept, sustainable development encompasses three main dimensions, economic, social and environmental, which are interconnected and complementary (Ciegis et al., 2009). This integrative viewpoint defines sustainable development as “the simultaneous pursuit of economic growth, environmental quality and social equality” (Elkington, 1997). When comparing these two definitions, it is worth noting that the Brundtland Report’s approach does not specify three dimensions. The three-dimensional concept lacks continuity and is primarily concerned with present activities. Therefore, it is preferable to adopt a holistic perspective by integrating the two definitions.

Hence, in this thesis, sustainable development entails the simultaneous pursuit of economic, environmental and social goals, addressing the demands of today's society without compromising those of tomorrow (Elkington, 1999; Keeble, 1987; Lozano, 2008).

Sustainable development is a world view that is both analytical and normative and can be presented in a comprehensive framework with a set of goals towards which a whole society should strive, as Sachs (2015) proposed. Also, in 2015, the United Nations member states approved the 2030 Agenda for Sustainable Development, including 17 Sustainable Development Goals (SDGs). These SDGs have 169 associated targets that are "integrated and indivisible," they represent an urgent call to action for all nations participating in a global partnership (UN, 2015). Furthermore, the SDGs exist to direct the future course of economic, social and environmental sustainability on the planet for the benefit of everyone, including present and future generations (UN, 2015). Specifically, the SDGs aim to bring about a society in which: extreme poverty is eliminated; there is widespread economic growth; social trust is fostered via community-building; and the environment is protected from human-induced deprivation (Sachs, 2015). In other words, it is the triple bottom line (TBL). This is described as "an accounting system that integrates three dimensions of performance: social, environmental and financial/economic" (Slaper, 2011).

Given the definition of sustainable development, the concept of environmental sustainability will be introduced in the next section.

2.1.2 Environmental sustainability

To explain environmental sustainability, it is important to distinguish *sustainable development* and *sustainability* because these two terms are sometimes used interchangeably, despite being quite different. Sustainable development is a path, process or journey towards sustainability, while sustainability is the "...potential for long-term continuation or the dynamic state" (Lozano, 2008). Furthermore, environmental sustainability is defined by Goodland (1995) as "a collection of constraints on the four main activities that regulate the scale of the human economic subsystem: the use of renewable and non-renewable resources on the resource side and pollution and waste assimilation on the sink side." Similarly, Glavič and Lukman (2007) defined sustainable development as a process that highlights the "evolution of human society from the responsible economic point of view, in accordance with environmental and natural processes", where our finite natural resources are considered a guiding factor. Moreover, Hacket and Dissanayake (2014) asserted that environmental sustainability necessitates an awareness of natural resource limits and the vulnerability of the environment, particularly the impact of human activities and decisions. As a result, the definition of environmental sustainability used in this thesis is the dynamic state of "fulfilling current and future generations' resource and service requirements without jeopardizing the health of the ecosystems that support them" (Keeble, 1987; Morelli, 2011).

When approaching environmental sustainability, there are different measures for addressing environmental impact and categorizing environmental indicators. For example, the National Institute of Standards and Technology (NIST) categorizes environmental indicators based on resource consumption, the impact of emissions and pollution and natural habitat protection (Joung et al., 2013).

Environmental sustainability cannot be isolated from the economic and social dimensions to attain the SDGs. Economic sustainability is associated with organizational vision. It creates economic value via cost-saving or enhancing production quality to ensure product and service delivery to market whilst accruing profit between revenues and expenses (Kiel et al., 2017). Being socially sustainable entails an organization having the vision to create value and undertake fair business operations that benefit its employees, the community and wider society (Margherita and Braccini, 2020).

Given the concepts of sustainable development and environmental sustainability, the following section introduces sustainable production systems.

2.1.3 Sustainable production systems

To start with sustainable production systems, it may be necessary to start by clarifying production and manufacturing. Production and manufacturing are used to describe the realization of products and are sometimes interchangeable. However, there is a distinction between them. Production is the process of creating goods and/or services using a combination of material, labor and capital (Bellgran and Säfsten, 2010). According to Bellgran and Säfsten (2010), manufacturing is "… a series of interrelated activities and operations involving the design, materials selection, planning, production, quality assurance, management and marketing of the products of the manufacturing industries". In a broader sense, manufacturing encompasses the physical transformation of raw materials into a product and the associated activities to realize this product and deliver it to market. Hence, this thesis treats manufacturing as superior to production.

A production system is an organized collection of material, labor, capital and methods required to accomplish the process of creating goods and/or services (Bellgran and Säfsten, 2010; Chrisholm, 1990). In this thesis, the specific type of production refers to goods produced in the industrial area; transforming raw materials into products in a production system. The lean production system (or lean manufacturing, a key element in Study D) provides considerable advantages to producers by lowering costs, increasing productivity and quality and enhancing operational efficiency (Bhamu and Sangwan, 2014; Hines et al., 2004; Shah and Ward, 2007). In general, lean has been defined from either a more philosophical view that tied to overall goals, or from a more practical perspective that providing guidelines for managers (Johansson and Winroth, 2009; Shah and Ward, 2007). The waste in lean production is commonly categorized into overproduction, waiting, transport, overprocessing, unnecessary inventory, unnecessary movements and defects (Hines and Rich, 1997).

Considering the triple-bottom-line paradigm, sustainable production systems are capable of manufacturing products through processes that preserve natural resources and energy, minimize negative environmental impact and are safe for consumers, employees and our society, whilst remaining economically sound (Powell et al., 2022; EPA, 2023; Haapala et al., 2013). Accordingly, environmentally sustainable production systems are defined as a collection of materials, labor, capital and methods that accomplish the goods-creation process with minimized environmental impact.

To achieve environmental sustainability, the operational activities in production systems could lead to environmental impact reduction through different pathways. The pathway adopted in this thesis is adapted from the improvement tactics proposed by Despeisse et al. (2013). The five impact pathways were developed by referencing Toyota's six attitudes but with more practical consideration (Salonitis and Ball, 2013). The improvements were ordered by priority as follows:

- Prevention: avoid unnecessary resource usage or waste generation. For instance, stopping or putting a process on hold when unused.
- Reduction: reduce resources or waste by housekeeping, repairing and maintaining equipment or similar activities.
- Optimization: match demand and supply levels to achieve the best efficiency in equipment use or improve the system's overall efficiency.
- Reuse: turn compatible waste output into resource input.
- Substitution: accomplish the operations by replacing inputs with more eco-friendly materials or technologies.

With a better understanding of sustainability in production systems, the next section will introduce the other important topic that is the focus of this thesis: digitalization.

2.2 DIGITALIZATION IN PRODUCTION SYSTEMS

To understand digitalization, it may be necessary to distinguish digitalization from digitization. Digitalization is "the manifold sociotechnical phenomena and processes of adopting and using these (digital) technologies in a broader individual, organizational and societal context" (Legner et al., 2017). On the other hand, digitization was described as "the technical process of turning analog signals into a digital form and eventually into binary digits and is the key notion pushed forth by computer scientists since the creation of the first computers" (Tilson et al., 2010). Specifically, digitization refers to the technical capability of transforming digital information from physical carriers and storage (Legner et al., 2017), while digitalization indicates a wide range of phenomena and processes consisting of both social and technical aspects (Yoo et al., 2010). Hence, digitalization is the impact of digitization on society (Ritter and Pedersen, 2020).

Therefore, reviewing the evolution of digitalization research is worthwhile, as shown in Figure 3.

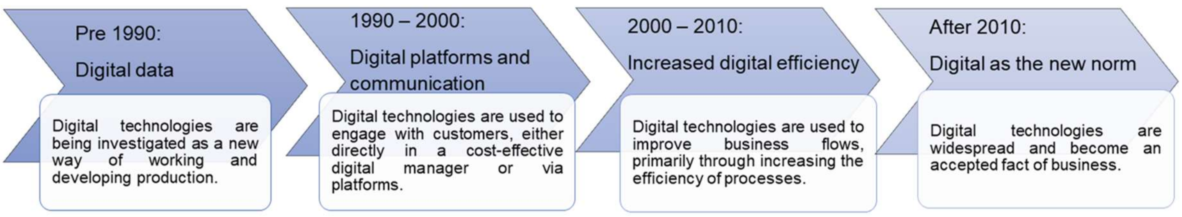

Figure 3. Stages of research into digitization (adapted from Ritter & Pedersen, 2020).

According to Ritter and Pedersen (2020), digitalization may be defined as the application of digital technology. When digital technologies became the new normal after 2010, they changed the competitive landscape of the manufacturing industry and accelerated the Fourth

Industrial Revolution, Industry 4.0.

2.2.1 Digital technologies

Industry 4.0 (Industrie 4.0) was first introduced in 2011 at Hannover Messe in Germany. A report was then published to recommend its implementation (Garcia-Muiña et al., 2018). Since then, many studies have been undertaken in the academic and industrial domains to investigate the nature of Industry 4.0. Industry 4.0 is driven by flexible manufacturing and real-time data exchange (de Sousa Jabbour et al., 2018), enabled and enhanced by advancements in digital technologies, such as information and communication technologies (ICTs) and data storage (Nascimento et al., 2019). The essential components of Industry 4.0 may be understood as a collaborative network containing eight key enabling technologies: cyber-physical systems (CPS), the Internet of Things (IoT), big data analytics, cloud computing, intelligent robots, industrial artificial intelligence (AI), virtual reality (VR)/ augmented reality (AR) and additive manufacturing (AM). The following section presents the definition of the digital technologies used in this thesis.

- *CPS:* Defined as transformative technologies which enable systems to be seamlessly integrated into their physical assets and computational capabilities (Lee et al., 2015). They provide and use data-accessing and data-processing services available on the Internet (Monostori et al., 2016). A CPS involves intelligent connectivity, sophisticated data management and advanced computational capacities and requires exponential growth in the ICT infrastructure (Raihanian Mashhadi and Behdad, 2018).
- *IoT:* 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 equipped with sensors and actuators to the Internet, thus enabling the machines to generate, process and communicate data to humans or machines in real-time (Tilson et al., 2010).
- *Big data analytics:* This refers to techniques adopted to analyze and acquire intelligence from big data (Gandomi and Haider, 2015), which is defined as "high-volume, high-velocity and/or high-variety information assets that demand cost-effective, innovative forms of information processing for enhanced insight, decision making and process automation" (Gartner Glossary, 2023). "Volume" refers to the quantity of data. "Velocity" refers to the rate of data generated and the speed at which it should be analyzed and acted upon. Finally, "variety" refers to the structural heterogeneity in a dataset (Gandomi and Haider, 2015).
- *Cloud computing:* A set of IT services provided over a network and allowing machine data and functionalities to be deployed in the Cloud (Ang et al., 2017). According to NIST, cloud computing is "a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources that can be rapidly provisioned and released with minimal management effort or service provider interaction" (Mell and Grance, 2011).
- *Intelligent robotics:* New generations of robots are evolving towards greater utility

and becoming more autonomous, flexible and cooperative (Rüßmann, 2015). Wang (2010) defines it as an autonomous robot capable of inferring, perceiving and learning based on the three levels of imperative, autonomic and cognitive intelligence.

- *Industrial AI:* This depends on integrating computer science, AI and domain knowledge and is determined by the characteristics of fragmentation, individualization and specialization of problems within the industry (Lee, 2020). Its primary aim is to make the hidden problems in an industrial system explicit, then to manage and avoid them while they remain hidden. The secondary objective is to "accumulate, inherit and apply knowledge on a large scale" (Lee, 2020).
- *VR/AR:* VR is an advanced, human-computer interface that "simulates a realistic environment and allows participants to interact with it," aiming to establish a relationship between the participant and the created environment (Latta and Oberg, 1994). AR turns the real environment into a digital interface by interacting with virtual objects in the real world (Ang et al., 2017).
- *AM:* An additive and automated process of joining materials to produce objects from digital data. These are usually added layer by layer to create physical prototypes, including components or a final product. Fabrication may occur directly through the digital model without needing process planning (Bogue, 2013; Gibson et al., 2015).

The term "digitalization" used in this thesis refers to the application of these eight digital technologies, focusing on the impact of digitization after 2010 (Figure 3, stage 4). The digital technologies that are applied may bring various functions to the manufacturing field; these will be introduced in the next section.

2.2.2 Technological functions

The digital technologies and functions that are introduced may be mapped according to the 5C architecture from its connection to configuration level, as defined by Lee et al. (2015). Furthermore, by integrating CPS with manufacturing, today's factories would be transformed into Industry 4.0 factories of significant economic potential (Lee et al., 2015). Hence, implementing CPS is essential in terms of structure and methods. A 5C architecture is therefore proposed by Lee et al. (2015) to provide step-by-step guidelines consisting of connection, conversion, cyber, cognition and configuration levels, as shown in Table 2.

Table 2. Description of the 5C architecture.

5C architecture	Description of each level
Connection level	Condition-based monitoring using sensor network, controller or enterprise manufacturing systems (e.g., ERP, MES) to seamlessly and tether-free manage, acquire and transfer data to the central server, plug & play, etc.
Conversion level	Meaningful information inferred from data, self-aware, self-predict, smart analytics, algorithms for prognostics and health management applications, degradation, performance prediction, etc.
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.
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.
Configuration level	Feedback from cyberspace to physical space acts as a supervisory control to enable self-configuration, self-adjustment, self-optimization and to apply corrective and preventative decisions by resilient control systems, etc.

Furthermore, IoT and its related digital technologies were noted as widely applied in production systems in studies A, B and D. The following subsection will explain more details regarding IoT.

As introduced earlier, IoT is a global infrastructure for the information society, allowing advanced services by interconnecting physical and virtual things using existing and emerging interoperable information and communication technologies (ITU, 2012). Industrial IoT is a subset of IoT that includes machine-to-machine (M2M) and industrial communication technology with automation applications (Sisinni et al., 2018). Furthermore, IoT is the fundamental level of the 5C architecture, coinciding with the connection level. It performs condition-based monitoring, using a sensor network, controller or enterprise manufacturing systems (such as ERP or MES) to manage, collect and transfer data to a central server tether-less (Lee et al., 2015). ERP, enterprise resource planning, is a centralized online platform within a company's information and communication technology system 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). While MES, a manufacturing execution system, is usually placed as a layer between ERP and the shop floor. Specifically, MES provides production management with the technology and situation-dependent information required to support improvement activities, including process definition, data measurement, data analysis and process control (Kletti, 2007).

According to Löffler and Tschiesner (2013), the Internet of Things might transform the physical world into an information system by integrating sensors and actuators into physical things and connecting them through wired and wireless networks via the Internet Protocol. In the manufacturing industry, IoT has been finding its way into production as a vital enabler of intelligent production systems, revolutionizing the current industrial processes (Xu et al., 2018). Furthermore, IoT-enabled value creation networks help to develop the advanced factory by assisting with item identification, location, tracking and monitoring (Li et al., 2017;

Xu et al., 2018). Barcodes, radio frequency identification (RFID) and wireless sensors are some technologies that may help the IoT continue to expand (Eurostat, 2022).

With the development of Industry 4.0, the trend towards smart sensors in the field of sensors and instrumentation has become well-established and entails such things as higher performance, greater integration, multi-parameter sensing, built intelligence and secure and safe networking (Schütze et al., 2018). Moreover, smart sensor systems, sometimes known as self-X, allow functions such as self-identification or diagnosis and self-configuration, calibration and repair (Johar and Koenig, 2011; Schütze et al., 2018).

Additionally, Study C investigated VR's application to environmental impact reduction. Therefore, the following section will introduce the functions of VR technology in the manufacturing industry.

Latta and Oberg (1994) describe VR as an advanced human-computer interface that generates a realistic world and enables participants to interact with it, implying that it creates a link between the participants and the generated environment. Similarly, Berg and Vance (2017) describe VR technology as a collection of technologies that enable users to have an immersive view of the world beyond reality.

VR aims to replicate how we understand the world via the information processing system and persuade us that we are physically positioned inside the virtual environment (Berg and Vance, 2017). VR technology is now prevalent in the industry and its value has been recognized for technological advancement and cost reduction (Choi et al., 2015). The most common applications of VR technology in manufacturing are maintenance and virtual training, with virtual training mostly utilized to assist employees in assembly jobs and offer a safer workplace (Berg and Vance, 2017). Furthermore, the immersive environment offered by VR facilitates product design, layout planning and activity planning for resource matching (Berg and Vance, 2017; Damiani et al., 2018; Gong et al., 2020).

Given the concepts of sustainability and digitalization, the following section will focus on the link between the two themes in the context of production systems.

2.3 DIGITAL TECHNOLOGIES FOR SUSTAINABLE PRODUCTION SYSTEMS

Regarding contributing to sustainable production systems, digital technologies offer significant prospects for promoting sustainable development. Specifically, digitalization supports economic sustainability by improving productivity, stabilizing quality and facilitating efficient communication. For social sustainability, digitalization mostly supports reducing heavy workloads, minimizing repetitive operations and improving communication efficiency. For environmental sustainability, the advancement of digitization has been discussed as a potential topic of systematic investigation for almost two decades (Berkhout and Hertin, 2001).

Research investigating digitalization in promoting production systems' environmental sustainability may be viewed from the strategic and operational levels. Strategically, investigations and analyzes of the influence of Industry 4.0 on operational scenarios in companies have explored the potential for merging the attributes of digitalization with SDGs, therefore giving policy advice to stakeholders and governments (Oláh et al., 2020).

Furthermore, de Sousa Jabbour et al. (2018) claimed that Industry 4.0 technologies have the potential to support environmental sustainability by identifying critical success factors to promote technology integration with environmental performance improvement. Stock et al. (2016) also posited that the distribution of resources, such as materials, energy and water, can be efficiently managed using smart, interlinked value-creation modules.

Operationally, previous research has studied the applications of digital technologies or digital platforms to environmental impact reduction. For example, CPS and the IoT facilitate a shift towards transparency in manufacturing, underpinned by the real-time monitoring of resource utilization; this empowers production management decision-making processes with a robust foundation for enhanced adaptability (Oláh et al., 2020; Song and Moon, 2017). Moreover, IoT-enabled interconnected processes allow machines to exchange information on parameter configuration, inventory status and defects, increasing material and energy efficiency while raising quality levels (Kiel et al., 2017). In line with Chang et al.'s (2017) proposition, VR or AR-supported platforms present an eco-friendly alternative to traditional physical prototyping by eliminating unnecessary resources and energy consumption during the design stage. Although the interest in applying VR to environmental benefits in manufacturing is growing, it is still in its infancy and needs further investigation (Khakpour et al., 2020).

According to Bittencourt et al. (2019) and Kamble et al. (2020), the successful application of lean principles allows industrial companies a better preparation for digital and green transformations. Moreover, previous studies show that lean can be a significant bridging factor (Ghaithan et al., 2021), a prerequisite (Schumacher et al., 2020) and an enabler (Yilmaz et al., 2022) of operational performance improvement. Considering both strategic and operational levels, digital technologies can improve operational and environmental performance by integrating lean production principles (Amjad et al., 2020; Leong et al., 2020; Touriki et al., 2021). However, given the proposed frameworks, it was claimed that the enabling mechanism between digitalization, lean and green requires further investigation to clarify which digital technologies could be integrated with which lean implementations (Buer et al., 2018; Lobo Mesquita et al., 2021; Varela et al., 2019) to yield environmental sustainability.

As a step further, the following subsection will present the technological functions that enhance environmental sustainability.

2.3.1 Technological functions for environmental sustainability

Research has been conducted to examine the mechanisms that explain *how* digital technologies influence the environmental sustainability of production systems.

Ghobakhloo et al. (2021) conducted a systematic review to identify technological functions for sustainable innovations. Eleven functions were identified by which digital technologies facilitate sustainable innovation. Of these, the following three directly involve environmental sustainability: green absorptive capacity development, green process innovation capacity and green product innovation capacity. This study focuses more on organizational and relational capabilities than operational practices.

Another literature review from Kamble et al. (2018) examined the process. This provided a sustainable Industry 4.0 framework to link Industry 4.0 technologies and sustainable outcomes with process integration. Process integration in this context results from the convergence of CPS and the interaction between humans and equipment, which is facilitated by implementing Industry 4.0 technologies. Process integration enables the development of smart products and processes, effectively addressing the increasing and changing market demands by offering enhanced functionalities and complexity (Kamble et al., 2018). Their study did address the process level and its intermediate role, but not the technology functions and the integration with the operational process.

On a more detailed level, Liu et al. (2022) conducted a thorough literature review to identify suitable digital functions for implementing circular economy strategies using a proposed framework. This framework identifies seven mechanisms to connect the three primary digital functions, namely: 1) collection and integration, 2) analysis and 3) automation, with the nine circularity strategies (from refuse to recover, as adapted from (Potting et al., 2017)) encompassing the manufacturing value creation process. This study provides an in-depth analysis of the correlation between digital technologies and environmental sustainability, relating operational practices from the literature. Nevertheless, the application of digital functions and enabled operations could be better elaborated with empirical findings.

To bring the functions closer to the operational practices, Berkhout and Hertin (2004) attempted to clarify the relationship between information technologies and environmental sustainability by categorizing it as having direct and indirect, positive and negative impacts. Moreover, the positive impacts include increased efficiency, dematerialization and virtualization, detecting and monitoring changes in environmental impact and transportation and distribution (Berkhout and Hertin, 2004), detailing the technological functions for improving environmental sustainability. Specifically, *reduced efficiency* refers to a reduction in the amount of processing time needed per product and an improvement in communication efficiency. This improvement has the potential to facilitate the effective utilization of resources and energy, leading to decreased emissions. The dematerialization process involves converting physical information into digital format, enabling the establishment of a workplace that operates without the need for paper-based documentation. This transformation can occur in various aspects of a business, including design, production and other manufacturing processes. Reducing resource consumption leads to a reduction in materials and energy use, waste generation and emissions. Using virtualization technology to detect and monitor environmental change presents a valuable opportunity to identify and mitigate areas of high environmental impact. It also has the potential to enhance the processes of design and communication, whilst decreasing the necessity for multiple prototypes. *Transportation and distribution* play a significant role in reducing energy consumption and emissions and may potentially be accomplished by optimizing travel routes and utilization rates.

3

RESEARCH METHODOLOGY

Research takes place whenever we acquire data and gather information to resolve an issue by answering a question (Booth et al., 2016). The concept of research methodology comprises a set of assumptions or a paradigm which forms the basis of the selected research methods and techniques. A research method is a narrower concept defining processes, procedures and techniques for conducting empirical studies and collecting and analyzing data (Cecez-Kecmanovic, 2011). Therefore, clearly explaining fundamental theoretical assumptions is imperative to outlining the research strategy and process (Creswell and Creswell, 2018). This chapter presents my perspective on research, the choice of research methodology and the research methods that help to answer the research questions, as illustrated in Figure 4.

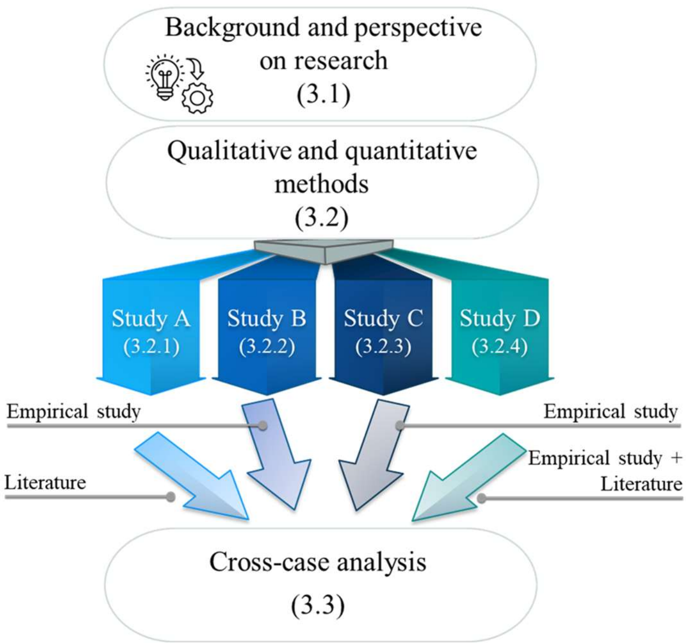

Figure 4. Research methodology.

3.1 BACKGROUND AND PERSPECTIVE ON RESEARCH

A researcher's philosophical world view refers to a set of values and views guiding the individual to research with a chosen methodology. The methodology that researchers adopt can affect the research design, selection of methods and what research results and contributions to knowledge are considered valid (Prescott and Conger, 1995). Moreover, personal knowledge, experience and interest also shed light on the values and perceptions that shaped the ontological beliefs and guided the choice of research methodology (Creswell and Creswell, 2018). Hence, this section will explain my choice of research topic and background.

Manufacturing plays an important role globally, contributing to countries' wealth, development and competitiveness (Herrmann et al., 2014; Qin et al., 2016). Because of the increasing attention on and care for our living environment, our Production Systems Division works closely with manufacturing industries to improve their sustainability performance. Since the Fourth Industrial Revolution, the main intention of manufacturing industries has been to increase productivity, reduce costs and maximize profits through advanced technologies. Meanwhile, economic and social development accelerates the generation of negative environmental impacts: species extinction, tropical deforestation, greenhouse gas emissions, ozone depletion, consumption and synthetic fertilizers (Hedenus et al., 2018). Fortunately, more and more Swedish industrial companies are aware of their environmental impact and are willing to improve the situation aided by technology, as indicated by the increasing number of collaborative sustainability projects in our division. Thus, there is a rising tendency for industrial companies to strive to achieve sustainable production systems.

During my research, I worked with manufacturing companies to conduct studies. Before my PhD, I worked in an international manufacturing company for eight years in China and Austria, focusing on on-site problem-solving, process improvement and lean implementation in production systems. My undergraduate education was in the mechanical and electrical engineering program, which involved problem-solving in manufacturing. My postgraduate studies were carried out in production engineering and lean production, closely related to performance improvement in production systems.

From my education and work experience, I see myself as a solution-orientated manufacturing practitioner because I was driven to solve problems and improve operational performance. On a personal level, since I became a mother, I have been increasingly aware of environmental issues and have developed a much deeper interest in strengthening sustainability for future generations. Concern for environmental sustainability has become a sense of responsibility relating not only to my professional life but also underlining my philosophical view and influencing how I think, act and live. Meanwhile, the development of digital technologies is reshaping the competitive landscape of the manufacturing industry. As a result, my PhD journey took the route of learning scientific methods to solve real-world problems and (supported by digitalization) developing knowledge to achieve a sustainable production system.

Being problem-centered and focused on real-world, practice led me towards a practical way of evaluating applicable knowledge and effective solutions used in solving problems. Hence, I was encouraged to use all available methods to understand and solve problems.

3.2 QUALITATIVE AND QUANTITATIVE METHODS

The multi-method approach combines qualitative and quantitative methods and allows flexibility in combining the strengths of intersecting methodologies (Creswell and Creswell, 2018). Furthermore, the multi-method approach fits the complex nature of the interdisciplinary topic covering digitalization and environmental sustainability, in which the methods could be complemented by each other (Johnson and Onwuegbuzie, 2004).

Qualitative research seeks to investigate and comprehend the significance that people or organizations attribute to a social or human issue and often uses open-ended questions (Creswell and Creswell, 2018). The research process involves collecting data in the participant's environment, analyzing it inductively and developing from specifics to general themes and the researcher's interpretation of what the data means (Creswell and Creswell, 2018). Quantitative research usually tests and validates existing theories in which identified variables can be measured as numbered data and analyzed using statistical procedures. The whole process is often carried out deductively (Creswell and Creswell, 2018; Johnson and Onwuegbuzie, 2004).

As to how they address research questions, both qualitative and quantitative methods have strengths and weaknesses (Johnson and Onwuegbuzie, 2004). However, a multi-method approach associates and combines qualitative and quantitative methods so that the resulting combination yields complementary strengths and reduces any weaknesses (Creswell and Creswell, 2018; Johnson and Onwuegbuzie, 2004). Furthermore, the multi-method approach can provide comprehensive knowledge of a research problem (Creswell and Creswell, 2018; Johnson and Onwuegbuzie, 2004). Therefore, a multi-method approach was chosen as the most suitable way to conduct investigations for this thesis.

Four studies were conducted to answer the research questions by combining the qualitative and quantitative methods, as shown in Figure 5.

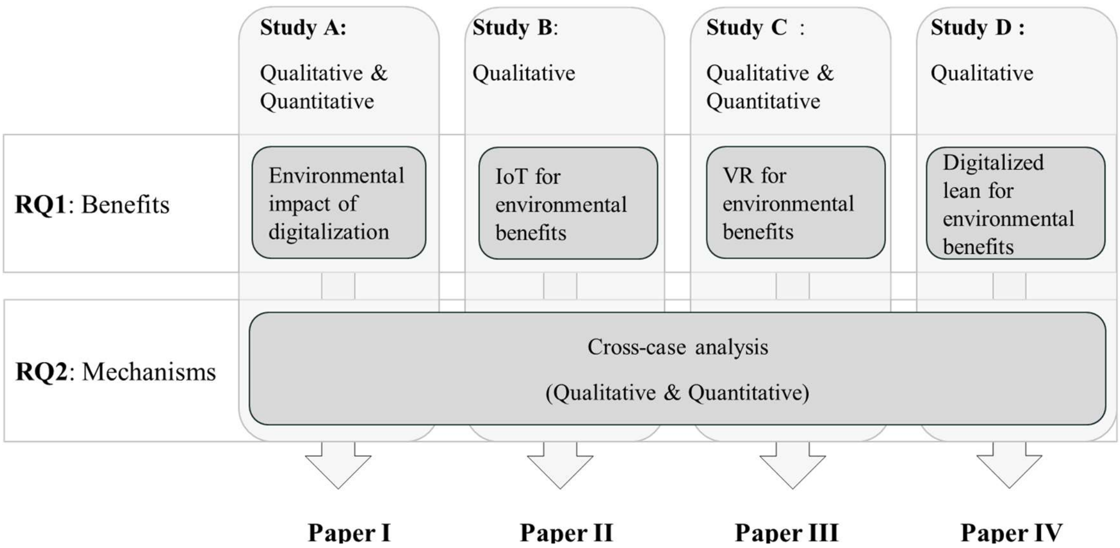

Figure 5. Design of studies, corresponding to the research questions and appended papers.

Study A was conducted first and explored the state-of-the-art of digitalization and environmental sustainability in production systems through a literature review. Study B then investigated the applications of digital technologies to improve the environmental performance of a case company. These two studies mainly identified the positive environmental impact of applying digital technologies in production systems.

Moreover, given the increased interest in VR technology and its potential for sustainability, Study C conducted a case study to explore the application possibilities and explain how they support environmental impact reduction. Furthermore, as observed in studies A and B, IoT and its related connection-level technologies were widely applied in production systems. Specifically, Study A indicated that the integration of green lean could encourage and support practitioners to overcome some challenges, such as compromising economic benefits for environmental ones. Therefore, Study D investigated digitalized lean implementations and the resulting environmental impacts in three small and medium-sized enterprises (SMEs). The findings led to the proposal of a framework that bridges IoT and environmental sustainability through lean principles.

Additionally, the practices identified in studies A, B, C and D exemplify the application of digital technologies in reducing environmental impacts within production systems and illustrates the mechanisms by which digital technologies improve environmental performance. A detailed cross-case analysis will be presented in Section 3.3.

The studies that were conducted jointly provided answers to the research questions:

RQ1 - Benefits of using digital technologies to improve environmental performance.

Studies A, B, C and D individually provide answers to RQ1, focusing on identifying the benefits of using digital technologies to improve the environmental performance of production systems.

Study A was first conducted to clarify the environmental impacts of applying digital technologies in production systems. It provides a picture showing what environmental impact could be generated by introducing digital technologies into the production system. As a result of the qualitative analysis and based on the literature, Study A summarized the type of environmental impact from applying digital technologies at each stage of the production system. Moreover, the amount of impact led to a quantitative analysis; this indicated the primary impact-generating stages of the product and technology life cycles.

Study B was conducted in a case company to provide real-world practices that illustrate the application of digital technologies to environmental impact reduction throughout the manufacturing value chain. Moreover, the practices were categorized according to the mechanisms by which digital technologies affect environmental performance (cf. Berkhout and Hertin, 2004). This categorization was conducted via a qualitative analysis.

In addition to studies A and B, VR was chosen as a representative digital technology in the context of Industry 4.0 because of its expanding applications in industry and for sustainable manufacturing. Therefore, Study C used a case study to explore and explain the support of VR technology in reducing environmental impact. Qualitative data was collected and analyzed through interviews and focus group analysis to provide quantitative analysis input.

As observed in the previous theoretical and empirical investigations, IoT and its related digital technologies have been given one of the highest priorities in the Industry 4.0 paradigm for sustainable development. Moreover, given the wide implementation of lean principles in the manufacturing industry and the lean-green integration indicated in Study A, Study D looked into the bridging role of lean principles for IoT and environmental sustainability. Qualitative data was collected and analyzed for both empirical and literature review findings.

RQ2 – Mechanisms by which digital technologies improve environmental performance.

Together, all four studies provided the best practices for using digital technologies to reduce the environmental impacts of production systems. The mechanisms by which digital technologies improve environmental performance were summarized and synthesized, providing answers to RQ2.

The practices provided by Study A were from the literature review and covered application of the eight enabling technologies, CPS, IoT, big data analytics, cloud computing, VR/AR, IAI, AM and intelligent robotics. Similarly, Study B provided best practices from a case study, focusing on applying IoT-related digital technologies. Study C focused on applying VR technology at a case company as a best practice. Lastly, Study D provided the best practices of digitalized lean implementations.

The details of each study will be explained in the following section.

3.2.1 Study A

Study A conducted a comprehensive literature review to explore the impacts of applying digital technologies to the environment. A systematic grasp of existing literature is critical in contributing to knowledge (Ahlstrom, 2016). Moreover, a comprehensive and well-structured review establishes a solid basis for increasing knowledge and supporting theory-building (Snyder, 2019; Webster and Watson, 2002).

Inductive coding was performed, gradually generating the environmental impacts of applying digital technologies at each stage of the manufacturing value chain. The literature analysis was deductive, including the use of digital technologies, the life-cycle stage, the type of environmental impact and the sustainability focus. The 5C architecture and technology categories (Lee et al., 2015) were referenced for deductive coding.

In Study A, a literature search was made using the Scopus and Web of Science and screening by title, abstract and content. This gathered 93 articles for content analysis, following the instructions suggested by Hart (2018). To enhance the research quality, the study also triangulated researchers and transparency of methods and results (Creswell and Miller, 2000). More details about the methods are available in Paper I, Section 2.

3.2.2 Study B

Study B aimed to uncover the environmental benefits of applying digital technologies to real-world examples. A case study was conducted at two manufacturing sites of an international company. The case study method was chosen because it can lead to new and creative insights, the development of new theories and a high level of validity with practitioners (the end users of research (Voss et al., 2002)). The validity can also be improved through triangulation using multiple means of data collection, such as interviews, onsite observations, documentation and so on (Yin, 2003; Voss et al., 2002).

The case company was chosen for the following reasons: 1) this company implements digital technologies at both manufacturing sites and keeps investigating new areas that can be digitalized to improve operational performance; 2) it values sustainability up to a strategic level and constantly improves its environmental performance; and 3) previous working experience provided access to the right people and a good basis for understanding their manufacturing processes.

This study employed a qualitative method. First, it inductively coded the use of digital technologies and their impact on the environment. Then, the impact pathways were grouped into four categories by referring to the mechanisms adapted from Berkhout and Hertin (2004). The results are presented in Paper II (Chen, Despeisse, et al., 2021).

Study B collected data through multiple methods, including interviews, observations and documents; it provided more accurate findings (Yin, 2009). The data was recorded and transcribed and inductive coding was applied. The research quality was enhanced by triangulating methods, prolonged engagement with participants, member checking and transparency of methods and results (Creswell and Miller, 2000; Voss et al., 2002). More details of the methods used in Study B are available in Paper II, Section 3.

3.2.3 Study C

Study C carried out a case study to explore the potential for using VR technology to support environmental impact reduction. This study was part of the SUMMIT project (SUstainability, sMart Maintenance and factory design Testbed), in which the application of VR technology was developed for sustainable manufacturing.

The case company was one of the partners in the project and was chosen for two reasons: 1) it intended to develop and implement VR technology to bridge its different functions between Sweden and China; 2) the company intended to increase the advantages of using VR for environmental benefits.

This study was conducted by combining both qualitative and quantitative methods. It used inductive coding, VR demo development and testing, interviews and focus group discussions to identify areas within which the company could feasibly apply VR. The applications identified were then analyzed deductively. This was vital input in designing a questionnaire to identify how far VR could support reducing the number of journeys traveled and thus help reduce emissions. The questionnaire data was summarized and analyzed using statistical procedures. Consequently, Paper III (Chen, Gong, et al., 2021) presents possible areas in which VR might support a reduction in environmental impacts.

Data collected during interviews and observations were transcribed and inductive coding was applied. To enhance the research quality, Study C used collection of multiple types of data, triangulation of methods, member checking and transparency. More details of the methods are available in Paper III, Section 3.

3.2.4 Study D

Study D aimed to identify an incremental innovation tactic, to bridge the applications of digital technologies in environmental sustainability by integrating them with lean principles.

A case study and integrative literature review was conducted at three SME companies. SME companies were chosen because they represent 99% of all businesses in the EU (European Union, 2021a). The three companies were chosen for the following reasons: 1) they are keen to apply digital technologies; 2) they intend to improve their environmental performance; 3) they implement lean production principles.

The study used a qualitative method and transcribed and analyzed data inductivity to summarize adopting lean, digitalization and environmental care strategies. Moreover, the literature data was analyzed inductively to identify the key takeaways of frameworks from the previous studies. Thirdly, the practices of digitalized lean implementations and the resulting changes in environmental impact were summarized inductively, then grouped into different levels referring to the 5C architecture (Lee et al., 2015). Meanwhile, data collected in the interviews was transcribed and inductively coded. Finally, the collection of multiple types of data, triangulation of investigators, prolonged engagement with participants, member checking and transparency in methods and results were applied to improve the research quality. More details of the methods are available in Paper IV (Chen et al., 2023), Section 3.

3.2.5 Summary of methods

Table 3 presents an overview of the research techniques used in the four studies, including data collection, analysis methods and measuring for enhancing research quality.

Table 3. Research designs and methods of the conducted studies.

Studies	Data collection	Data analysis	Measures for research quality
Study A: Environmental impact of digitalization	Screening of relevant articles	Inductive and deductive coding	Triangulation of researchers, transparency
Study B: Applications of digital technologies for environmental benefits	Recording of interviews, observation notes	Transcription of interviews, inductive coding	Triangulation of methods, prolonged engagement, member checking, transparency
Study C: VR supports environmental impact reduction	Recording of interviews, focus groups, questionnaire	Transcription of interviews, inductive coding and questionnaire summary (deductive analysis)	Collection of multiple types of data, triangulation of investigators, prolonged engagement, member checking, transparency
Study D: Digital technologies support the environment through lean principles	Recording of interviews, observation notes, screening of relevant articles	Transcription of interviews, inductive coding	Collection of multiple types of data, triangulation of methods, member checking, transparency

3.3 CROSS-CASE ANALYSIS

A cross-case analysis was conducted to draw explanations for the mechanisms by which digital technologies improve environmental performance. Practices from studies A, B, C and D were collected, analyzed and synthesized to detail the mechanisms using three main steps: practice collection, descriptive analysis and content analysis. These are shown in Figure 6.

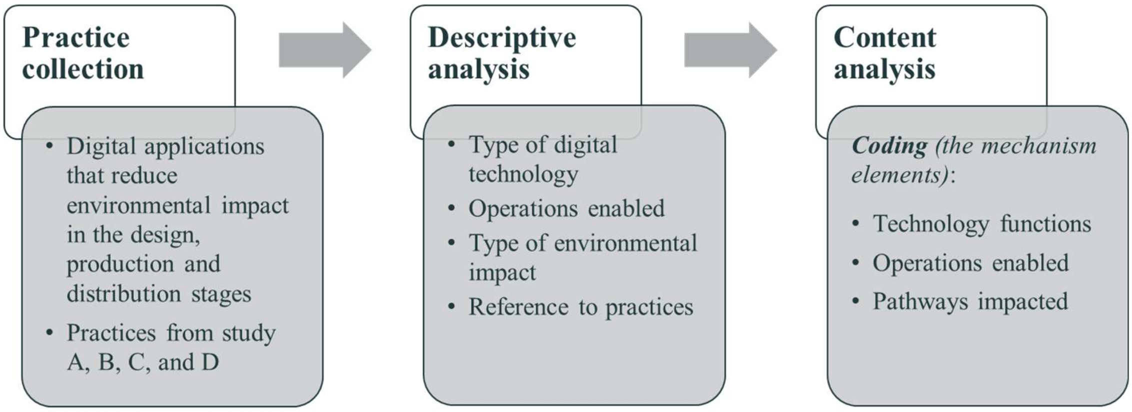

Figure 6. Data analysis process.

Practice collection

The selected practices fulfil the following criteria: 1) digital applications that reduce environmental impact; 2) applications that operate in the design, production and distribution process of production systems; 3) practices from studies A-D, in which studies A and D provided practices from the literature and studies B, C and D provided practices from empirical findings, as shown in Table 4. In total, 97 practices were collected.

Table 4. Number of practices from each study.

Study	Empirical	Literature	
A		46	
B	9		
C	1		
D	16	25	
Total	26	71	97

Descriptive analysis

In this phase, the analysis was conducted using raw data and grouped the practices into the following categories:

1) Type of digital technology. The technologies were categorized into IoT smart sensors, AM, AR, VR, CPS, simulation, big data analytics, cloud computing and IAI (Chen et al., 2020). Codes were assigned to practices with technology abbreviations to enable traceability. For example, "I" refers to IoT smart sensors, A refers to AM and R refers to intelligent robotics. The ones relying on IoT's connection functions or being applied together with IoT, were coded I^{+}. Examples could be taken from I^{+5} (No. 3 from page 1, APPENDIX I), where IoT and big data analytics were used and IoT acts as an enabling platform.

2) Enabled operations are those operations enabled by using technology functions. For example, IoT smart sensors can track and monitor energy flows and provide energy consumption data, so practitioners can locate the most energy-intensive processes and take actions to reduce consumption. The actions taken with the support of technology functions are called *enabled operations*.
3) Type of environmental impact. This was grouped by the indicator categorization adapted from NIST (Joung et al., 2013) and considered the main impact generated from each practice. It referred mainly to resources, energy, industrial waste and emissions.
4) References to practices. The practices from the literature were marked with the corresponding reference. Meanwhile, the ones from case findings were marked with the corresponding study, such as B, C or D. This was particularly the case for Study D; the practice was labelled as from (Study) D – (company) A, B or C.

<u>Content analysis</u>

After descriptive analysis, the data was coded by focusing on the elements of the mechanisms: technology functions, enabled operations and impact pathways.

1) Technology functions: the functions were grouped into four categories, as adapted from Berkhout and Hertin (2004): increased efficiency, tracking and monitoring, dematerialization and transport. Their categorization was adopted because the previous attempt (in Study B) was able to classify all digital applications for environmental impact reduction into these four groups.
2) Enabled operations: the operations were divided into two sub-categories to differentiate the operations directly enabled by using digital technologies and the pathways leading to the changed environmental impact.
3) Regarding the impact pathways, they can be categorized into *prevention*, *reduction*, *optimization*, *reuse* and *substitution*, referring to the definition from Despeisse et al. (2013).

While coding the enabled operations, the author attempted to link the enabled operations with OEE underlying factors – availability, performance and quality – a well-established operational performance measurement (Ylipää et al., 2017). The operations that were difficult to link to OEE have a more direct link to environmental performance (Joung et al., 2013) and were hence grouped into Pe.

After coding analysis, a complete list of practices was generated, see APPENDIX I, including coding, stages of product realization, type of digital technology, technology functions, detailed enabled operations, impact pathways, reduced environmental impact, reference and study.

Based on this list, similar mechanisms were combined and synthesized. It was observed that not all the technology functions defined by Berkhout and Hertin (2004) were the causal factors. Hence, the functions were adjusted according to the actual location where they took place. Consequently, the mechanisms were summarized according to the design, production and distribution stages and presented in Section 4.3.3.

4

RESULTS

This chapter presents the results of the conducted studies and the contributions towards answering the research questions.

Table 5 provides an overview of this chapter, its section layout and its main contributions to the research questions.

Table 5. Overview of the chapter sections and their main contributions to the RQs.

Section	**Subsection**	**Main contribution**	**Appended paper**
4.1 Impact of digitalization on the environment	4.1.1 The impact on the product life cycle	Description and categorization of the environmental impacts of digitalization in production systems.	Paper I
	4.1.2 The impact on the technology life cycle		
4.2 Environmental benefits of digital technologies	4.2.1 IoT-related practices	Identification of the support of IoT on environmental performance improvements.	Paper II
	4.2.2 VR-related practices	Identification of the support of VR for environmental impact reduction.	Paper III
	4.2.3 Digitalized lean practices	Mapping of the integration paths that Lean production bridges IoT and environmental sustainability.	Paper IV
4.3 The generation mechanisms	4.3.1 Descriptive results	Explanation of the mechanisms by which digital technologies improve environmental performance.	Paper I - IV
	4.3.2 The mechanisms generate environmental benefits		
	4.3.3 Practices in the design, production and distribution stages		
4.4. Summary of results		Summary of the key findings.	

4.1 IMPACT OF DIGITALIZATION ON THE ENVIRONMENT

To identify the potential of digital technologies for environmental sustainability, this thesis first takes an overview of the environmental impact of digitalization in production systems. Therefore, this section presents the impact of digitalization on the environment.

The impact of digitalization on environmental sustainability can be viewed from the perspective of multiple life cycles: the *product* life cycle (the life cycle of products manufactured with the aid of digital technologies) and the *technology* life cycle (the life cycle of digital technology hardware). Figure 7 summarizes and illustrates this perspective using an entity-relationship model (ERM). The multiple life cycle perspective captures and characterizes the relationship between digitalization and the environmental impact it generates.

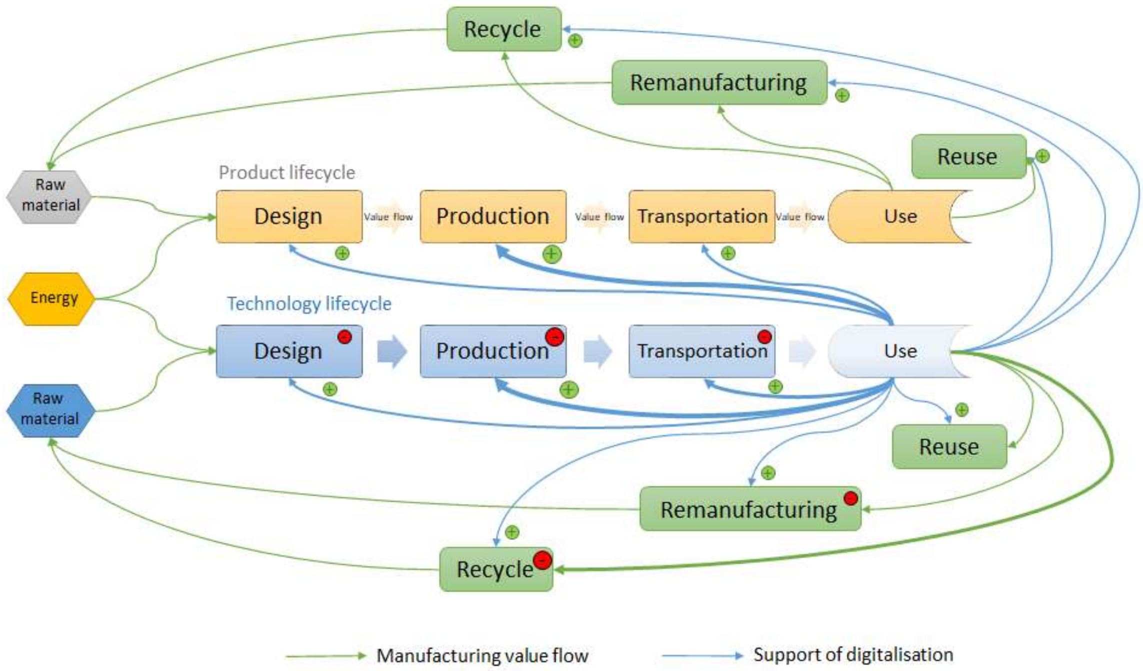

Figure 7. Value chain of product life cycle and technology life cycle (adapted from Paper I).

In the product life cycle (the upper part of Figure 7), digital technologies contribute primarily to a reduced environmental impact via greater material and information efficiency in manufacturing, particularly during the production phase. Similarly, implementing digital technologies in both life cycles could reduce their environmental impact by enabling processes to be more efficient. However, the technology life cycle's production, use and end-of-life phases (the lower part of Figure 7) generate a negative environmental impact due to greater energy and resource consumption and increased emissions.

Hence, the multiple life cycle perspective provides an overview of the environmental impact generated by introducing digital technologies into the production systems, including the product and technology life cycles (with both positive and negative impacts).

4.1.1 The impact on the product life cycle

The environmental impact of digitalization is mainly positive in the design, production, transportation, use and end-of-life stages of the product life cycle. Table 6 summarizes the findings from the literature by categorizing the environmental impact of digital technologies and life cycle stages. The abbreviations in green indicate positive environmental impacts, while the ones in red signify negative impacts. The digital technologies were grouped, (with reference to the 5C architecture) by their functions, as described in Section 2.2.2 Technological functions.

The environmental impacts that digitalization may help mitigate are those related to energy, materials and pollution. As shown in Table 6, relatively speaking, the CPS and ICT/IoT-enabled platforms have more practices and mostly support reductions in materials, energy consumption and emissions. Moreover, most digital practices observed in the production stage bring positive impacts by consuming fewer materials and less energy and generating less waste and pollution. However, it may also be observed that some stages of the product life cycle require more studies, such as design, transportation and end-of-life; especially for intelligent robotics, cloud computing, VR/AR and IAI.

Some negative environmental impacts in the product life cycle may also be identified. For example, increased energy and emissions could be generated from increased transportation frequency due to customized design and delivery when implementing IoT/ICT in transportation.

Table 6. Environmental impact of digitalization in the manufactured product life cycle (adapted from Paper I).

5C/digital technologies	Design	Production	Transportation	Use	End of Life
Configuration					
IAI		EN: Smarter scheduling (Bonilla et al., 2018; Carvalho et al., 2018)		EM: Instant support (Zheng et al., 2018)	
Cognition level					
VR/AR	M, EN: Replacing physical product (Zheng et al., 2018)			EN: Working virtually, Server virtualization (Cosar, 2019)	
Cyber level					
Big data	EN: Layout design(Kumar et al., 2018)	M, EN: Optimization of consumption (Bonilla et al., 2018) EN: Preventative maintenance (Bonilla et al., 2018); Condition monitoring (Ang et al., 2017; Corbett, 2018; Santos et al., 2019) M, WS: Reuse waste (Fisher et al., 2020; Oláh et al., 2020) M: Data-driven decision support (Tucker et al., 2018) WA, EM, HA: Predictability and control (Gobbo et al., 2018)	EM: Autonomous distribution (Bai et al., 2020); Data support optimization (Kerin and Pham, 2019)		
Cloud computing		WA, EM, HA: Predictability and control (Gobbo et al., 2018)			
Conversion level					
Intelligent Robotics		M, EN, WS: Damage reduction, better quality (Kumar et al., 2018)			

		M, EN: Higher efficiency (Ghobakhloo, 2020; Kumar et al., 2018) EN: High consumption (Ghobakhloo, 2020)			
AM	M, EN, WS: Prototyping (Malshe et al., 2015; Sartal et al., 2020; Song and Moon, 2017; Tucker et al., 2018)	WS, M, EN: Manufacturing of tool and product (Griffiths et al., 2016; Oláh et al., 2020; Tucker et al., 2018) EN: Reduced by optimized design (Ghobakhloo, 2020; Griffiths et al., 2016) WS: Using waste as raw material (Nascimento et al., 2019) M, EN: Optimized quality (Ford and Despeisse, 2016) EN: Heating required (Annibaldi and Rotilio, 2019; Ford and Despeisse, 2016)	EM, WS: Onsite production (Annibaldi and Rotilio, 2019; Bonilla et al., 2018; Ford and Despeisse, 2016; Müller et al., 2018; Oláh et al., 2020; Sartal et al., 2020; Zheng et al., 2018)	M, EN, EM: Customization (Bonilla et al., 2018; Ghobakhloo, 2020)	M: Optimizes quality in remanufacturing (Ford and Despeisse, 2016; Kerin and Pham, 2019); Improves efficiency in reuse, repair and recycling; reduces waste. (Ford and Despeisse, 2016; Sartal et al., 2020)
Connection level					
ICT/IoT	M, EM, W, EN: Customized outsourcing/design. Efficient/transparent communication (Haapala et al., 2013; Müller et al., 2018; Sartal et al., 2020; Zhang et al., 2019) EM: Frequent transportation (Zhang et al., 2019)	M, EN, WS: Improvement of parameter setting (Ang et al., 2017; Kiel et al., 2017; Müller et al., 2018; Sartal et al., 2020; Zhang et al., 2019) EN, EM: Higher efficiency (Berkhout and Hertin, 2004; Kiel et al., 2017; Zhang et al., 2019) M, EN: Availability of reliable data (Bai et al., 2020; Bonilla et al., 2018; Braccini and Margherita, 2018) EN: Condition monitoring and control (Bai et al., 2020; Bonfá et al., 2019; Lins and Oliveira, 2017; Oláh et al., 2020; Santos et al., 2019) WS: Tracking of weight and reason (Jagtap and Rahimifard, 2019) HA: Proactive reduction (Gobbo et al., 2018)	EN, EM: Frequent delivery (Zhang et al., 2019) EM, EN: Reduced within-plant transport (Zhang et al., 2019); Autonomous distribution (Bechtsis et al., 2017; Gružauskas et al., 2018; Kiel et al., 2017) M, EM: Efficient communication (Kiel et al., 2017; Müller et al., 2018)	EN: Condition monitoring (Ang et al., 2017)	M: Disassembly to order (Tozanlı et al., 2020) WS: Monitoring of waste generated in remanufacturing (Kerin and Pham, 2019)
CPS	EN: Optimized fuel consumption (Ang et al., 2017); Flexible design configuration (Tucker et al., 2018)	M, EN: Availability of reliable data (Bonilla et al., 2018; Ghobakhloo, 2020; Stock and Seliger, 2016; Thiede, 2018) M: Reduced production (Song and Moon, 2017) EN: Optimized material handling (Yazdi et al., 2018) EN: LCA data collection (Ballarino et al., 2017) EN: Smart scheduling (Inderwildi et al., 2020; Waibel et al., 2017)	EN: Reduced material delivery (Song and Moon, 2017)	EN: Condition monitoring; Remote support (Ang et al., 2017)	M: Monitors, controls and optimizes (Hannula et al., 2020)

EM = Emission. EN = Energy. H = Hazardous waste. M = Materials. WS = Waste. WA = Wastewater.

4.1.2 The impact on the technology life cycle

The negative environmental impact comes primarily from the technology (hardware) life cycle and mainly in the production, use and end-of-life stages, as shown in Table 7.

Table 7. Environmental impact of digital technologies in the technology life cycle (adapted from Paper I).

Design	Production	Transportation	Use	End of Life
/	EM, M, EN: ICT manufacturing (Arushanyan et al., 2014; Berkhout and Hertin, 2004; Bonilla et al., 2018) WA, WT-E: ICT manufacturing (Nnorom and Osibanjo, 2008) EM: Life cycle of big-data-related devices, such as data centres and ICT devices (Corbett, 2018; Lucivero, 2020) EM: Components (Thiede, 2018) M, EN: AM manufacturing (Malshe et al., 2015; Mele et al., 2019) HA: AM manufacturing (Malshe et al., 2015) WA: Fresh water for material production (Mele et al., 2019)	/	EN: ICT use (Arushanyan et al., 2014; Berkhout and Hertin, 2004; Bonilla et al., 2018) EN: Use of CPS (Supekar et al., 2019) EM: Use of data centre (Corbett, 2018; Lucivero, 2020)	EN: ICT disposal transport (Bonilla et al., 2018) WS: ICT disposal (Berkhout and Hertin, 2004; Bonilla et al., 2018; Nnorom and Osibanjo, 2008; Williams, 2011) EM: Life cycle of big-data-related devices, such as data centres and ICT devices (Corbett, 2018; Lucivero, 2020)

EM = Emission. EN = Energy. H = Hazardous waste. M = Material. WS = Waste. WA = Wastewater. WT-E = Water emission.

Producing and using digital technologies consumes resources and energy and generates pollution and emissions, harming the environment (Berkhout and Hertin, 2004; Chiarini et al., 2020; Oláh et al., 2020). Specifically, RFID, microchips, semiconductors, sensors, displays and so on are incorporated into Industry 4.0 technologies (Stock et al., 2018; Williams, 2011), constituting an increased demand for ICT and necessitating enormous consumption of resources and energy. Due to the increased efficacy brought about by the accelerated development of digital technology applications, a rebound effect may occur (Pohl and Finkbeiner, 2017). Again, the ubiquitous use of digital devices requires an enormous quantity of ICT, accelerating the depletion of natural resources. Research and innovation accelerate the development and updating of technology and the proliferation of digital devices, with each successive generation having a shortened lifespan. Furthermore, the disposal of ICT devices and components remains a challenge and has become a priority in waste management (Nnorom and Osibanjo, 2008; Williams, 2011). Due to the absence of readily identifiable economic incentives, only a small portion of ICT devices are recycled and RFID lacks better recycling systems (Stock et al., 2018). This increases the amount and complexity of electrical and electronic waste (Nnorom and Osibanjo, 2008; Stock et al., 2018).

4.2 ENVIRONMENTAL BENEFITS OF DIGITAL TECHNOLOGIES

In addition to the positive impacts identified in Study A, the environmental benefits of using digital technologies were further investigated in studies B, C and D. This section will present the IoT (4.2.1), VR (4.2.2) and digitalized-lean (4.2.3) related practices that generate environmental benefits.

4.2.1 IoT-related practices

Supporting the fundamental level of the 5C architecture (Lee et al., 2015), IoT indicates an extensive potential to enhance environmental performance. This section will present the applications of IoT for environmental sustainability, as observed in Study B.

Practices of using IoT-related digital technologies for environmental benefits were observed and summarized in Table 8, categorized by the manufacturing processes and the four mechanisms adopted by Berkhout and Hertin (2004).

Table 8. How practices of digital technologies affect the environment (from Paper II).

Operation Processes		Improved efficiency	Dematerialization	Monitoring	Transport
Design support			VR	VR	VR
Production planning		sensor ERP	MES sensor	ERP sensor	ERP
Material handling		digital signal	ERP		MES AGV
Manufacturing processes		ERP MES robot GCM	sensor robot GCM	sensor	
Application	Customer support	COMO		COMO	COMO
	Anti-counterfeit		digital signal		
Facility management		sensor		sensor	

AGV = automated guided vehicle. COMO = condition monitoring system. ERP = enterprise resource planning. GCM = grinding cycle monitoring. MES = manufacturing execution system. VR = virtual reality.

Introducing the practices by mechanisms, the environmental benefits generated through *increased efficiency* were realized by enabling immediate communication between manufacturing processes and facilitating material handling with digital signals. Using the enterprise resource planning (ERP) system enabled a pull system to coordinate overall resources, allowing minimal inventory levels to be maintained.

Sensors were used to enable *tracking* of material and energy flows; these provide data for identifying and eliminating constraints. For example, at the planning stage, energy is monitored to identify the fact that the most energy-intensive process is heat-treatment. This provides data support to ERP to jointly plan product types and sizes that require similar conditions and thus avoid dramatic adjustments. As a result, energy consumption is reduced due to the heating furnaces being required less frequently. A more precise temperature adjustment yields a lower scrap rate. Furthermore, IoT-enabled energy flow tracking and visualization provide a solid data basis to adjust the temperature and recover/reuse heat within the facility. For instance, the heat collected from the running machine, compressors and furnaces could be reused to heat the offices and water supply. Moreover, the collected data provides a decision-making basis to adjust the temperature of each area differently, according to the process and equipment requirements. Hence, the energy efficiency could be improved by having an adequate supply adjusted by the system.

The condition *monitoring* system's (COMO) instantaneous feedback on product applications enabled efficient problem-solving and provided data to improve product design. Moreover, the grinding cycle monitoring (GCM) system and robots contribute to higher levels of productivity and quality, thereby preventing excessive energy consumption and material waste. Digitalization contributes to more efficient use of energy and resources because of quicker product realization, higher quality levels, plus less time spent responding to and implementing changes.

Implementing VR, ERP, sensor technology and COMO could facilitate *virtualization and monitoring*. During the design phase, product development engineers may use virtual reality to simulate the product's application environment on the consumer side to better comprehend the state of the application. The monitoring and traceability made possible by sensors and the ERP system provide the opportunity to identify material and energy consumption hotspots. The COMO also provides failure detection with real-time condition monitoring, aiding customers with shortened response times and preventative maintenance service.

Dematerialization could be achieved by deploying VR, ERP, MES, robots, GCM, sensors and the digital signals enabled at different stages of the manufacturing value chain. For example, product development engineers may use VR to design and develop products without creating a physical prototype, thus conserving resources and energy. By communicating through digital devices, ERP and MES enable a paperless work environment and reduce errors. The improved quality (which might also be enabled by robots and GCM) contributes to dematerialization by reducing waste and rework. At the application stage, digital signals could ensure authenticity when preparing an installation, thus eradicating the risk of energy resource waste caused by counterfeit products.

Utilizing VR, MES, ERP, COMO and the automated guided vehicle (AGV) could bolster contributions attributed to reduced *transportation*. With the support of VR, fewer prototypes will be created and less travel will be required for production and transportation. ERP, MES and AGV enable optimized routes and frequency of commodities transportation and delivery, as well as reduced inventory levels, bringing in transport cost savings. Less travel is required during the application phase owing to preventative maintenance and real-time condition monitoring. Reduced transportation positively affects the environment, due to lower energy consumption and fewer emissions.

To sum up, IoT and its related digital technologies could improve the environmental performance of the production system through the four mechanisms illustrated above. Figure 8 presents an overview of the application of IoT-related technologies and the resulting environmental impact reduction in the four grouped stages of the manufacturing value chain. In this figure, the categories introduced earlier are represented by four different signs:

- Increased efficiency: 
- Dematerialization: 
- Virtualization detection and monitoring of environmental change: 
- Transportation: 

The signs show a relatively easy-to-achieve application at this stage, such as reduced transport at the logistics and application stages.

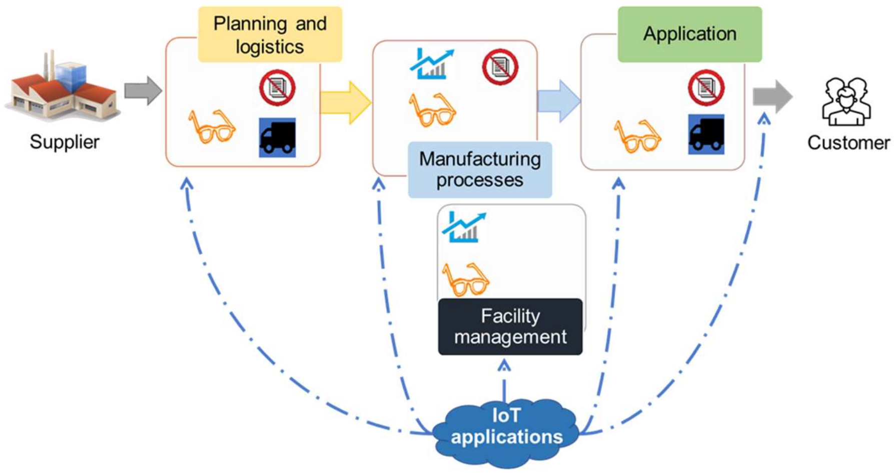

Figure 8. The environmental impacts reduced by implementing the IoT platform at different stages of the manufacturing value chain (adapted from Paper II).

4.2.2 VR-related practices

Virtual reality has been researched as an emerging technology for its potential for environmental sustainability. Study C investigated the possibilities for using VR to improve environmental sustainability at an international automobile company whose research centre is in Gothenburg in Sweden and its manufacturing in China. Paper III has in-depth explanations of this investigation.

A VR demo was developed with improved connection stability and real-time synchronization quality. Seventeen potential functions for VR application in the case company were then identified, emphasizing *analysis, communication* and *visualizatio*n based on the frequency mentioned in the interview. Specifically, *analysis* indicates the study of ergonomics, assembly geometry assurance, equipment verification and process study. *Communication* refers to claim support, collaboration, discussions, meetings and status reporting. Finally, *visualization* means an application in concept verification or experiencing the layout of a manufacturing cell. A more comprehensive description of the functions identified is available in Paper III, table 1.

The potential application areas call for a considerable amount of long-distance communication between Sweden and China, in which discussion of technical details and analysis would need high-quality communication support. Otherwise, physical travel would be required to ensure the same understanding between different parties, especially when testing car crashes, perceived quality, assembly precision and production processes.

A focused group discussion was therefore held to identify VR application areas that could support environmental sustainability, with reduced travel identified as having the greatest potential in the case company's scenario. Furthermore, the main reasons for traveling were given as:

(a) relationships/networking

(b) verification for the BOP (balance of plant) and plant verification

(c) simulation verification

(d) education

(e) fixture design reviews

(f) production support

(g) reviewing for MTO (machine try-out)

(h) product support

(i) support in RFQ (request for quotation).

This was followed by a questionnaire to identify opportunities for replacing travel by using VR for the listed tasks and 14 responses were collected right after a demo test. For its first result, the questionnaire showed that the main reasons for traveling to China were point (a) with ten votes and point (b) with nine votes. After that, points (f) and (h) were the next two on the list, with five votes each. Point (e) followed, with three votes (as shown in Figure 9).

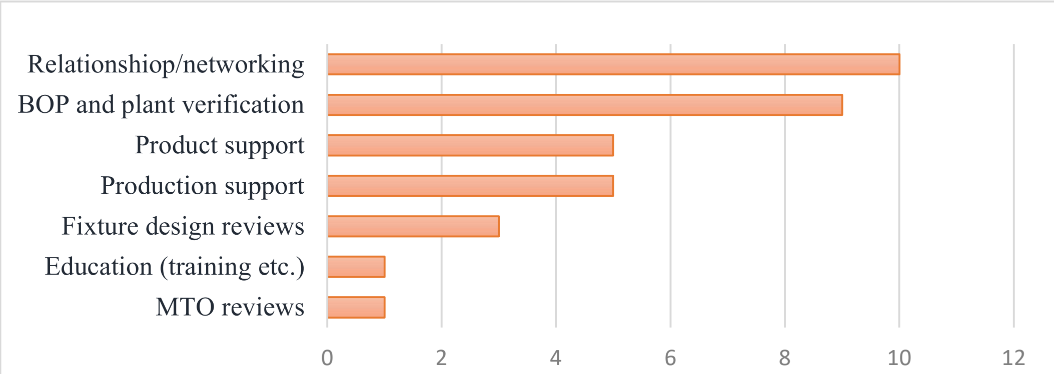

Figure 9. Reasons for traveling between Sweden and China.

Secondly, it also revealed that 13 out of the 14 respondents felt VR could allow a 20% decrease in travel frequency, as illustrated in Figure 10. Furthermore, six of the 14 respondents stated that using VR may decrease travel frequency by at least 60%. This was two more responses than using traditional remote communication methods (such as Skype).

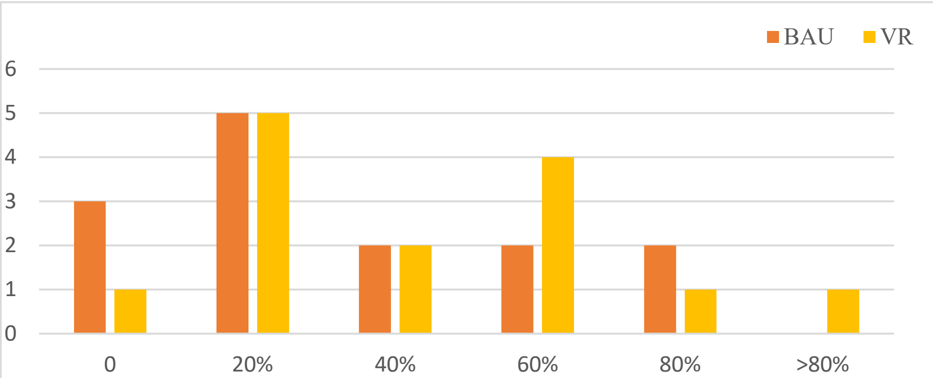

Figure 10. Potential to replace travel with other business as usual (BAU) tools versus VR.

Thirdly, 11 of the 14 respondents estimated that reducing travel frequency may lead to a 20% decrease in environmental impact. Moreover, the positive influence of immersive VR on everyday work was also recognized. Eleven of the 14 respondents believed that VR could make their work easier, of which two responded: “much easier.”

In conclusion, this study found that the immersive environment enabled by VR technology could provide more detail from different angles to support remote technical communication. It thus contributed to environmental sustainability by replacing physical travel.

4.2.3 Digitalized lean practices

Previous studies (Brozzi et al., 2020) and research projects show that manufacturing companies prioritize using digital technology to improve economic growth over environmental benefits. Moreover, as recognized in Study A, green-lean integration could encourage practitioners to use digital technologies to enhance environmental sustainability. Hence, Study D was conducted to investigate opportunities for using lean principles as a bridge linking the application of digital technologies and environmental performance improvement. The findings were collected from studies at three SME companies and a complementary literature review. A more detailed introduction to this study is available in Paper IV.

Previous research has investigated opportunities for using lean principles to bridge digitalization and environmental sustainability (Amjad et al., 2021; Leong et al., 2020; Touriki et al., 2021) and built a theoretical framework to illustrate such connection, as shown in Figure 11.

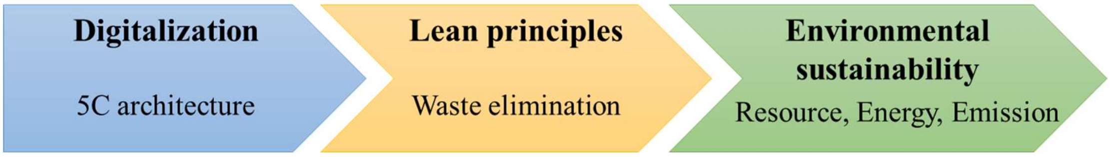

Figure 11. Theoretical framework built upon existing research.

Study D tended to enrich the theoretical framework with empirical findings from both the strategic and operational levels. The following section will present the strategies from digitalization, lean and environmental sustainability and the operational practices of digitalized lean implementations and their environmental impact. Finally, an improved framework, the DISEL (**DI**gitalization **S**upports **E**nvironmental sustainability through **L**ean principles), will be introduced.

<u>Strategies</u>

Similarities between the strategies adopted in the three case companies could be easily identified, including implementing digital technologies, lean principles and pursuing environmental sustainability.

Regarding digitalization, *monitoring/tracking, communication* and *automation* are the three most widely implemented functions at the strategic level. Specifically, monitoring/tracking could update machines' running status, the level of safety stock and products' status, thus enabling a faster response to machine breakdowns, stock adjustment and product traceability. Meanwhile, digital signals enable effective communication with suppliers for machine and material supply and with consumers for delivery planning. Moreover, automation improves the efficiency of machining, assembly and personnel training.

Regarding lean production principles, the case companies regard lean as a *culture*, a shared set of values and practices within their organizations that formed over a reasonably long period (Taras et al., 2009). All three organizations have adopted lean production 1) for many years, 2) daily, 3) in everything possible and 4) without noticing. Furthermore, *value-adding* serves as a common thread in lean implementation, implying that lean means providing value to the process with minimum cost.

When it comes to environmental sustainability, the three companies advocate environmental care. Moreover, companies B and C have implemented environmentally key performance indicators (KPIs). Their motivations stem mainly from their customers' requests and are cost-driven. When selecting material providers, customers are concerned about their suppliers' environmental performance.

Environmental KPIs are monitored to track energy and resource consumption and emission generation, such as materials (raw materials, packing materials and so on), liquid (water, lubricant, cutting fluid and so on) and the generation of emissions and waste (water, liquid, raw material, packaging materials and so on).

Representative quotes from the interviews involving the strategies of digitalization, lean production and environmental sustainability are available in Paper IV, Section 4.1.1.

Operational practices

The case findings and complementary literature review summarized the operational practices.

In the case companies, the implemented digital technologies are mainly IoT-related connection-level technologies, as referring to in Lee et al. (2015). This includes the ERP system, MONITOR, smart sensors, MindSphere and digital screen. Visualization (eight practices, such as Kanban and VSM), waste elimination (transport, defects, motion, waiting), poka-yoke (four practices), communication (five practices) and standardization (four practices) are the lean principles enhanced by digital technologies.

Visualization, communication, standardization and lean waste removal are supported by IoT-related connection-level technology. Specifically, real-time updates enabled by the IoT platform strengthen visualization, while the instant feedback loop enhances communication. Standardization is also supported by IoT-related connection technology to reduce deviations. Finally, lean waste is eliminated by monitoring the conditions of the machine, equipment or crucial components, such as spindles. As a crucial component of the machine, monitoring the spindles' condition could provide data to suggest and perform timely preventative maintenance, avoiding potential quality issues and waiting time.

The environmental impact of digitalized lean implementations is mostly attributed to the reduction of resource and energy consumption and waste and emission generation. This reduction is achieved through the enhanced visibility afforded by production data monitoring and through increased efficiency arising from the prevention of unplanned breakdowns and minimizing of waste and errors/scrap/defects. Furthermore, lower resource and energy consumption may be ascribed to increased material/product lifespan by reusing the material/product through real-time monitoring and communication.

Table 9 summarizes the operational practices of digitalized lean implementations and their corresponding environmental impact. The technologies are grouped according to the 5C architecture (Lee et al., 2015) based on the functions they perform. The respective case company (A, B or C) that provided the practices is noted in the last column.

Table 9. Digitalized lean implementations and their corresponding environmental impact (case findings).

5C/digital technologies	Integrated lean principles	Impact on ES	#
Connection level			
ERP (MONITOR)	Visualization	RE, EN	A
	Waste elimination: *defects* Visualization	RE, EN	
	Communication Waste elimination: *transport*	EM	
	Communication	RE, EN	
ERP	Visualization: *kanban*	RE, EN	B
	Poka-yoke	RE, EN	
	Visualization Waste elimination: *transport*	EN	C
Smart sensors	Visualization	EN	
	Visualization: *standardization*	RE, EN	
	Waste elimination: *defects, waiting*	RE, EN	
MindSphere	Visualization Communication	RE, EN	B
	Communication: *transport*	EM	
Digital screen	Standardization Visualization	RE, EN	A
Animated instruction SOPs	Waste elimination Standardization Poka-yoke	RE, EN	
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 Poka-yoke	RE, EN	B
Cognition level			
Pick-by-voice (Audio AR)	Waste elimination Standardization Poka-yoke	RE, EN	C
AR: augmented reality. EM: emission. EN: energy. ES: environmental sustainability. RE: resource. SOP: standard operating procedure.			

Table 10 summarizes the operational practices of digitalized lean implementation and the environmental benefits that are generated. Similar to Table 9, the technologies are grouped by referring to the 5C architecture (Lee et al., 2015) and according to the functions they perform. The reference that provided the practices is provided in the last column.

Table 10. Digitalized lean implementations and their corresponding environmental impact (literature findings).

5C/digital technologies	Integrated with lean	Impact on ES	References
Connection level			
IoT	FIFO, TPM	EM	(Amjad et al., 2021)
	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	(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	(Mesquita et al., 2021)
Digital instruction	Visualization; Standardization	RE, EN, WS	(Kurdve, 2018)
Simulation	Visualization: *VSM*	EM	(Amjad et al., 2021)
		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	(Mesquita et al., 2021)
	Visualization and monitoring	EN, WA, EM	(Santos et al., 2019)
	Communication	RE, EN, WS	(Tseng et al., 2021)
IoT and cloud computing	Visualization	RE (SCA)	(Khanzode et al., 2021)
Conversion level			
AM	Inventory reduction	RE, EN	(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	(Mesquita et al., 2021)
Cloud-based system and big data analytics	Visualization	EM	(Amjad et al., 2021)
Configuration level			
Machine learning	Waste elimination	RE, EN, EM	(Leong et al., 2020)

AM: additive manufacturing. EM: emission. EN: energy. ES: environmental sustainability. 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.

From the literature review, IoT-related connection-level digital technologies (including IoT, smart sensors, ERP and simulation) are frequently used to strengthen lean implementations and account for 80% of all applications (25 out of 31). Simulation is classified as a connection-level technology because it monitors operational status and gathers data to provide a foundation for improvement. However, in the studied literature, no practices of cognition-level technology were observed, as shown in Table 10.

The technologies from other layers of the 5C architecture, including conversion, cyber and configuration, are more complex and are often enabled by the IoT platform. For example, big data analysis was based on IoT-collected data for future analysis. Furthermore, the cloud-based system collects and analyzes real-time data connecting to an IoT platform. As a result, IoT and other IoT-enabled digital technologies are primarily employed to enhance the implementation of lean principles.

The lean principles enhanced by IoT and connection-level digital technologies include visualization, standardization, lean waste reduction and communication. Increased visibility was enabled by providing more accurate information from monitoring materials, water, energy consumption, production efficiency, waste generation, stock levels of raw materials, machine status and so on. Moreover, the real-time visibility of resource and energy usage provides a greater chance of finding areas for optimization, such as decreasing the consumption of resources (material, water, tools) and energy.

Another enhanced lean principle is standardization, which is sustained by using automated and intelligent scheduling to achieve first in, first out (FIFO). Specifically, it means applying smart sensors to predict an optimal time for total productive maintenance (TPM), ensuring quality and using simulation to prevent deviations from standard fuel consumption. Consequently, reduced energy consumption and emission generation could be achieved through reduced lead-time, improved quality and less fuel consumption.

The DISEL framework

The findings of the strategies and operational practices led to the development of the DISEL framework, DIgitalization Supports Environmental Sustainability through Lean principles, based on the theoretical framework of Figure 11. The DISEL framework describes strategic and operational levels of digitalization, lean production and environmental sustainability, as shown in Figure 12.

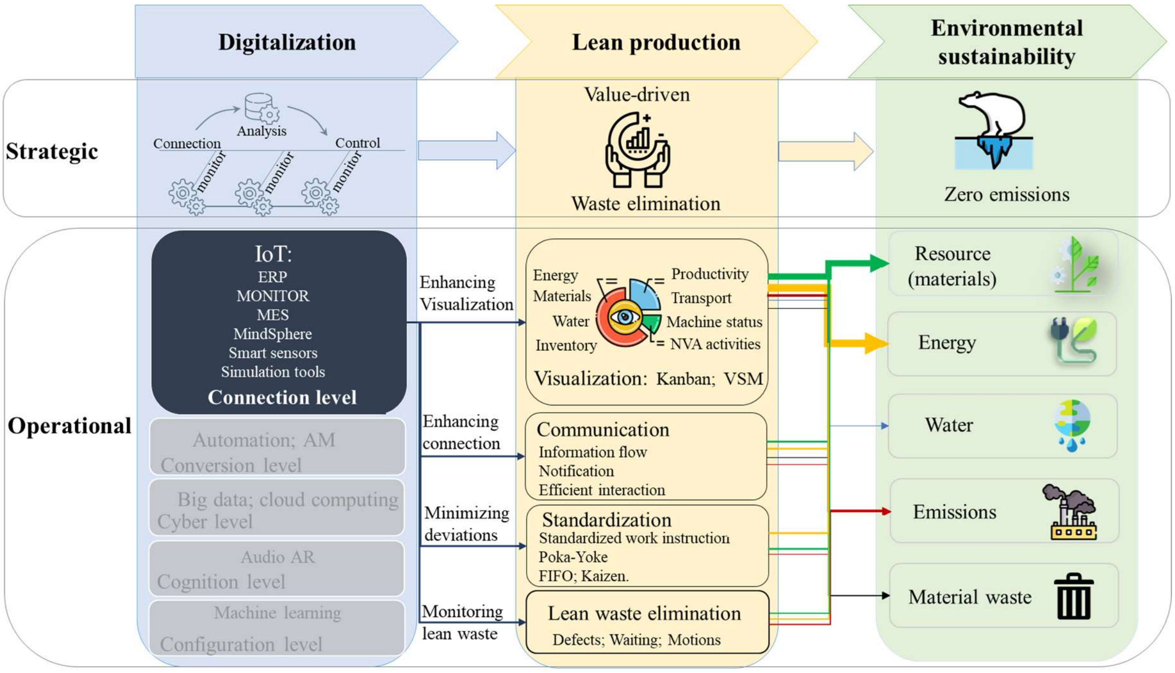

Figure 12. The DISEL framework (Digitalization Supports Environmental Sustainability through Lean principles, as adapted from Paper IV).

Strategically, digitalization primarily fulfils the functions of monitoring and tracking data, connecting through data and information transfer, analyzing data to assist decision-making and executing control instructions based on the self-awareness as according to Lee et al.'s (2015) 5C architecture. Moreover, lean production mainly involves the value-driven and waste-elimination concepts; what value is and what constitutes waste are ultimately decided by customers (Hines et al., 2004; Liker, 2021). Finally, environmental sustainability in manufacturing entails minimizing environmental impact and prioritizing emission elimination due to the pressure of climate change (European Union, 2021b).

Operationally, IoT and related connection-level technologies provide great operational potential to support the application of lean principles. The facilitation pathways involve enhancing visualization and communication, minimizing deviations and monitoring lean waste. Specifically, enhanced visualization may be accomplished by enhancing the visibility of production data, such as machine running states, productivity, resource consumption (materials, water/lubricant/cooling liquid), energy consumption and waste and emission generation. Kanban or VSM may be visualization tools for specific areas or activities. Enhanced communication entails connecting and integrating operations, industrial activities and people in real-time to improve communication efficiency. Standardization may be improved by recognizing and limiting deviations, such as assuring working procedures (poka-yoke), safety stock level (raw materials, package materials, tooling) and material handling sequence (FIFO). Finally, measuring and monitoring product quality status, motions and machine status could help to enhance lean waste elimination/reduction.

IoT-enabled visualization, communication, standardization and lean waste elimination minimize environmental impact, including resource (materials and water) and energy consumption, as well as emissions and industrial waste generation. Compared to the other lean principles, increased visualization has a relatively high chance of contributing to reduced resource and energy use and emissions production.

To sum up, digital technologies, especially IoT-related connection level technologies, could enhance the implementation of lean principles to realize environmental benefits. Specifically, visualization, communication, standardization and lean waste identification could be enhanced to improve environmental performance, such as reducing the consumption of materials, energy and water and generating emissions and industrial waste.

4.3 THE GENERATION MECHANISMS

In addition to recognizing the environmental benefits, it is vital to understand the mechanisms by which digital technologies generate these benefits. Hence, the cross-case analysis examined the steps comprising the mechanism that explains the transformation process from the digitalization phenomenon to the desired environmental benefits, as shown in Figure 1, the conceptual mechanism. This section presents the results from the cross-case analysis.

4.3.1 Descriptive results

Digital technology

The number of practices shows that smart IoT sensors are the most widely applied digital technology in literature (35) and case (22) findings among the 97 practices. It monitored applications based on IoT platforms or smart sensors, such as big data analytics or cloud computing, with 17 practices. Based on the type of digital technology, the literature has more variety than the case findings, such as applications of AM, big data, IAI and intelligent robotics.

Elements of the generation mechanisms

Figure 13 compares the number of practices between the literature and case findings by categorizing the elements of the generation mechanisms: technology functions, enabled operations and impact pathways.

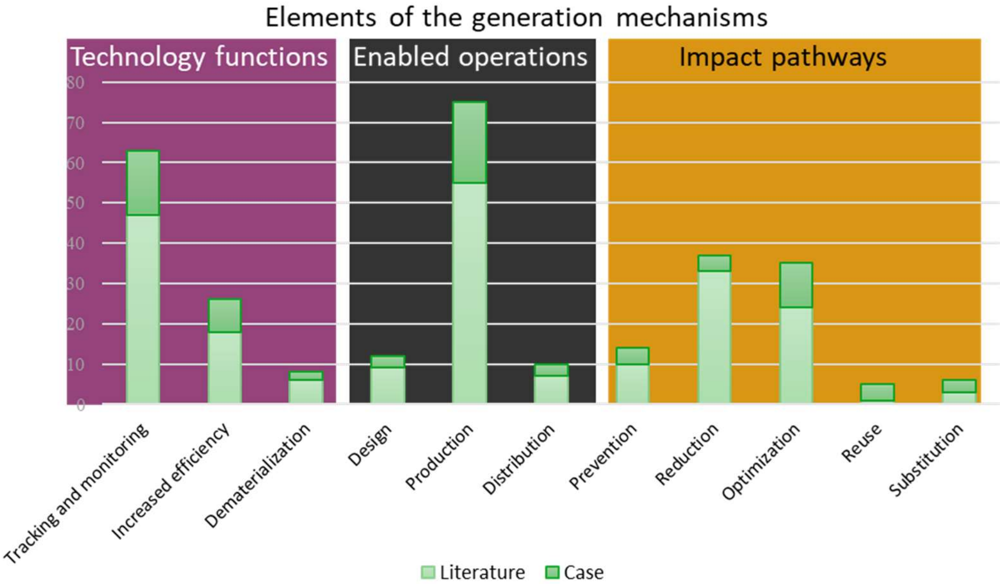

Figure 13. Comparison of the number of practices in the literature and case findings by the elements of the generation mechanisms.

Technology functions have the most practices (63) for tracking and monitoring, both in the literature (47) and the case (16) findings. Twenty-six practices follow increased efficiency and dematerialization has eight practices.

Concerning enabled operations, the production stage has many more practices (75) than the design (12) and distribution (10) stages. In terms of linking to OEE underlying factors, the literature and case findings show a similar trend, having a higher number of performance practices (L:28; C:13) than *availability* (L:7; C:4) and *quality* (L:9; C:5). When linked to the environmental performance (Pe), the literature has a higher number of practices (27) than the case findings (4), indicating more environmental performance-driven practices were identified in the literature.

Regarding impact pathways, *reduction* (37) and *optimization* (35) have many more practices than *prevention* (16), *substitution* (6) and *reuse* (5). Among all the practices, the production stage reduces impact through all five pathways, while the design stage is mainly through *optimization*, *substitution and prevention* and the distribution stage is mainly through *optimization* and *reduction*.

4.3.2 The mechanisms generate environmental benefits

The mechanisms consist of three key elements, technology functions, enabled operations and impact pathways, explaining the transformation process of using digital technologies to reduce environmental impacts, as shown in Figure 14.

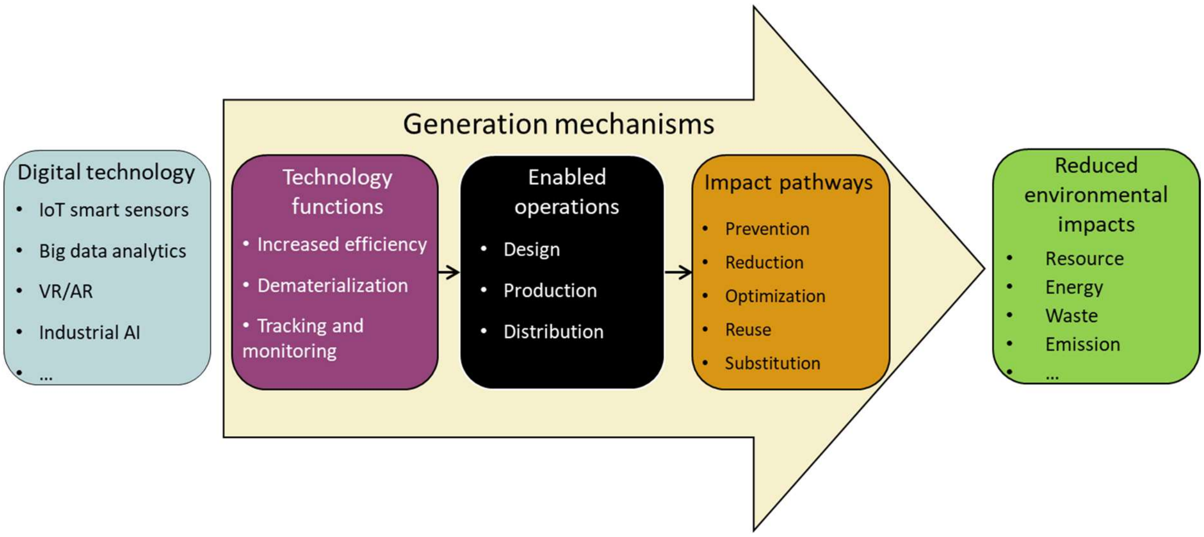

Figure 14. The mechanism for using digital technology to reduce environmental impact.

When digital technology is introduced into a production system, its function of increasing efficiency, dematerializing or tracking and monitoring may enable design, production or distribution operations that lead to environmental impact reduction through prevention, reduction, optimization, reuse or substitution.

Specifically, increased efficiency means improved communication or processing efficiency, implying less processing time required per product or a shorter time required per response. Dematerialization involves using digital documents, instructions or information to enable a paperless or dematerialized working environment, such as virtual modeling or barcode traceability systems. Monitoring and tracking supports the observation and detection of status changes to provide decision-making data and information.

Enabled operations are operations enabled by the above-mentioned technology functions and may take many different forms. The enabled operations will be presented in more detail in Section 4.3.3.

Regarding impact pathways, prevention means avoiding unnecessary resource usage or waste generation. Reduction involves waste or resource reduction by housekeeping, repairing and maintaining equipment or similar activities. Optimization attempts to match demand and supply levels, achieving the best efficiency point of equipment use or improving the system's overall efficiency by, say, optimizing the production schedule, resource input and the like. Reuse turns compatible waste output into resource input and includes such things as recovering waste heat or wasted materials. Substitution means replacing inputs with more eco-friendly materials or technologies to accomplish operational functions.

As an example, take the design stage from Figure 15. I1, IoT-supported real-time communication (*technology functions*), increases supplier communication efficiency. Timely communication could enable smart scheduling and module design to integrate components (*enabled operations*), leading to optimized resource and energy use (*impact pathway*). More examples will be given in the following sections.

4.3.3 Practices in the design, production and distribution stages

In the following section, practices are presented by the design (Figure 15), production (Figure 16, Figure 17, Figure 18 and Figure 19) and distribution (Figure 20) stages. These figures organize practices by technology function, enabled operations and impact pathways, explaining the mechanism that generates environmental benefits. Specifically, the impact pathways were used to group the enabled operations, collecting the operations that lead to the same pathway for reducing environmental impact. The codes representing each practice were marked right after the operations and could be used to trace back to the detail of practices in APPENDIX I. In the enabled operations, the actions enabled or strengthened by using digital technologies are described in the box; the text in grey indicates the linked categorization to OEE or Pe. The technology functions were also color-coded into four categories, with only three displayed as causes of the enabling operations. Reduced transport is placed at a later stage of the transforming process because it is usually an effect of certain operations.

Design stage

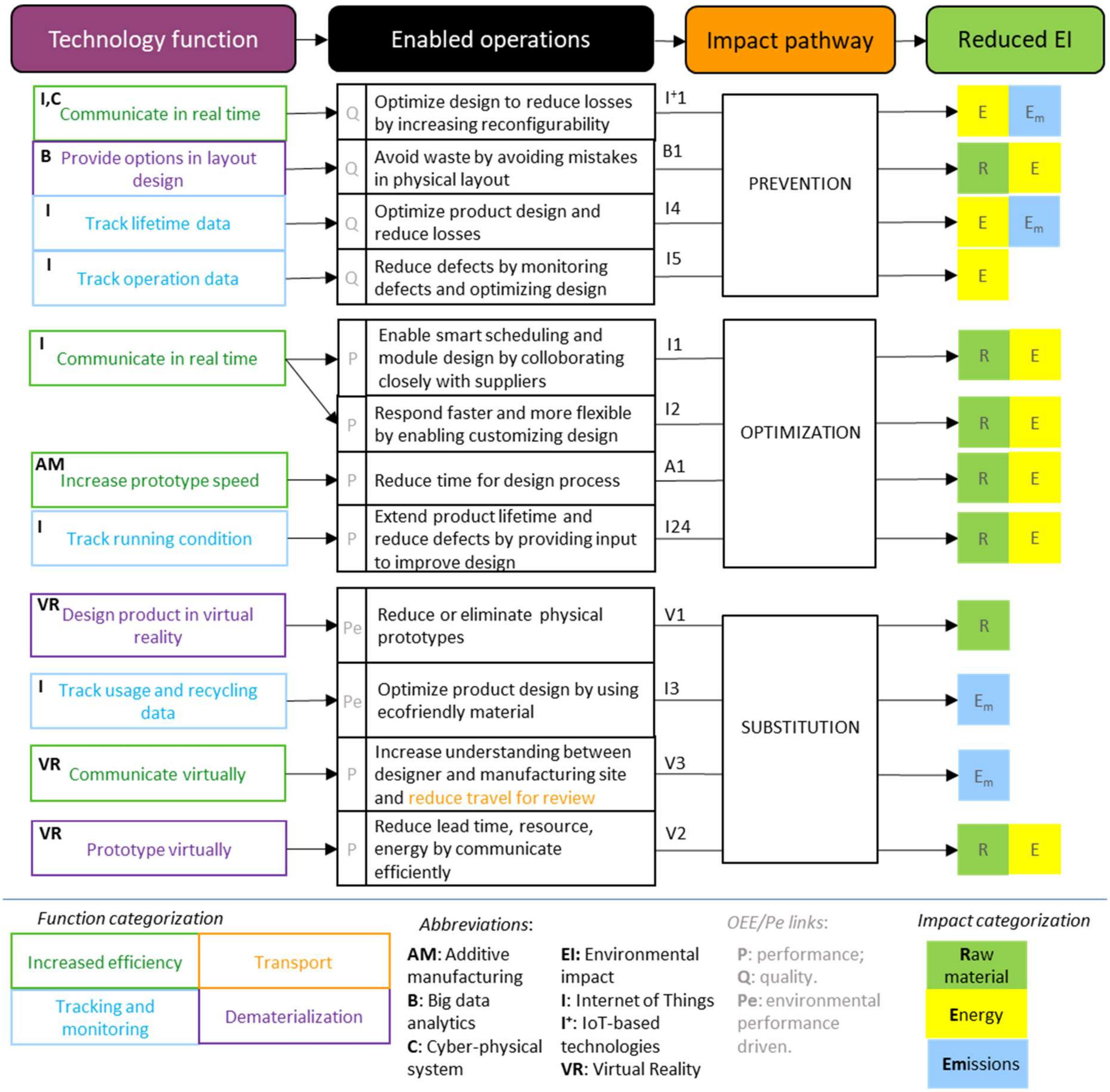

Figure 15. The mechanisms of generating environmental benefits from using digital technologies at the design stage.

At the design stage, increased efficiency, tracking and monitoring and dematerialization are somehow uniformly used as inputs by applying IoT, VR, big data analytics, CPS and AM. The enabled operations mainly involve improving the product design by virtualizing prototypes and integrating input from later life cycle stages. Reduced transport could be achieved by using virtual communication to replace travel.

Furthermore, design is at the early stage of a product's life cycle, making it relatively easier to use a *substitution* pathway to optimize the design with more eco-friendly material compared to the production and distribution stages.

Production stage

The following five figures present the mechanisms by which digital technologies enhance environmental impact reduction at the production stage, illustrating the pathways of *prevention, reduction, optimization, reuse and substitution.* The links to the OEE underlying factors/environmental performance driven were marked as secondary categorization under the reduction, optimization and reuse pathways.

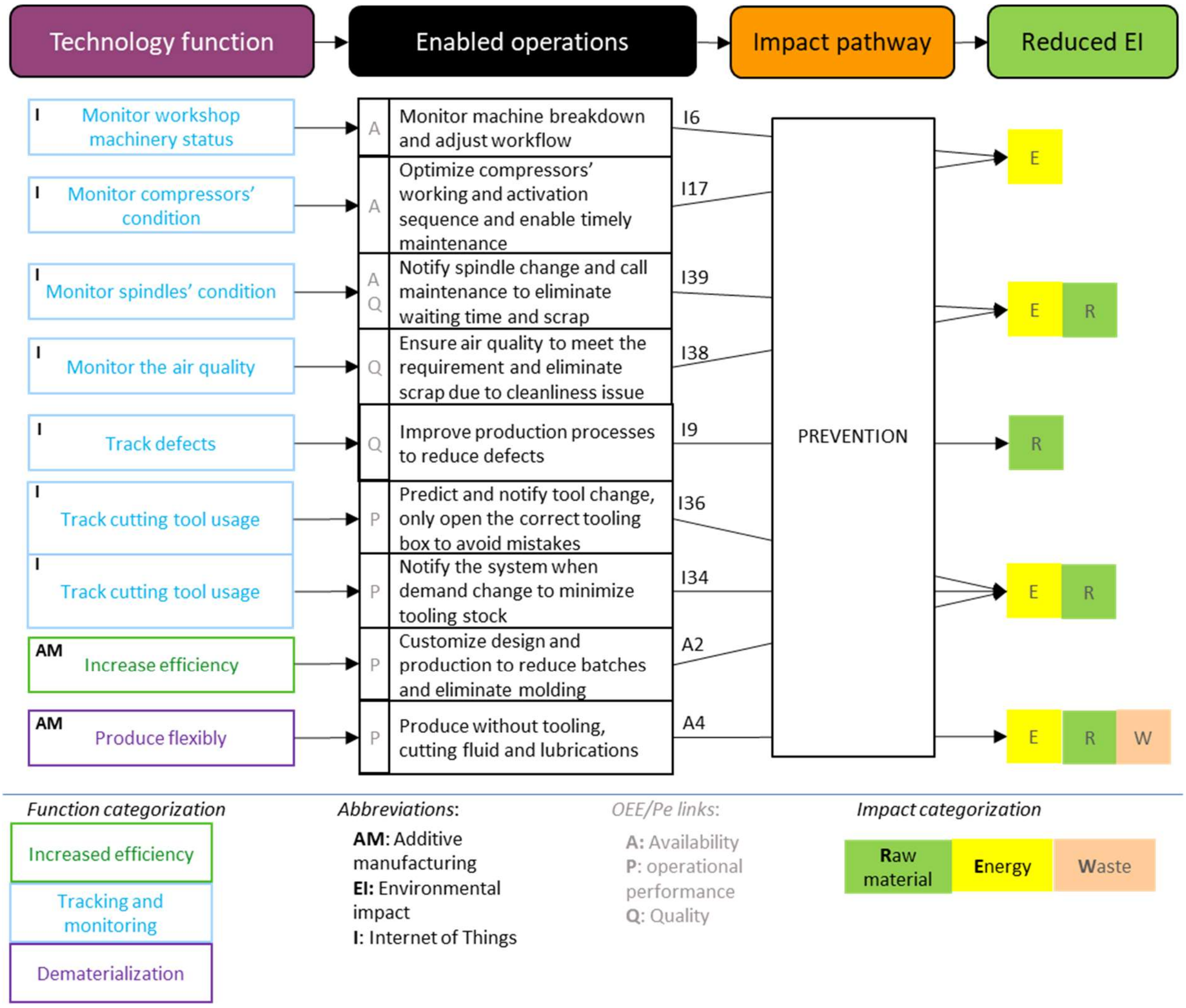

Figure 16. The mechanisms of generating environmental benefits from using digital technologies at the production stage: *prevention*.

As shown in Figure 16, through the *prevention* pathway, IoT tracks and monitors machinery and tooling conditions, which enables operations aiming at improving all three performance factors: availability, performance and quality. AM could increase efficiency and enable production without tooling and liquid, thus improving operational performance. Consequently, unnecessary resource usage and waste generation could be avoided, leading to less raw material and energy consumption and less industrial waste.

Figure 17 shows that many more practices achieved environmental impact reduction through the *reduction* pathway.

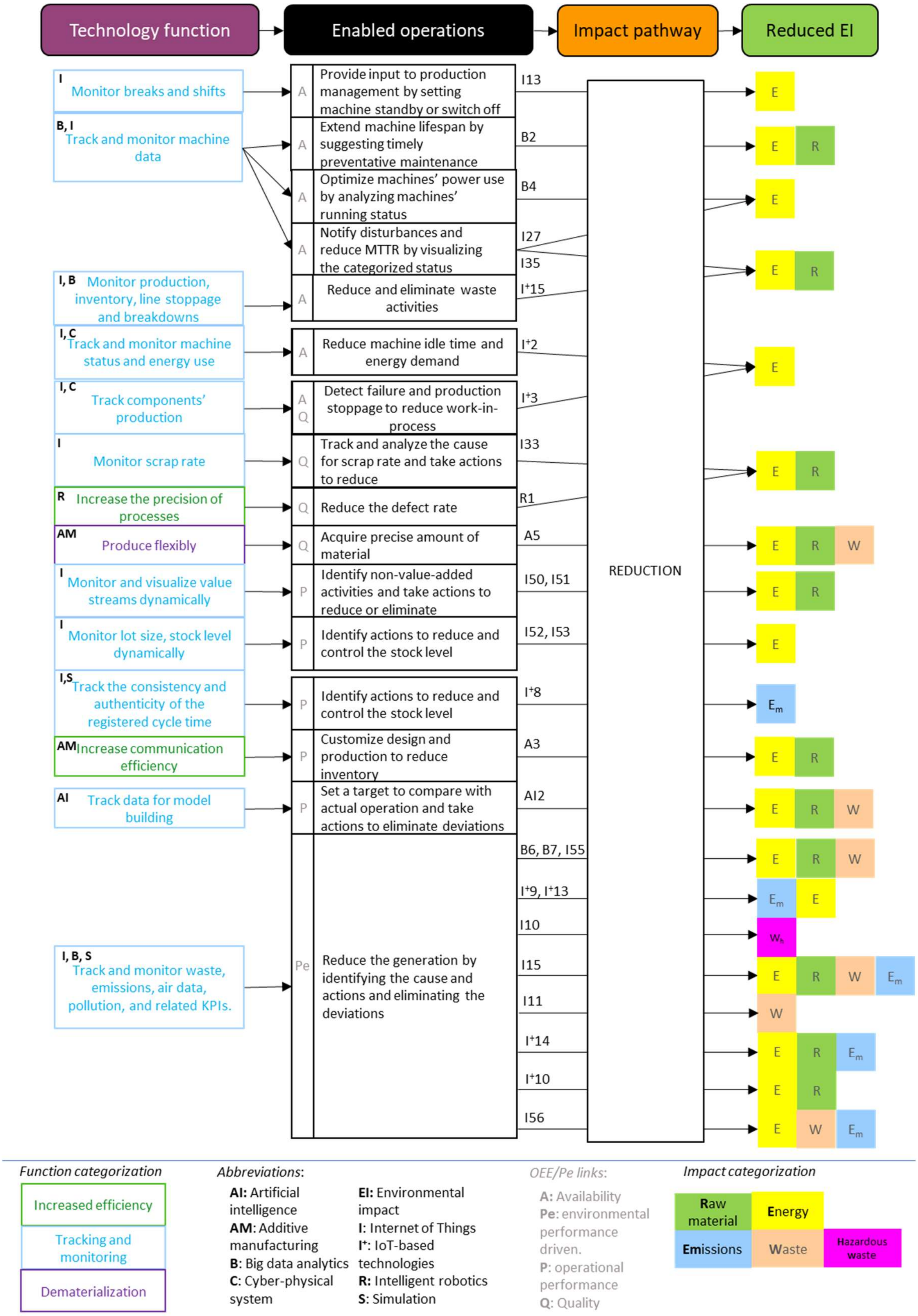

Figure 17. The mechanisms of generating environmental benefits from using digital technologies at the production stage: *reduction*.

Tracking and monitoring are most adopted through the use of IoT, big data analytics, CPS, simulation and AI. This mainly enables improved availability and performance, such as expanding machines' lifetime, reducing idling time and reducing inventory levels. Some actions are directly driven by environmental performance, such as identifying the causes of waste generation, emissions, air pollution and related KPIs and eliminating the deviations. As a result, various environmental impacts could be reduced, including energy, resource, industrial waste, emissions and hazardous waste.

Increased efficiency and dematerialization involve several practices that use intelligent robotics and AM. This enables defect reduction, acquisition of precise material quantities and inventory reduction. Thus, resource and energy consumption and industrial waste generation could be reduced.

Figure 18 illustrates the practices of the generation mechanisms through the *optimization* pathway.

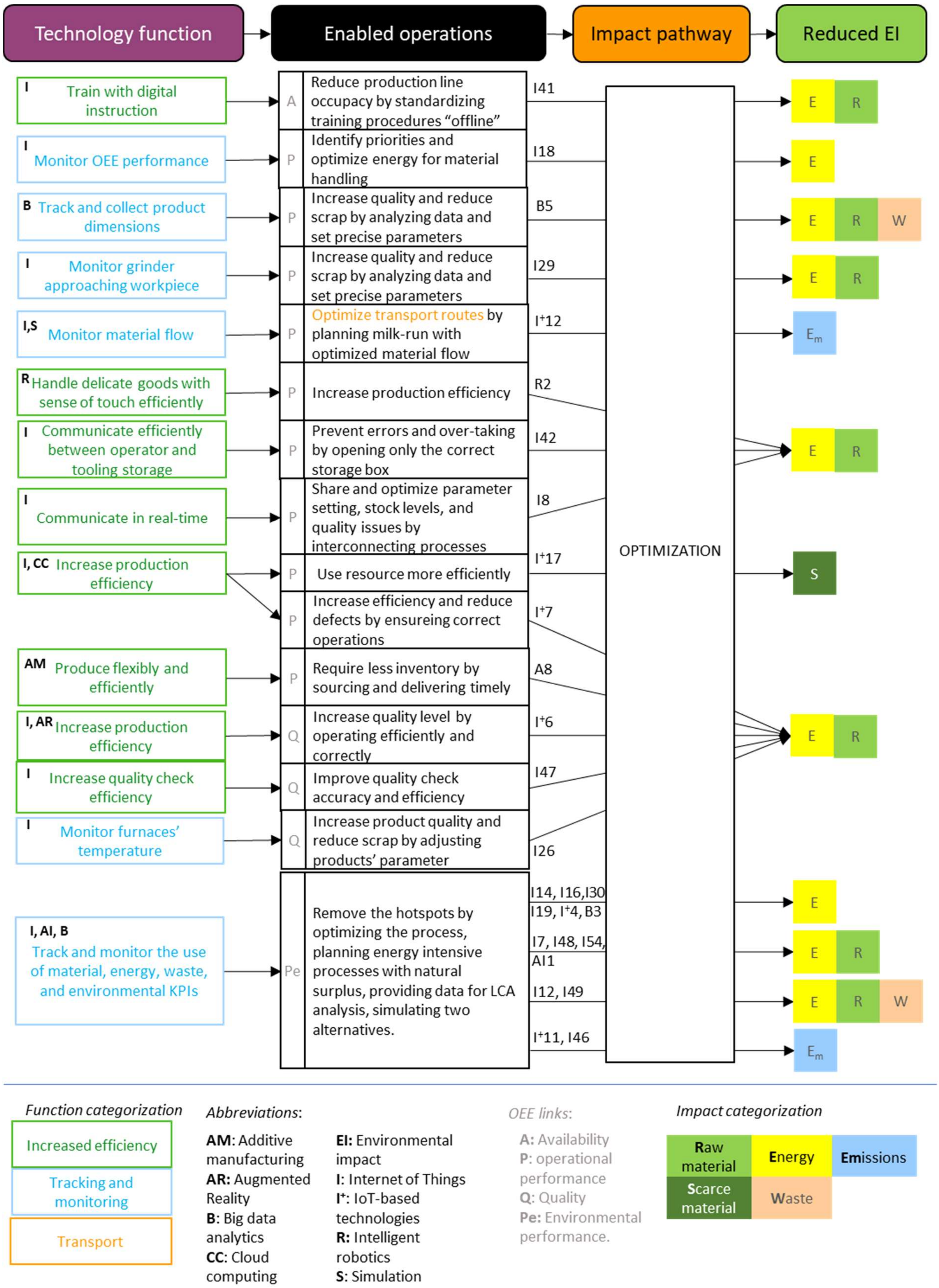

Figure 18. The mechanisms of generating environmental benefits from using digital technologies at the production stage: *optimization*.

The increased efficiency and tracking and monitoring afforded by IoT applications, big data analytics, simulation, intelligent robotics, cloud computing, simulation, AM and AR could mostly be used to enhance operational performance (by, say, increasing productivity, decreasing inventory level and preventing mistaken operations). A few practices show possible improvements in quality by increasing quality check efficiency and tracking furnace temperatures. Environmental performance-driven practices were also observed by using IoT, big data analytics and AI to track material, energy and waste-related KPIs to identify hotspots and by taking action to optimize the process.

One practice shows the possible reduction in transport ($I^{+}12$), achieved by monitoring the material flow and planning milk runs accordingly using IoT and simulation. Thus, it is a subordinate function compared to the other three.

Regarding the reduced environmental impacts, most practices show considerable resource and energy consumption reduction through *optimization*.

Figure 19 presents the practices of the generation mechanism through the pathways of *reuse* and *substitution* at the production stage. These are relatively fewer than through the other pathways.

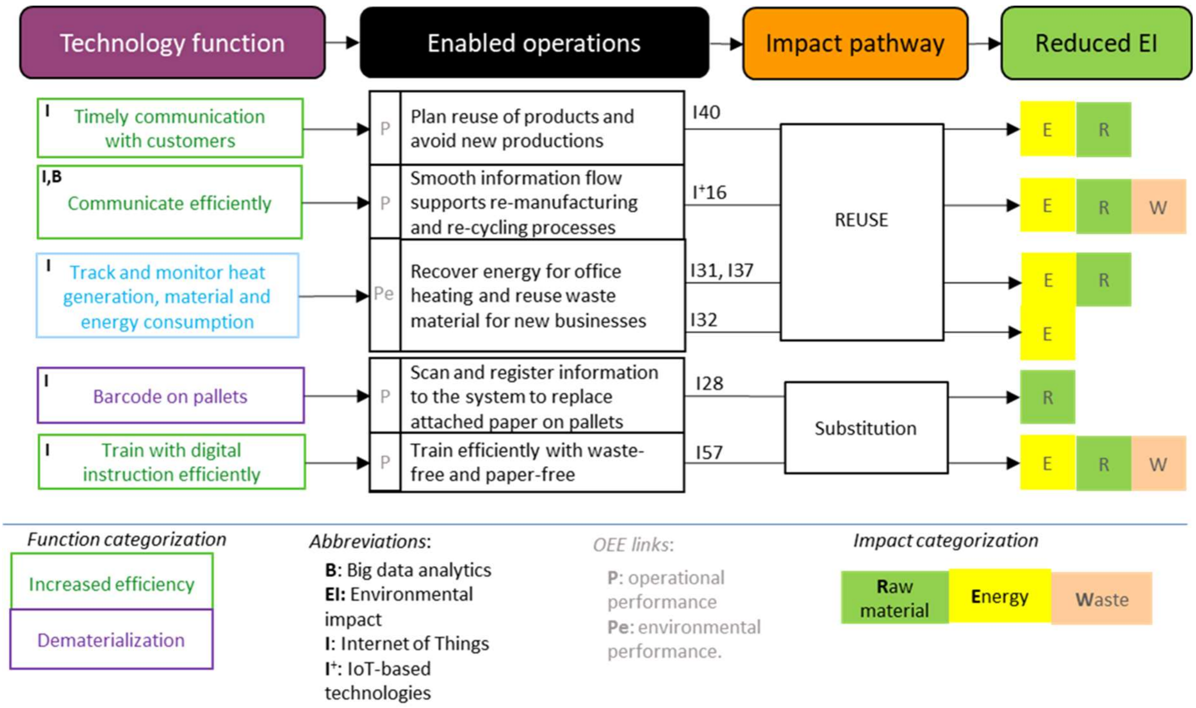

Figure 19. The mechanisms of generating environmental benefits from using digital technologies at the production stage: *reuse and substitution.*

Through *reuse*, increased efficiency enables reusing products, re-manufacturing and recycling, thus leading to reduced energy and resource consumption and less waste generation. By tracking and monitoring heat generation and material and energy consumption, heat could be recovered to heat offices and waste materials could be used for new businesses.

A couple of practices indicate improved environmental performance through substitution, whereby paper communication could be replaced by barcode scanning and registration and paper instruction could be replaced by digital instructions. Both practices require investment in new systems, which may explain the scarcity of practices through substitution.

To sum up, *reduction* and *optimization* account for most practices explaining the generation mechanisms by which digital technologies enhance environmental impact reduction. Ultimately, this is followed by *prevention* and *reuse* and *substitution*. Moreover, increased efficiency and tracking and monitoring dominate the application of technological functions, with IoT and its enabled digital technologies making the primary contribution. Dematerialization was mainly achieved using IoT and AM to replace traditional production or communication methods. Additionally, reduced transport is usually a subsequent step after realizing the other three functions, making it a subordinate technological function.

<u>Distribution stage</u>

Compared to the production stage, distribution has far fewer practices illustrating the mechanisms of using digital technologies to enhance environmental performance, as shown in Figure 20. However, certain patterns can still be concluded based on these practices.

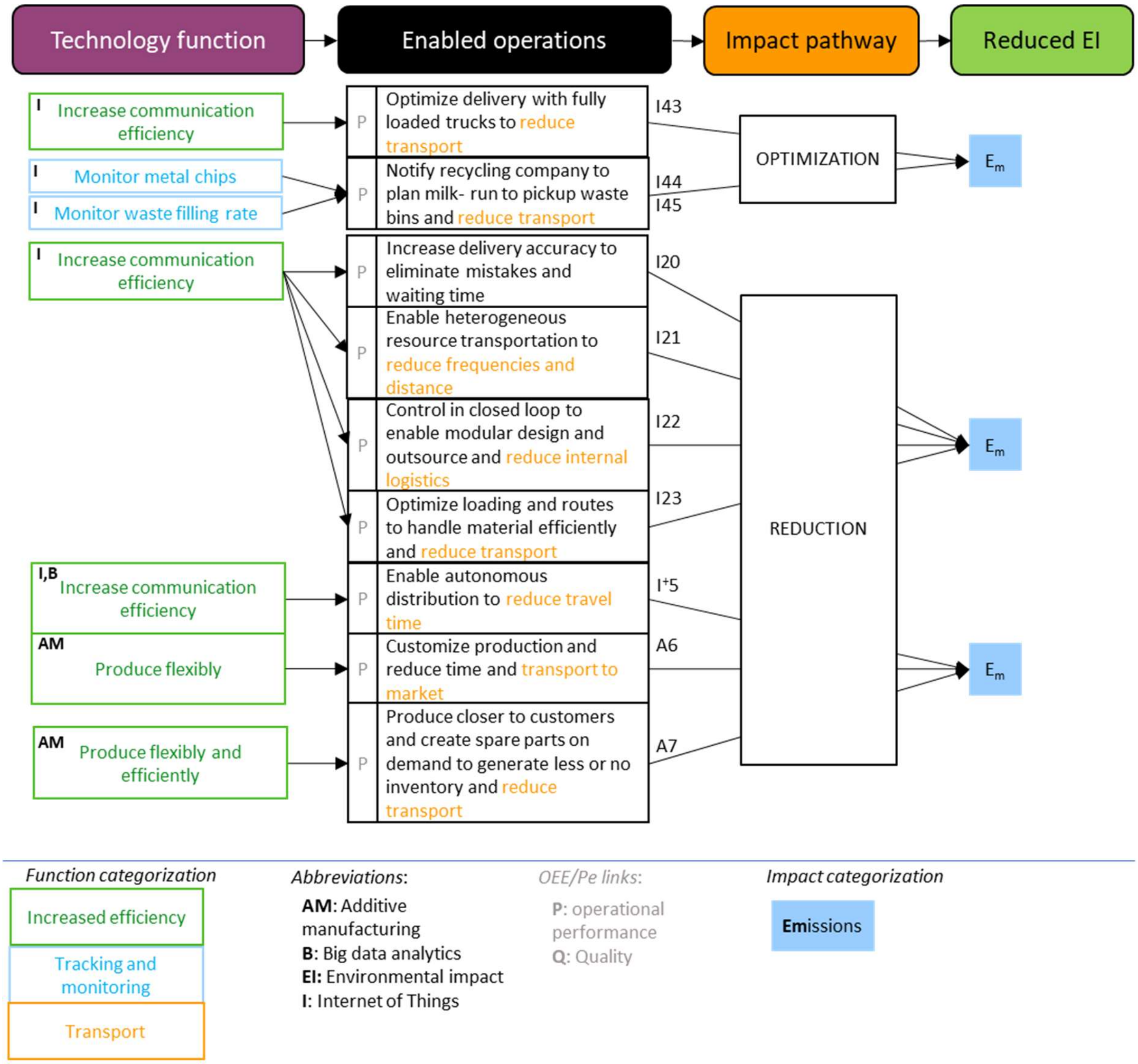

Figure 20. The mechanisms of generating environmental benefits from using digital technologies at the distribution stage.

As shown in Figure 20, *reduction* and *optimization* are the main impact pathways leading to the reduction of environmental impact. Specifically, *optimization* could be achieved by delivery optimization actions that are enabled by increased efficiency and tracking and monitoring, including freight loading and timely pickups. Regarding *reduction*, increased efficiency from using IoT and AM could enable heterogeneous transportation, optimized travel routes and loading, closer to production and greater accuracy. Almost all the applications of digital technologies could lead to reduced transport, thus reducing emissions. Consequently, emissions are the main reduced environmental impact at the distribution stage.

4.4 SUMMARY OF RESULTS

Given the results presented from each study above, this section summarizes the key findings.

First, this thesis shows both positive and negative impacts of digital technologies on the environment identified from the product and technology life cycles, formulating a multiple life cycles perspective. Digital technologies enable environmental impact reduction in the product life cycle primarily via increased material efficiency and information support during production. Meanwhile, the technology life cycle requires a greater consumption of resources and energy and produces more emissions, mostly at the production and end-of-life stages.

In addition to the positive impact generated in the product life cycle, this thesis identified the environmental benefits of using digital technologies from the other three aspects: IoT, VR technology and digitalized lean-related practices. As the foundation of digitalization, IoT is a platform that enables a connected system to track and monitor the consumption of resources and energy. It promotes the efficient use of material and energy, advocates dematerialization and reduces transport, as identified in Study B. Specifically, increased efficiency enables immediate communication between production processes and facilitates material handling with digital signals. Using ERP, the overall resources can be well coordinated with a pull system, to minimize the inventory level. Tracking and monitoring were enabled to track material and energy flows, providing data for identifying and removing hotspots. Furthermore, ERP and MES could provide a paperless work environment and reduce defect rates by communicating via digital signals. Improved quality (which may also be achieved by robotics and GCM) could lead to dematerialization by minimizing waste and rework.

Given the increased interest in adopting VR in industrial companies, the application for environmental sustainability improvement is worth exploring. VR could improve communication efficiency by allowing objects to be viewed from different angles and in more detail, thus replacing physical meetings for technical discussions. The ongoing dialogue enabled between remote communicators could promote instant feedback and changes in design modification at an earlier stage. Consequently, the replaced physical visits could lead to less travel and contribute to reduced carbon emissions.

Moreover, digitalized lean implementations were investigated to bridge the application of digital technologies for environmental benefits. A DISEL framework, DIgitalization Supports Environmental Sustainability through Lean principles, is proposed to integrate IoT and connection-level technologies with lean principles. IoT and related connection-level digital technologies were the main technologies applied, as observed at the case companies (including ERP, MONITOR, MES, MindSphere and advanced sensors) and identified in the literature (such as IoT, advanced sensors and simulation). From a strategic perspective, companies can enhance their sustainable development by adopting the paradigms of digitalization, lean production and environmental sustainability. Digitalization is primarily used to monitor and track data, transfer information, analyze data for decision-making and execute control commands based on self-awareness. Lean production focuses on value-driven principles and reducing waste. Environmental sustainability in manufacturing prioritizes minimizing environmental impact and emissions to address the challenges of climate change. At an operational level, IoT and related technologies provide opportunities for implementing lean principles by improving visualization and communication, reducing deviations and monitoring waste generation. The enhanced lean implementations reduce environmental impact, such as reducing the use of resources and energy, decreasing energy consumption and minimizing the generation of emissions and industrial waste.

Aiming to understand the mechanisms by which digital technologies generate environmental benefits, this thesis examined the four studies' best practices of digital applications. The generation mechanisms could be explained as a transformation process consisting of three steps: the technological functions of digital technologies, the enabled operations and the impact pathways.

The results show that IoT smart sensors are the most widely applied digital technologies. This is followed by applications based on IoT platforms or used with smart sensors, such as big data analytics or cloud computing.

These digital technologies mainly classified the technological functions as tracking and monitoring, increased efficiency and dematerialization. Reduced transport acts as a subordinate function because it usually comes after realization of the above three functions.

The technological functions could enable operations to improve operational performance, such as increasing the availability of machines or equipment by reducing idle time or waiting time, improving productivity and quality, optimizing resource and energy utilization and goods delivery, etc.

The enabled operations could enhance environmental performance through five impact pathways: prevention, reduction, optimization, reuse and substitution. Specifically, prevention involves avoiding unnecessary resource consumption and waste production. Reduction means reducing waste or resources by cleaning, restoring and maintaining equipment or similar activities. Optimization aims to match the levels of demand and supply, achieve the highest point of equipment efficiency or improve the overall efficiency of a system, by optimizing the production schedule, resource input and so on. Reuse converts waste output compatible with resource input by, say, recovering waste heat or wasteful materials. Substitution replaces inputs with more environmentally favorable materials or technologies to fulfil operational functions.

By going through the three steps, applying digital technologies could reduce environmental impacts, such as less resource consumption (the general raw materials, scarce raw materials and water) and energy and reduce industrial and hazardous waste and emissions generation.

5

DISCUSSION

This chapter discusses the key findings and how they relate to answering the research questions. Furthermore, it highlights the contributions of this research towards a sustainable production system. Lastly, the chapter reflects on the methodology adopted in this thesis and the prospect of future work.

5.1 ANSWERING THE RQS

Through four studies using qualitative and quantitative methods, this thesis expands on the potential of digital technologies for strengthening the environmental sustainability of production systems by answering two research questions: 1) *What are* the *potential benefits of using digital technologies to improve the environmental performance of production systems?* 2) *What mechanisms can generate environmental benefits from using digital technologies in production?* This section will discuss the key findings and their implications that provide answers to the questions.

5.1.1 The environmental benefits of digital technologies in production systems

The environmental benefits are identified from four aspects: the general impact of applying digital technologies on the product life cycle, IoT-related practices, VR-related practices and digitalized lean-related practices.

From a multiple life cycle perspective, the positive environmental impact of using digital technologies is mainly generated in the product life cycle from the increased efficiency of material consumption and information exchange at the production stage. The digital technologies here refer to the eight Industry 4.0 enabling technologies presented in Section 4.1.1: CPS, IoT/ICT, AM, intelligent robotics, cloud computing, big data analytics, VR/AR and IAI. This result supports Nascimento et al. (2019) and Oláh et al.'s (2020) statement that Industry 4.0 might enable green manufacturing to reach its full potential by offering more accurate, high-quality data and real-time event management. Moreover, digitalization enables intelligent, interconnected value-creation models that effectively distribute resources and energy (Stock and Seliger, 2016).

IoT-related practices were investigated in Study B, with environmental benefits identified by increased efficiency, tracking and monitoring, dematerialization and reduced transport. Corresponding to Kiel et al. (2017)'s finding, interconnected IoT processes enable machines to communicate information on workpiece parameters, inventory status and energy consumption hotspots, resulting in greater material and energy efficiency while boosting quality levels. The enhanced transparency supported by real-time monitoring of resource and energy consumption with empirical findings deepens Oláh et al. (2020) and Song and Moon's (2017) claim of providing production management decision-making processes with a solid data foundation for greater flexibility. Moreover, IoT-enabled interconnected processes allow machines to exchange information on parameter configuration, inventory status and defects, increasing material and energy efficiency while raising quality levels (Kiel et al., 2017).

Study C explored the potential for using VR technology for environmental benefits. Previous research indicates that VR-enabled platforms could offer an environmentally friendly alternative to traditional physical prototyping by avoiding excessive resource and energy use throughout the design stage (Chang et al., 2017). In addition to replacing the physical prototypes, Study C shows that VR could improve communication efficiency by allowing users to view objects from different angles and in greater detail, thereby replacing physical meetings for remote communicators with less travel. Moreover, Study C contributes to expanding the application of VR technology for environmental benefits with an industrial case (Khakpour et al., 2020).

The DISEL framework shows that IoT-based digital technologies could enhance lean implementations and improve environmental performance. Study D identified that IoT-related digital technologies from the 5C architecture's connection level were most extensively used in supporting lean principles. Together with the IoT-related practices identified in Study B, this finding again coincides with Ghaithan et al. (2021)'s claim that the application of IoT is highly valued in manufacturing, among other I4.0 technologies. Moreover, the findings from the case studies point to higher-level IoT applications, such as intelligent robots and cloud computing, at the case companies. This is consistent with the previous research, in that IoT generates big data and serves as a foundation for improving operational performance, such as machine running status, productivity, failure rates and so on (Lobo Mesquita et al., 2021). It also verifies prior study findings that factories' digital transformation might begin with deploying IoT and CPS technologies (Reyes et al., 2021), particularly for SMEs with limited financial incentives (Leong et al., 2020).

Furthermore, Study D shows that lean production was a culture implemented at all three companies to engage people throughout the organization, which was crucial for initiating change management that led to digital and green transitions. This finding strengthens the idea that implementing lean principles allows industrial companies to better prepare for digital and green transformations (Bittencourt et al., 2019; Kamble et al., 2020). Operationally, the increased visibility of operational performance could lead to more improvement opportunities, including resource and energy consumption and efficiency and carbon emission generation. This finding adds to earlier research indicating that lean can be a key bridging element

(Ghaithan et al., 2021), a requirement (Schumacher et al., 2020) and an enabler (Yilmaz et al., 2022) of better operational performance.

Additionally, the case companies could have applied digital technologies to improve environmental performance but did not, which indicates the necessity of conducting Study D. This observation also coincides with Bittencourt et al.'s (2019) claim that digitalization may not contribute directly to environmental sustainability if developed as a standalone application. As a result, the findings show that using digital technologies for environmental benefits could be enhanced if lean is used as a bridge.

Lastly, Study D enriched the theoretical framework with empirical findings, providing further clarity on which digital technologies could be integrated with which lean implementations for environmental benefits (Buer et al., 2018; Lobo Mesquita et al., 2021; Varela et al., 2019).

5.1.2 The mechanisms generate environmental benefits by using digital technologies

The generation mechanism by which digital technologies improve environmental performance consists of three elements, technological functions, enabled operations and impact pathways. This section will discuss the implications of the generation mechanism from its overall function and the specific elements, especially the technological functions and enabled operations.

The generation mechanism was developed based on the best practices collected from the four studies, breaking down the transformation process of the theoretical mechanism (Figure 1) from the phenomenon of digitalization to the desired state of environmental sustainability. Explaining the mechanisms by analyzing the actual generation processes at the operational level deepens Ghobakhloo et al. (2021)'s claim with detailed operational practices. The focus on process integration coincides with Ghobakhloo et al. (2021) and Kamble et al. (2018)'s findings that emphasize green process innovation and the process's intermedia role.

Furthermore, the technological functions identified in the generation mechanism specify the application of digital technologies and environmental impact reduction. Similar to Berkhout and Hertin's (2004) and Liu et al.'s (2022) approach, the cross-case analysis for examining the details of the transformation process went down to the level of operational practices. Compared to the mechanisms between digital functions and circular economy strategies identified by Liu et al. (2022), the generation mechanism identified in this thesis breaks down the connection between technological functions and environmental performance with operational details. The enabled operational practices increase transparency and further explain *how* the technological function works and brings changes to the environmental impact.

Moreover, the four pathways adapted from Berkhout and Hertin's (2004) classification, improved efficiency, dematerialization, virtualization and monitoring of environmental performance and reduced transport, were first applied in analyzing the digital applications for environmental benefits in Study B. It worked by categorizing the applications into these four categories. However, when using cross-case analysis to further break down each practice, the four functions could be distinguished from the places where they work. Specifically, increased efficiency, tracking and monitoring and dematerialization usually occur right after the application of digital technologies, with reduced transport working at a later stage as a resulting step. This observation also places increased efficiency, tracking and monitoring and dematerialization more in the position of causative factors that enable operations for environmental impact reduction.

Lastly, the generation mechanism identified in this thesis is based on the best practices collected from two literature studies and three case studies, providing additional empirical implications compared to the previous studies (Ghobakhloo et al., 2021; Kamble et al., 2018; Liu et al., 2022).

5.2 CONTRIBUTION TO AN ENVIRONMENTALLY HARM-FREE PRODUCTION SYSTEM

This research provides a deeper understanding of the potential environmental benefits of using digital technologies and the mechanisms that enable such benefits. By doing this, the aim of identifying the potential of digital technologies for the environmental sustainability of production systems is achieved as a step towards an environmentally harm-free production system. The following section will discuss the research implications from theoretical and practical perspectives.

5.2.1 Theoretical contribution

This thesis contributes to the body of theory by adding knowledge in identifying the environmental benefits generated from using digital technologies and explaining the mechanisms by which the benefits are generated.

This research first proposed a multiple life cycle perspective considering the environmental impact of the product and technology life cycles, including positive and negative impacts from different stages of the manufacturing value chain. Moreover, it described where and how the positive environmental impacts are generated when introducing digital technologies to the production system, where the connection level of digitalization (in the 5C architecture) has relatively major applications in the production processes. Specifically, IoT and its related connection-level technologies were widely applied in production systems and could improve environmental sustainability by increasing efficiency, dematerialization, monitoring and tracking and reducing transport.

Moreover, this thesis has proposed a DISEL framework to provide an overview of integrating digital technologies and lean principles to improve environmental performance. Specifically, IoT-related digital technologies have great potential to enhance lean implementations, thus leading to environmental benefits. The intermediary role of lean in bridging digitalization and environmental sustainability could lay a foundation for commencing digital and green transitions. Furthermore, DISEL targets environmental performance improvements in the production system. This serves as an attempt to reshape the situation and tends to prioritize digital applications for economic opportunities over environmental benefits. Finally, it provides more detail by explaining which digital technologies could be integrated with which lean implementations to yield environmental benefits.

In addition to the identified environmental benefits, this thesis proposed a more detailed generation mechanism. This was to explain the transformation process from the phenomenon of digitalization to the desired state of environmental sustainability, including technological functions, enabled operations and impact pathways. Context-based examples from literature and empirical studies were identified, providing the best practices to showcase the application of digital technologies in production to achieve environmental benefits. These best practices show context-based digital applications and various operations that could be enabled, indicating limited generalizability. However, the context difference should be acknowledged when introducing digital technologies to gain environmental benefits.

Furthermore, the generation mechanism is developed based on previous research exploring the mechanisms of using digital technologies for environmental benefits and expanding the implications of digitalization for environmental sustainability. More studies are ongoing (and more are needed) to strive towards the same goal. Hence, this thesis is a stepping-stone between previous research and future studies, aimed at formulating sustainable digitalization principles for using digital technologies in an environmentally sustainable manner.

5.2.2 Practical contribution

This thesis provides implications for practitioners in learning the potential environmental benefits of using digital technologies and understanding *how* those benefits are generated.

First, the multiple-life cycle perspective provides an overview of the environmental impact when introducing digital technologies into production systems. With a better knowledge of both the positive and negative environmental impacts that digital technologies may bring, industrial practitioners can reposition themselves as producers and consumers by considering the overall environmental impact of digitalization on both life cycles.

Secondly, the examples summarized at each stage of the manufacturing value chain provide best practices, enabling practitioners to learn where and how to use digital technologies to produce environmental benefits. Specifically, the practices from the IoT-related connection level that account for most of the findings could indicate easily attainable goals.

Moreover, using VR technology for environmental impact reduction could help practitioners identify similar environmental benefits, especially for those with regular remote communications regarding technical details. The methods adopted in Study C (which first qualitatively identified the potential technology application areas and then quantitatively assessed the potential environmental impact reduction) could be used to further expand the implications of technology in terms of environmental benefits.

Furthermore, Study D presents an incremental innovation study using lean's intermediary role to bridge digitalization and environmental benefits. As an incremental change, applying digital technologies based on lean principles could be easier than introducing brand-new technology. Moreover, digitalized lean implementations mean minimizing the risk of accelerating waste generation or improving non-value-added activities because waste is identified, visualized and removed. Additionally, IoT-enabled data tracking and monitoring could enable efficient visualization and communication with real-time updates. This is indicated as an easily attainable goal for digitalized lean implementation. Thus, lean principles may be used as one approach to bridging the application of digital technologies for environmental benefits.

With a better understanding of the potential environmental benefits, practitioners could learn *how* the mechanisms generate the benefits. Context-based best practices provide possible digital applications for environmental benefits that practitioners could learn, according to their own situation. It is difficult to generalize an implementation handbook for using digital technologies for environmental benefits. However, it is also vital to understand that it takes time to develop sustainable digitalization principles with clear step-by-step guidance, especially when considering the specific implementation context.

As a step towards sustainable digitalization principles, the generation mechanisms identified in this thesis could provide practitioners with three major elements that enable digital technologies to generate environmental benefits: technological functions, enabled operations and impact pathways. With that, this thesis contributes to explaining *how* digital technologies enhance environmental performance with best practices summarized from literature and empirical studies.

5.3 METHODOLOGICAL REFLECTIONS

Reflections on the research, including "the presuppositions, choices, experiences and actions during the research process," make the constructed nature of research outcomes visible to the reader (Ortlipp, 2008). Hence, looking back on the research process, it was practically orientated and used multiple methods to perform four studies. This choice was made mainly because of my previous practical knowledge in the manufacturing industry and the complex nature of the interdisciplinary topic spanning digitalization and environmental sustainability.

My previous work mainly focused on on-site problem-solving, process improvement and lean implementation in production systems, which motivated me to tackle a real-world problem to uncover the potential of digital technologies for environmental sustainability. Moreover, my experience drove me to actively engage with industrial partners and combine different methods to provide answers. On the one hand, the collaboration with industrial partners in all empirical studies enhanced the practical relevance of this research. And on the other, my manufacturing work experience helped me better understand the context of the interviews and onsite observations regarding data collection, analysis and conclusion.

To minimize potential personal bias, in conducting each study, I followed scientific methods, applied research techniques to enhance the quality and presented the results transparently.

First, to learn the state-of-the-art environmental impact of digitalization in production systems, Study A conducted a literature review by following the steps suggested by Hart (2018). The literature selection process was documented to support transparency and reliability and the criteria for analysis were derived from the research questions to enhance construct validity. Moreover, triangulation among researchers was applied to enhance the validity.

However, this study reviewed relevant literature published by July 2020. When I used the same keywords to search literature in Scopus in April 2023, the number had already doubled over the previous two years, indicating increasing attention on this topic and calling for a constant review.

Unlike Study A, Study D performed an integrative literature review to complement practices of digitalized lean implementations from the literature. This process followed Snyder's (2019) and Torraco's (2005) suggestions, covering important and relevant literature on digitalization, lean and environmental sustainability.

Furthermore, studies B, C and D adopted interviews, onsite observations, questionnaires and focus groups, involving interpretation of the findings. To enhance research rigor, triangulation (research methods and researchers' lens), member-checking and transparency was applied, as presented in Table 3. Moreover, onsite observation was used to enhance the understanding of interviews in studies B and D. The conversations with the onsite workers were added to the notes and conclusions. In Study C, close collaboration with the case company allowed me to constantly present and discuss my findings with industrial partners. Their feedback was valuable in supporting the validity of the research.

Additionally, the quantitative method used in Study C was based on the application areas identified from interviews and focus group discussion, in which 14 responses from the questionnaire may not represent the general perception of using VR to reduce environmental impact. However, the questionnaire was conducted right after a demo session where the actual VR users had just tested a customized demo at their workplace. Hence, the target user group with domain expertise was involved in the study. Besides, the context of developing the demo and generating and conducting the questionnaire was clearly described and available in Paper III, Session 3.

Lastly, a cross-case analysis was performed to identify the mechanisms by which digital technologies generate environmental benefits. This analysis was an iterative process examining the best practices of using digital technologies for environmental benefits from all four studies. The mechanisms were developed by combining previous research and pattern identification from the practices, which may provide some implications for future scholars who intend to carry out a similar practice-based study.

5.4 FUTURE WORK

From studies A, B and D, IoT and connection-level of the 5C architecture technologies are widely implemented and studied for environmental benefits, indicating that more studies are needed on the other levels, especially the technologies realizing the cyber, cognition and configuration functions.

Digitalized lean-related practices demonstrate an incremental innovation approach to link digitalization and environmental benefits. It would be interesting and valuable to further explore and verify this approach with more empirical studies because of lean principles' considerable maturity and extensive implementation in the manufacturing industry.

Examining the generation mechanisms of using digital technologies for environmental benefits requires further investigation, especially considering the context difference when applying digital technologies. Future research could use the three elements identified in this thesis to continue elaborating the mechanisms by examining the transformation process of digitalization to desired environmental benefits, contributing to expanding the environmental implications of using digital technologies.

6

CONCLUSIONS

Envisaging an environmentally harm-free production system in the context of Industry 4.0, this thesis identifies the environmental benefits of using digital technologies and explains the mechanisms that enable those benefits. It has contributed to identifying the potential of digital technologies for environmental sustainability from the following aspects:

- The multiple life cycles perspective of considering the environmental impact of both the product and technology life cycles provides an overview to considering both positive and negative impacts throughout the manufacturing value chain.
- The environmental benefits are mainly generated in the product life cycle, in which IoT-related digital technologies enhance material and communication efficiency. The description of where and how the benefits happen indicates the potential of technological advancement for sustainable manufacturing.
- VR's application for environmental benefits is expanded by providing remote communicators with technical details, thus reducing physical meetings and travel. The benefits may also be achieved by digitalizing lean implementations, where the intermediary role of lean in bridging digitalization and environmental sustainability could lay a foundation for commencing digital and green transition.
- The generation mechanisms entail technological functions, enabled operations and impact pathways, where the technical functions distinguish *reduced transport* as a secondary function to *tracking and monitoring*, *increased efficiency* and *dematerialization*. With that, it provides a better understanding of ***how*** to use digital technologies to strengthen the environmental sustainability of production systems.
- The context-based best practices motivating the generation mechanisms provide operational details explaining the transformation process from digitalization to desired environmental benefits.

Jointly, the findings provide industrial practitioners with implications to harness digital technologies in a more environmentally friendly manner, thus achieving smooth transitions of being both digital and green and eventually contributing to a sustainable society.

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APPENDIX I

Summary of the affecting mechanisms

No.	Digital technology	Code	Stage	Function of technology	(Guiding principles)	Enabled operation 1	Enabled operation 2	Operation category	Impact pathway	Reduced impact	Reference	Study
1	AM	A3	Production	Increase communication efficiency	/	Customize design and production	Reduce inventory of raw material and final products	Performance	Reduction	Resource, energy	Ford and Despeisse, 2016; Malshe et al., 2015	A
2	IoT and CPS	$I^{+}1$	Design	Communicate in realtime	/	Increase reconfigurability	Optimize design to reduce losses	Quality	Prevention	Energy, emission	Tucker et al., 2018	A
3	IoT and big data	$I^{+}5$	Distribution	Increase communication efficiency	/	Autonuous distribution	Reduce travel time	Performance	Reduction	Emission	Gružauskas et al., 2018	A
4	Intelligent robotics	R1	Production	Increase the precision of processes	/	Reduce the defects rate	Reduce scrap and waste	Quality	Reduction	Resource, energy	Braccini and Margherita, 2019	A
5	IoT smart sensors	I18	Production	Monitor OEE performance	/	Identify priorities and optimize energy for material handling		Performance	Optimization	Energy	Yazdi et al., 2018	A
6	Big data analytics	B1	Design	Provide options in layout design	/	Avoid mistakes in physical layout	Avoid waste	Quality	Prevention	Resource, energy	Kumar et al., 2018	A
7	AM	A1	Design	Increase prototype speed	/	Reduce time for design process		Performance	Optimization	Resource, energy	Ford and Despeisse, 2016	A
8	AM	A2	Production	Increase communication efficiency	/	Customize design and production	Reduce batches and eliminate molding	Performance	Prevention	Resource, energy		A
9	AM	A5	Production	Produce flexibly	/	Acquire precise amount of material	Increase quality level and reduce scrap	Quality	Reduction	Resource, energy, waste	Ford and Despeisse, 2016; Griffiths et al., 2016	A
10	AM	A7	Distribution	Produce flexibly and efficiently	/	Produce close to customers and create spare parts on demand	Generate less or no inventory and reduce transport	Performance	Reduction	Emission	Ford and Despeisse, 2016; Sartal et al., 2020; Annibaldi and Rotilio, 2019; Müller et al., 2018; Bonilla et al., 2018	A
11	IAI	AI1	Production	Track material, energy, water	/	Analyze data and optimize allocation	Self-regulating the allocation	Direct	Optimization	Resource, energy		A
12	Big data analytics	B2	Production	Track and collect machine data	/	Analyze data and suggest time for maintenance	Extend machine lifespan by preventative maintenance	Availability	Reduction	Resource, energy	Bonilla et al., 2018	A
13	IoT smart sensors	I7	Production	Monitor material and energy flows	/	Remove the consumption hotspots and optimize consumption		Direct	Optimization	Resource, energy		A
14	VR	V1	Design	Design product with a digital twin	/	Reduce or eliminate physical prototypes		Direct	Substitution	Resource	Zheng et al., 2018	A

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Summary of the affecting mechanisms

No.	Digital technology	Code	Stage	Function of technology	(Guiding principles)	Enabled operation 1	Enabled operation 2	Operation category	Impact pathway	Reduced impact	Reference	Study
15	IoT smart sensors	I19	Production	Track the energy consumption	/	Plan energy intensive task with natural overproduction	Increase the energy utilization rate	Direct	Optimization	Energy	Waibel et al., 2017	A
16	IoT and CPS	$I^{+}4$	Production	Track energy data	/	Provide realtime data for LCA analysis and identify key optimization areas		Direct	Optimization	Energy	Ballarino et al., 2017	A
17	IoT smart sensors	I23	Distribution	Increase communication efficiency	/	Optimize loading and routes to handle material efficiently	Reduce transport and manual work	Performance	Reduction	Emission	Bechtsis et al., 2017	A
18	IoT and CPS	$I^{+}3$	Production	Track components production	/	Detect failure and production stopage to reduce work-in-process		Quality Availability	Reduction	Energy	Song and Moon, 2017	A
19	IoT smart sensors	I21	Distribution	Increase communication efficiency	/	Enable heterogeneous resource transportation	Reduce frequencies and distance	Performance	Reduction	Emission	Song and Moon, 2017; Kiel et al., 2017	A
20	IoT and CPS	$I^{+}2$	Production	Monitor energy consumption	/	Reduce idle and process energy demand		Availability	Reduction	Energy	Thiede, 2018	A
21	AM	A6	Distribution	Produce flexibly	/	Customize production and reduce time to market	Reduce transport to market	Performance	Reduction	Emission	Sartal et al., 2020	A
22	IoT smart sensors	I4	Design	Track lifetime data	/	Optimize product design and reduce losses		Quality	Prevention	Energy, emission		A
23	IoT smart sensors	I2	Design	Communicate in realtime	/	Customize design	Respond faster and more flexible	Performance	Optimization	Resource, energy	Kiel et al., 2017	A
24	IoT smart sensors	I20	Distribution	Increase communication efficiency	/	Increase delivery accuracy	Eliminate mistakes and waiting time	Performance	Reduction	Emission	Kiel et al., 2017; Müller et al., 2018	A
25	AM	A4	Production	Produce flexibly	/	Require no tooling, cutting fluid, and lubrication		Performance	Prevention	Resource, energy, waste	Nascimento et al., 2019; Ford and Despeisse, 2016; Bonilla et al., 2018	A
26	IoT smart sensors	I12	Production	Monitor material, energy, waste	/	Locate the hotspots and optimize the process		Direct	Optimization	Resource, energy, waste	Stock and Seliger, 2016; Ghobakhloo, 2020;Braccini and Margherita, 2019	A
27	IoT smart sensors	I16	Production	Monitor energy flow	/	Increase energy consumption efficiency		Direct	Optimization	Energy	Santos et al., 2019	A

Summary of the affecting mechanisms

No.	Digital technology	Code	Stage	Function of technology	(Guiding principles)	Enabled operation 1	Enabled operation 2	Operation category	Impact pathway	Reduced impact	Reference	Study
28	IoT smart sensors	I1	Design	Communicate in realtime	/	Collaborate closer with suppliers	Enable smart scheduling and module design	Performance	Optimization	Resource, energy	Zhang et al., 2019	A
29	IoT smart sensors	I22	Distribution	Increase communication efficiency	/	Control in closed loop to enable modular design and outsource	Reduce inner logistics	Performance	Reduction	Emission		A
30		R2	Production	Handle delicate goods with sense of touch efficiently	/	Increase production efficiency		Performance	Optimization	Resource, energy	Ghobakhloo, 2020	A
31	Big data and cloud computing	B^{+}1	Production	Track and collect water and air data	/	Control and predict contamination	Prevent contamination from hazardous waste	Direct	Prevention	Hazardous waste	Junior et al., 2018	A
32	IoT smart sensors	I10	Production	Monitor environmental conditions	/	Reduce equipment and environmental related hazards		Direct	Reduction	Hazardous waste		A
33	Big data analytics	B5	Production	Track and collect product dimensions	/	Analyze data and set precise parameters	Increase quality and reduce scrap	Performance	Optimization	Resource, energy, waste	Oláh et al., 2020	A
34	IoT smart sensors	I14	Production	Monitor energy flow	/	Increase energy consumption efficiency		Direct	Optimization	Energy		A
35	Big data analytics	B3	Production	Track and collect energy data	/	Analyze data and suggest optimization	Optimize energy consumption	Direct	Optimization	Energy	Oláh et al., 2020; Bonilla et al., 2018	A
36	IoT smart sensors	I15	Production	Monitor and detect resource and energy consumption	/	Trace and analyze waste and emissions		Direct	Reduction	Resource, energy, emission, waste	Bai et al., 2020	A
37	Big data analytics	B6	Production	Track and collect resource waste	/	Analyze data and identify the root cause	Take actions to avoid waste generation	Direct	Reduction	Resource, energy, waste	Fisher et al., 2020	A
38	Big data analytics	B4	Production	Track and collect equipment data	/	Analyze data and suggest improvement	Optimize equipment's power usage	Availability	Reduction	Energy	Ang et al., 2017	A
39	IoT smart sensors	I5	Design	Track operation data	/	Monitor defects and optimize design to reduce defects		Quality	Prevention	Energy		A
40	IoT smart sensors	I6	Production	Minitor workshop machinery	/	Monitor machine breakdown	Adjust workflow	Availability	Prevention	Energy		A
41	IoT smart sensors	I8	Production	Communicate in realtime	/	Interconnect processes	Share and optimize parameter setting, stock levels, and quality issues	Performance	Optimization	Resource, energy	Ang et al., 2017; Berkhout and hertin, 2004; Sartal et al., 2020; Kiel et al., 2017	A

Summary of the affecting mechanisms

No.	Digital technology	Code	Stage	Function of technology	(Guiding principles)	Enabled operation 1	Enabled operation 2	Operation category	Impact pathway	Reduced impact	Reference	Study
42	IoT smart sensors	I9	Production	Track defects	/	Improve production processes	Reduce defects	Quality	Prevention	Resource	Ang et al., 2017; Müller et al., 2018	A
43	IoT smart sensors	I17	Production	Monitor compressors' condition	/	Optimize compressors' working and activation sequence	Enable timely maintenance	Availability	Prevention	Energy	Bonfá et al., 2019	A
44	IoT smart sensors	I11	Production	Track waste generation	/	Collect causes of waste generation	Identify actions to reduce waste	Direct	Reduction	Waste	Jagtap and Rahimifard, 2019	A
45	IoT smart sensors	I13	Production	Monitor breaks and shifts	/	Provide input to production management	Set standby or switch off	Availability	Reduction	Energy	Lins and Oliveira, 2017	A
46	IoT smart sensors	I3	Design	Track usage and recycling	/	Optimize product design	Enable eco-design with new materials	Direct	Replace	Emission	Müller et al., 2018	A
47	Simulation	$I^{+}9$	Production	Track energy consumption and emission generation	Visualization: VSM Standardization	Reduce deviations and consumption		Direct	Reduction	Energy, emission	Heilala et al., 2008; Heilala et al., 2010	D
48	IoT smart sensors	I46	Production	Monitor energy consumption	FIFO; TPM	Schedule energy efficient production		Direct	Optimization	Emission		D
49	IoT smart sensors	I47	Production	Monitor quality check based on sensors	FIFO	Improve quality check accuracy and efficiency		Quality	Optimization	Resource, energy	Amjad et al., 2021	D
50	Simulation	$I^{+}8$	Production	Track the consistency and authenticity of the registered cycle time	Visualization: VSM	Reduce deviations and working hours		Performance	Reduction	Emission		D
51	IoT and big data	$I^{+}14$	Production	Monitor resource and energy consumption	Visualization	Optimize the consumption by eliminating deviations		Direct	Reduction	Resource, energy, emission	Amjad et al., 2021; Amjad et al., 2020; Bittencourt et al., 2019; Santos et al., 2019; Castiglione et al., 2022	D
52	IoT and big data	$I^{+}16$	Production	Communicate efficiently	Communication	Support remanufacturing and recycling		Performance	Reuse	Resource, energy	Tseng et al., 2021	D
53	IoT and cloud computing	$I^{+}17$	Production	Increase production efficiency	Communication	Use resource more efficiently		Performance	Optimization	Scarce material	Khanzode et al., 2021	D
54	IAI	AI2	Production	Track data for model building	Waste elimination	Set a target and compare with actual operation	Take actions to minimize the deviations	Performance	Reduction	Resource, energy, waste	Leong et al., 2020	D
55	IoT smart sensors	I48	Production	Monitor waste generation and energy consumption	Visualization Communication	Promote efficient energy use and waste reduction		Direct	Optimization	Resource, energy	Dixit et al., 2022	D

Summary of the affecting mechanisms

No.	Digital technology	Code	Stage	Function of technology	(Guiding principles)	Enabled operation 1	Enabled operation 2	Operation category	Impact pathway	Reduced impact	Reference	Study
56	IoT smart sensors	I49	Production	Monitor waste, energy, and production efficiency	Visualization	Promote efficient production and energy use		Direct Performance	Optimization	Resource, energy, waste	Duarte and Cruz-Machado, 2017	D
57	IoT smart sensors	I50	Production	Monitor and visualize the non-value added activties	Visualization: VSM	Identify actions to eliminate or reduce NVAs by using VSM		Performance	Reduction	Resource, energy	Ferrera et al., 2017	D
58	IoT smart sensors	I51	Production	Monitor and visualize energy value stream dymanically	Visualization: VSM	Identify actions to eliminate or reduce NVAs by using VSM		Performance	Reduction	Resource, energy	Kabzhassarova et al., 2021	D
59	IoT smart sensors	I52	Production	Monitor lot size, stock, delivery	Visualization: Kanban	Reduce inventory by monitoring material movement		Performance	Reduction	Energy		D
60	IoT smart sensors	I54	Production	Monitor and visualize resource and energy	Visualization	Promote more efficient resource and energy use		Direct	Optimization	Resource, energy	Kabzhassarova et al., 2021; Yilmaz et al., 2022	D
61	IoT smart sensors	I53	Production	Monitor data and visualize stock level dymanucally	Visualization: VSM	Identify actions to reduce and control the stock level		Performance	Reduction	Energy	(Mesquita et al., 2021)	D
62	IoT smart sensors	I56	Production	Monitor energy, water, pollutant, emission	Visualization: VSM	Identify actions to reduce water and energy consumption		Direct	Reduction	Energy, emission, waste		D
63	IoT and big data	I$^+$15	Production	Monitor production, inventory, line stoppage, machine breakdown	Visualization	Reduce and eliminate waste activities		Availability	Reduction	Resource, energy,emission		D
64	AM	A8	Production	Customize production	Inventory	Source and deliver timely	Require less inventory	Performance	Optimization	Resource, energy		D
65	Big data	B7	Production	Track environmental KPIs	Kaizen	Identify deviations with data analytics	Minimize the deviations	Direct	Reduction	Resource, energy, waste		D
66	Simulation	I$^+$10	Production	Track energy and resource consumption	Visualization: VSM Standardization	Reduce deviations and consumption		Direct	Reduction	Resource, energy	Yilmaz et al., 2022	D
67	Simulation	I$^+$11	Production	Track gas and electricity consumption	Visualization: VSM Standardization	Optimize consumption by comparing two alternatives		Direct	Optimization	Emission		D
68	Simulation	I$^+$12	Production	Collect and monitor data for material flow	Waste elimination: transport Kanban	Optimize material handling flow	Optimize transport routes by planning milk-run	Performance	Optimization	Emission		D
69	Simulation	I$^+$13	Production	Track energy consumption	Poka-yoke Jidoka	Reduce and eliminate deviations	Reduce energy consumption	Direct	Reduction	Energy, emission		D

Summary of the affecting mechanisms

No.	Digital technology	Code	Stage	Function of technology	(Guiding principles)	Enabled operation 1	Enabled operation 2	Operation category	Impact pathway	Reduced impact	Reference	Study
70	IoT smart sensors	I55	Production	Monitor and visualize water and energy consumption and waste generation	Visualization: VSM	Identify actions to reduce consumption and waste		Direct	Reduction	Resource, energy, waste	Phuong and Guidat, 2018	D
71	IoT smart sensors	I57	Production	Train with digital instruction	Visualization: Standardization	Train efficently, waste-free and paper-free		Performance	Substitution	Resource, energy, waste	Kurdve, 2018	D
72	IoT smart sensors	I24	Design	Track running condition	/	Provide input to improve design	Extend product lifetime and reduce defects	Quality	Optimization	Resource, energy	Case	B
73	IoT smart sensors	I25	Production	Communicate in realtime	/	Minimize inventory level by pulling material	Reduce stock and inventory space	Performance	Reduction	Resource, energy	Case	B
74	IoT smart sensors	I26	Production	Monitor the temperature of furnaces	/	Control better the product parameters	Increase product quality and reduce scrap	Quality	Optimization	Resource, energy	Case	B
75	IoT smart sensors	I27	Production	Monitor machine running status	/	Visualize the categorized status	Notify disturbances and reduce MTTR	Availability	Reduction	Energy	Case	B
76	IoT smart sensors	I28	Production	Barcode on the pallets	/	Scan and register information to the system	Replace attached paper on pallets	Performance	Substitution	Resource	Case	B
77	IoT smart sensors	I29	Production	Monitor grinder approaching workpiece	/	Adjust work speed and feedrate	Reduce efficiency loss	Performance	Optimization	Resource, energy	Case	B
78	IoT smart sensors	I30	Production	Monitor and track energy consumption	/	Schedule products with same heating requirement	Reduce the change of temperature	Direct	Optimization	Enegry	Case	B
79	IoT smart sensors	I31	Production	Monitor and track energy consumption	/	Regulate the temperature by recovering energy	Reducing sourcing energy	Direct	Reuse	Energy	Case	B
80	VR	V2	Design	Prototype virtually	/	Communicate efficiently	Reduce lead time, resource and energy	Performance	Substitution	Resource, energy	Case	B
81	VR	V3	Design	Communicate virtually	/	Increase understanding between designer and manufacturing site	Reduce physical travel for design review	Performance	Substitution	Emission	Case	C
82	IoT and cloud computing	$\text{I}^{+}7$	Production	Work with interactive instruction	Visualization Standardization Waste elimination: scrap	Ensure correct operations	Increase efficiency and reduce defects	Performance Quality	Optimization	Resource, energy	Case	D-A
83	IoT smart sensors	I32	Production	Monitor material consumption	Visualization	Estimate waste	Reuse waste for new business	Direct	Reuse	Resource, energy	Case	D-A

Summary of the affecting mechanisms

No.	Digital technology	Code	Stage	Function of technology	(Guiding principles)	Enabled operation 1	Enabled operation 2	Operation category	Impact pathway	Reduced impact	Reference	Study
84	IoT smart sensors	I33	Production	Monitor scrap rate	Waste elimination: defects visualization	Track and analyze the cause for scrap rate	Take actions to reduce scrap rate	Quality	Reduction	Resource, energy	Case	D-A
85	IoT smart sensors	I40	Production	Communicate timely with customers	Communication	Plan the reuse of products	Avoid new production	Performance	Reuse	Resource, energy	Case	D-A
86	IoT smart sensors	I41	Production	Train with digital instruction	Visualization Standardization	Standardize training procedures	Reduce production line occupacy	Availability	Optimization	Resource, energy	Case	D-A
87	IoT smart sensors	I43	Distribution	Increase communication efficiency	Waste elimination: transport Communication	Optimize delivery with fully loaded trucks	Reduce transport	Performance	Optimization	Emission	Case	D-A
88	IoT smart sensors	I44	Distribution	Monitor metal chips	Waste elimination: transport Communication	Notify recycling company for picking up	Plan milk-run to reduce transport	Performance	Optimization	Emission	Case	D-B
89	IoT smart sensors	I34	Production	Track cutting tool storage	Visualization: Kanban	Notify the system when demand changes	Minimize tooling stock	Performance	Prevention	Resource, energy	Case	D-B
90	IoT smart sensors	I35	Production	Monitor the machine status	Visualization Communication Waste elimination: waiting	Notify with error code when machine stops	Reduce waiting time	Availability	Reduction	Resource, energy	Case	D-B
91	IoT smart sensors	I36	Production	Track cutting tool usage	Communication : Poka-yoke	Predict and notify tool change	Open only the corret tooling and avoid mistaken	Performance	Prevention	Resource, energy	Case	D-B
92	IoT smart sensors	I42	Production	Communicate efficiently between operator and tooling storage	Poka-yoke	Open only the correct storage box	Prevent errors and over-taking	Performance	Optimization	Resource, energy	Case	D-B
93	IoT and AR	I†6	Production	Interact by voice instruction	Waste elimination: defects standardization	Operate efficiently and avoid mistakes	Avoid defects	Quality	Optimization	Resource, energy	Case	D-C
94	IoT smart sensors	I37	Production	Monitor the temperature and heat generation	Visualization	Recover, clean and reuse for office heating		Direct	Reuse	Energy	Case	D-C

Summary of the affecting mechanisms

No.	Digital technology	Code	Stage	Function of technology	(Guiding principles)	Enabled operation 1	Enabled operation 2	Operation category	Impact pathway	Reduced impact	Reference	Study
95	IoT smart sensors	I38	Production	Monitor the air quality	Visualization Standardization	Ensure air quality to meet the requirement	Eliminate scrap due to cleanliness problem	Quality	Prevention	Resource, energy	Case	D-C
96	IoT smart sensors	I39	Production	Monitor the spindle condition	Waste elimination: Defects, waiting	Notify spindle change and call maintenance	Eliminate waiting time and scrap	Availability Quality	Prevention	Resource, energy	Case	D-C
97	IoT smart sensors	I45	Distribution	Monitor waste filling level	Waste elimination: transport Visualization	Notify recycling companies to replace waste bin	Plan milk-run to reduce transport	Performance	Optimization	Emission	Case	D-C