Connecting Digitalisation and Research and Development to Green Production: A Green Link?

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Abstract

There is an increasing interest in sustainability practices for organisations. Industry 4.0 promises to enable organizations to act more sustainably. The growing use of technologies allows manufacturing companies to introduce green processes to reduce the impact of production on the environment and to obtain a competitive advantage. However, few empirical studies focus on digitalization during Industry 4.0 and its implications for green production while factors such as R&D and interoperability. Therefore, this study focuses on the relationship between digitalization and green production including R&D and interoperability as moderators. This study also investigates whether R&D has a direct effect on green production. Different R&D and managing interoperability approaches are studied to gain insights into the best ways to practice both concepts. A mixed-method approach is being applied within this study, meaning that a quantitative and qualitative research method is used. Besides using a database from the European Manufacturing Survey, six interviews were conducted targeting Dutch manufacturing companies.

The results show that digitalization in itself positively stimulates green production. For R&D and interoperability as moderators, results in quantitative and qualitative research differ. Although for the direct impact of R&D, both types of research show a positive relationship. Additionally, qualitative research made clear that a combination of both R&D approaches is best for performance. A continuous improvement as a management style for interoperability seemed preferable over a radical change approach. This research contributes to the academic literature by adding R&D and interoperability to the relationship between digitalization and green production and focusing on their approaches to stimulate green production. The results call attention to how and why managers need to perceive R&D and interoperability for practicing green production.

Keywords: *Digitalisation – Industry 4.0 – Green production – R&D modes – Interoperability*

Preface

This thesis is written by Tom Kessels, to complete the Master's program of Strategic Management at the Radboud University in Nijmegen. This thesis marks the challenging yet rewarding journey of studying at this university. It was a wonderful journey that helped me grow academically, intellectually, and mentally. I learned lessons, got to meet a lot of new people, and experienced different cultures all along. I'm thrilled to announce that my journey as a student will be extended for six months at the Tor Vergata University in Rome. I will increase my knowledge by following additional courses from the Master's track of Business Administration at the School of Economics. Because this is and will be my last big project as a student, I would like to acknowledge and thank multiple individuals who have supported and motivated me to reach this achievement during my journey.

First, I would like to express my appreciation to my thesis supervisor, Dr. P.E.M. Ligthart, for helping me with my research project. Besides being my supervisor for my Master Thesis, you were also my supervisor for my Bachelor Thesis. Therefore, I would like to thank you personally for guiding me through both projects and having a significant positive impact on my academic journey as a student.

Secondly, I would like to thank the participating Dutch manufacturing companies who helped me to get a sufficient amount of interviews and provided me with useful data to do research. I hope that participating in this research was useful and that the highlights will help your company to have better performances for digitalization and green production.

Finally, I would like to show my appreciation to my friends, family, and my girlfriend for being in my life throughout this period. A big thank you to my friends, for having a laugh and helping to clear my mind when needed. Thank you to my dad for driving countless times back and forth from Eindhoven to Nijmegen. Thank you to my sister and brother-in-law for giving me a second home and helping me when needed. Last but not least, I would like to thank both my mom and my girlfriend for the unconditional love and support I received.

Completing this thesis was a collective effort and I appreciate all the contributions and support I have received. Thank you all.

Tom Kessels,

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Content

1. Introduction

The environmental concern in the world is rising because of problematic ecological catastrophes caused by high pollution (Viswanathan & Varghese, 2018). The pressure on society including companies is increasing to act sustainably and change their behaviour to reduce e.g. greenhouse gas emissions and waste (Lange et al., 2020). Companies can be part of a solution to this problem by initiating green practices in their business model (Andiç et al., 2012; Patidar et al., 2022). These practices can for example be applied to their supply chain management processes resulting in green purchasing, green manufacturing, and green logistics (Feng et al., 2022; Trujillo-Gallego et al., 2022). Green manufacturing or green production is defined by D'Angelo et al. (2022) as: "environmental consciousness in production and related interventions, such as employing a broader range and quantity of green renewable resources of energy and engaging in green supply chains" (p. 2). Green production covers the 6Rs (reduce, reuse, recycle, recover, redesign, and remanufacturing) and includes practices such as green products, eco-designing, and end-of-life management (Seth et al., 2018). In the context of this, recent literature has shown that high levels of green production have effects on factors such as environmental, operational, and financial performance (Bai et al., 2020; D'Angelo et al., 2022; Rupa & Saif, 2022). Thus showing the importance of successful green production resulting in benefits for the company itself and society (Mao & Wang, 2019). Verma et al. (2022) found that digitalisation and research and development (R&D) investments are contributing to green production performances. Digitalisation and R&D help create new or developing current production processes that reduce energy consumption, waste, and emission and therefore stimulate sustainability (Ben Khalifa, 2023; Verma et al., 2022).

Digitalisation can be used to optimise the business models and strategies of companies that are operating in a highly competitive and dynamic environment (Malacina & Teplov, 2022). Digitalisation improves analytics, customer experience, collaboration, and communication and creates new revenue streams and opportunities for market spaces (Bleicher & Stanley, 2017). Thus stimulating competitiveness, decision-making, strategic directions and business model improvements (Cohen et al., 2017; Elhamma & El-Moumane, 2023; Li et al., 2018). According to Brennen & Kreiss, (2016), digitalisation can be defined as: "The adoption or increase in the use of digital or computer technology by an organization, industry, country, etc." (p. 6). Digitalisation can be applied by companies in their products, services, and business processes (Liu et al., 2023). This study focuses on the use of digitalisation and the technologies in the production process within companies. In the current Industry, 4.0 different technologies such as CPS, IoT, IoS, cloud, AI and big data are crucial for leveraging digitalisation in production processes (Frank et al., 2019; Liu et al., 2020). It provides quality, reliable production, and problem-solving and helps with (re)designing and analysing the manufacturing system

(Verma et al., 2022). Digitalisation in production could reduce costs, increase efficiency and knowledge and therefore stimulate organisations financial performance (Kannan et al., 2022). If not implemented well, digitalisation has detrimental effects such as increased costs and inefficiency (Philbin et al., 2022). Thus digitalisation can be seen as one of the most important tools for companies to boost their overall performance (Kohtamäki et al., 2020; Liu et al., 2023).

As digitalisation and green production are both very popular topics, recent papers have also been discussing the relationship between both phenomena (Lerman et al., 2022; Trujillo-Gallego et al., 2022; Wei & Sun, 2021). This remains unclear hence multiple papers highlighting a positive relationship (Matt et al., 2023; Philbin et al., 2022; Trevisan et al., 2023) but also a possible negative relationship (Braccini & Margherita, 2019; Kayikci, 2018; Kunkel & Tyfield, 2021). This relationship is highly affected by the interoperability or integration of implemented technologies. Interoperability is defined by Verma et al. (2022) as: "the ability of different devices and technologies to communicate and connect (sensors, devices, machines, etc.) and have meaningful human/machine interpretation performance" (p. 12). This interconnectedness or interoperability of technologies creates synergies by stimulating productivity, efficiency, and reliability (Kamble et al., 2018). Without well-managed interoperability between technologies, negative green production outcomes could arise which consists of a 'rebound effect' (Font Vivanco et al., 2022; He & Xie, 2022). Compared to well-managed interoperability, it would lead to increased inefficiencies, costs, energy consumption, emissions, and waste (Andreoni & Anzolin, 2019).

Interoperability can be managed based on two perspectives: the radical changes perspective and the continuous improvement perspective (Martinez, 2019). The radical changes perspective wants to achieve interoperability by implementing more technologies in a shorter timeframe, leading to more benefits but is likely to face more complex challenges related to interoperability (Martinez, 2019). These challenges could be a lack of knowledge, change in needed employee skills, and data security (Cohen et al., 2019). The continuous improvement perspective takes the implementation more slowly and therefore misses out on benefits but faces easier or less interoperability challenges (Cohen et al., 2019). Interoperability and managing this is, therefore, an important element in the relationship between digitalisation and green production. Despite the importance, the interoperability between technologies and their effects on green production has not been established yet. There is no understanding of which technologies create more synergy in green output than other technologies. The specialized literature that focuses on the relationship with connected technologies is scarce and the existing studies suggest a relation without any empirical validation (Tortorella & Fettermann, 2018). Research needs to be done to examine these interconnections between technologies and their impact on green production (Dionisio & Paula, 2024).

Besides the connection between digitalisation and green production, research shows that R&D and green production also have a relationship (Martin & Nguyen-Thi, 2015). Kainulainen (2014) defined R&D as: “systematic activities to increase knowledge and use of this knowledge when developing new products, processes, or services” (p. 5516). R&D can therefore be used as a way of improving or creating green production in a company (Jabbour et al., 2016). In the paper of Jensen et al. (2007), there are two modes of innovation mentioned that are central to R&D: STI (Science, Technology, and Innovation) and DUI (Doing, Using, and Interacting). STI mode is based on the use of scientific and technical knowledge while DUI relies on learning and experience-based know-how (Jensen et al., 2007). STI and DUI have different impacts on innovations (Alhusen & Bennat, 2021), and the process innovations related to green production (Ben Khalifa, 2023). This leads to different outcomes in studies which find a positive (Baek & Lee, 2024; Paramati et al., 2021; Shen & Lin, 2020), or no significant relationship (Wang & Zhang, 2020) between R&D and green production. This shows the importance of different R&D modes in the relationship between R&D and green production. However, little to no research has directly focused on the different innovation modes and their direct impact on green production. To get a broader understanding of this relationship, more research needs to be done on this topic (Santos et al., 2022).

This research contributes to the current academic literature by providing knowledge about the interoperability of different technologies and their impact on green production outcomes. As already mentioned, current literature shows a lack of knowledge about the interoperability of these technologies and the way of managing this, resulting in studies with different outcomes about digitalisation and green production. This study gives insight into these phenomena and clarifies the relationship. Additionally, the study will provide knowledge about how R&D based on the different innovation modes (STI and DIU) are impacting green production outcomes. Literature shows a relationship between R&D and green production but does not focus on these specific innovation modes. By considering this, the study will clarify earlier research outcomes between R&D and green production. It explains why there would be a positive or no significant relationship.

Besides the importance of this research because of the academic value, the acquired knowledge will also have useful practical implications. This study highlights the importance of the interoperability of different technologies and R&D innovation modes on the impact of green production. The knowledge will be valuable for companies who want to implement digitalisation and want to effectively create green production. It can be of use by optimising, analysing, and monitoring green production in the company. Newly acquired knowledge could also be used for additional justification for decision-making regarding green production or supply chain decisions. Apart from an organisational perspective, this study is also valuable for policymakers who use industrial strategies and environmental plans to create a long-term policy that suits both society and industry (Trujillo-Gallego et al., 2022; Umar et al., 2022). With the knowledge this study provides, it will contribute to a better environment, society, and performance of companies (Chen et al., 2023).

The study provides knowledge insights regarding the relationship between digitalisation and green production which is of academic and practical relevance and directly of use in real-world applications. The main problem in this study is the lack of knowledge about the interoperability of technologies and R&D approaches with their impact on green production. Studies show positive (Lerman et al., 2022; Trujillo-Gallego et al., 2022) and negative relations (Lange et al., 2020; Niehoff, 2022) between digitalisation and green production with interoperability and its management as an important factor influencing this (Dionisio & Paula, 2024; Martinez, 2019). For the impact of R&D, there is a positive (Baek & Lee, 2024; Paramati et al., 2021) and no significant relationship in the literature (Wang & Zhang, 2020). The different R&D modes and their characteristics are impacting these outcomes (Alhusen & Bennat, 2021; Ben Khalifa, 2023), but little research has focused on this direct relationship and its implications (Santos et al., 2022). This would suggest that both interoperability and R&D approaches are influencing green production. After having addressed the main problem, the research question can be formulated which will be the focus of this study. The research question is as follows: *"What is the impact of digitalisation, interoperability, and R&D on green production? And how could interoperability and R&D best be organised?"*

Outline of the thesis

In the upcoming chapters of this study there first will be a theoretical background given for the most important concepts. After these are outlined and there is enough information provided, hypotheses will be based upon the information of recent literature. Furthermore, the design/methodology/approach of this study will be explained. It will provide a detailed description of how the study will be conducted and information will be gathered to answer the research question of this study. The results will be collected and written down to give a clear overview of what information is available. In the conclusion of this study, the results will be summarised to be able to provide an answer to the research question. The last chapter will be the discussion to reflect on the conclusion with current literature. Also, the limitations of this study and directions for future research will be mentioned at the end of the last chapter.

2. Theoretical Background

The Theoretical Background section discusses the theory of the main concepts to get an idea of what can be found in the current literature. First of all, it focuses on the concept of green production. This is followed by the relationship between digitisation and sustainable production focusing on the different stages of production and the role of interoperability. Moreover, the concept of R&D will be discussed, its relation to green production, and as a moderator for digitalisation and green production. The last main concept will be interoperability and its role as a moderator for digitalisation and green production. The chapter ends with a hypothesis development to summarise the current literature and what will be tested in the empirical phase.

2.1 Green Production

In the article of Toke & Kalpande (2019) Green Production (GP) is defined as: "minimising environmental impact by reducing toxins, waste, pollution, optimising use of raw material and energy by applying end of life (EOL), cradle to cradle and close loop approach". The history of green production dates back a few decades ago with the first research published in 1996 (Luo et al., 2018). After the introduction of ISO 14001, the concept of GP has become more prominent in society. ISO 14001 forced the manufacturers to come up with effective environmental management systems including GP practices (Kannan et al., 2022). Several other agreements such as the Paris Agreement and the UN 2030 agenda, encourage companies to practice GP stimulating positive sustainability outcomes (Jin et al., 2022). Over the last few years, consumers and other stakeholders also demanded more manufacturing companies practice GP and be more environmentally conscious (Kannan et al., 2022). Given multiple sustainable strategies, GP is effective in reducing environmental impacts and achieving the desired sustainable development goals (SDGs) (N. K. Sharma et al., 2021). It supports the development of various sustainable strategies within the manufacturing sector which results in different integration perspectives of GP. Those strategies include lean, agile, and sustainable manufacturing (Kannan et al., 2022).

For practicing GP in manufacturing companies, the research identified multiple barriers (Ghazilla et al., 2015; Jabbour et al., 2016; Karuppiah et al., 2020; Mao & Wang, 2019; Rupa & Saif, 2022). The research of Kannan et al. (2022) showed that there are five main categories of barriers or challenges that companies can influence. Challenges related to the environment (e.g. green design and environmental management systems), organisation (e.g. education/training, market/resource management, and stakeholder involvement), economy (e.g. capital investments, increasing prices), governance (e.g. support and policy) and society (e.g. reputation and perceptions) could impact companies GP practices and outcomes (Kannan et al., 2022). Furthermore, multiple studies show that a lack of R&D investment is a main challenge that organisations need to face (Ghazilla et al., 2015; Karuppiah et al., 2020; Rupa & Saif, 2022). In the article by Seth et al. (2018), it is shown that the size of the company (SME or large firms) can have differences in barriers. The lack of resources, governmental support, or the low impact on the environment is more related to SMEs than to large firms (Seth et al., 2018). Contrary, reputation and the amount of pollution are for large firms more impactful barriers. Other barriers to implementing GP are Poor management, lack of technical support, lack of guidelines, high costs, resistance to change, uncertainty, and competition (Ghazilla et al., 2015; Jabbour et al., 2016; Karuppiah et al., 2020; Rodriguez & Weingarten, 2017; Rupa & Saif, 2022).

As opposed to the highlighted barriers and challenges of implementing GP, research also identified drivers for implementing GP practices (Ghazilla et al., 2015; Seth & Rehman, 2022; L. Shen et al., 2013). Environmental awareness, competitiveness, stakeholder involvement, and management commitment are all important drivers (Seth & Rehman, 2022). Ghazilla et al. (2015) added the importance of customer demands and Shen et al. (2013) identified also reputation as an important driver for GP. By comparing the barriers and drivers, it can be concluded that multiple barriers could be drivers and vice versa. Therefore it is relevant that these barriers and drivers such as management commitment, stakeholder involvement, and environmental awareness are being acknowledged and optimised in the company's favor. Leveraging these impacts will result in optimal GP practices thus maximizing the benefits of GP for the company and its environment (Kiel et al., 2017). Rupa & Saif (2022) found that benefits related to GP practices have a significant impact on cost, waste disposal, resource consumption, and greenhouse gas emissions. Other positive consequences are a reduction in resources, higher sales, improved green image, and competitiveness and leadership (Bhatia & Jakhar, 2021; Gandhi et al., 2018; Gedam et al., 2021). Also, the supply chain partners of the company that implements GP can benefit from these practices (Liu et al., 2019). The benefits of integrating green manufacturing in the manufacturing sector have given rise to companies in all sorts of industries (Kannan et al., 2022).

As aligned with the definition of Toke & Kalpande (2019), GP includes making or creating products/systems that consume fewer materials, less energy, substituting input materials (non-toxic for toxic, renewable for non-renewable) reducing unwanted outputs, wastes, emissions, and converting outputs to inputs (recycling) (Seth et al., 2018). This combination of actions is understood as initiatives and techniques that positively affect the environmental, social, or economic performance and help to mitigate the impacts of the firm's operations in the triple bottom line (Alayón et al., 2017). These GP practices can be used in the three stages of the production process: input, throughput, and output (Cho et al., 2023). Splitting the production processes into categories gives companies a better understanding of the GP process (Cho et al., 2023). The input refers to the resources and materials at the beginning of the production process including raw materials, energy, and water. Applying a green or sustainability perspective is essential to create a green input stage for the production process of the manufacturer (Deif, 2011). This would lead to the usage of less needed energy, water, and raw materials (Verma et al., 2022). The throughput refers to the actual process of the transformation from raw materials to finished products with all the activities included. This would include emissions, energy consumption, and waste. The output refers to the final product with waste or emissions as by-products. This stage is often overlooked because there is more focus on actually producing in a sustainable way instead of the sustainability of the product. The output stage can contribute to GP by sustainable products, reducing the ecological footprint, and having a positive impact on the environment (Lerman et al., 2022). While each stage presents opportunities for implementing GP practices, it is important to apply GP practices to all categories for better performances and maximized benefits (D’Angelo et al., 2022).

2.2 Digitalisation

2.2.1 Digital Technologies

The type of various digital technologies implemented depends on the production stage and the GP practices a company wants to execute. The main digitalisation technologies which are being used in the input and output stage are the Internet of Things (IoT), Big Data, and Cloud (Frank et al., 2019). IoT is an emerging industrial ecosystem that facilitates the combination of intelligent machines, advanced predictive analytics, and machine-human collaboration (Koh et al., 2019). This includes physical devices enriched with embedded electronics (sensors, actuators, radio frequency identification, etc.) to a network or internet (Kamble et al., 2018). Big Data is obtaining advanced data that improves decision-making by using analytics (Koh et al., 2019). Cloud technology can be used to capture and save huge amounts of data which can be used for Big Data analysis to boost organisations performance (Mitra et al., 2017). Data Analytics is a way to analyse the large amounts of data generated during the throughput and the output stage (Koh et al., 2019). This data is generated by technologies such as IoT, Big Data, other ICT systems, or digital machines which store data (Wang et al., 2022). Data Analytics is used within companies to support decision-making and to predict future scenarios (Kamble et al., 2018).

Digital technologies that are often being used in the throughput stage are automated machines and Robotics, Digital Twins, 3D printing and Augmented (AR), and Virtual Reality (VR). Robotics are characterised as systems that offer autonomy, flexibility, and cooperation (Kamble et al., 2018). Robotic systems can be used individually but also interact with other robotic systems and humans (Fengque et al., 2017). A Digital Twin is defined by Mihai et al. (2022) as: “a system-of-systems which is a replication of all the elements, processes, dynamics, and firmware of a physical system into a digital counterpart” (p. 2255). The two systems (physical and digital) exist side by side, sharing all the inputs and operations using real-time data communications and information transfer (Pylianidis et al., 2021). AR is referred to as a physical environment, whose elements are augmented with and supported by virtual input and VR is referred to as a simulated virtual environment, representing a physical environment (Noghabaei et al., 2020).

2.2.2 Digitalisation and Green Production

When applying these digital technologies to the production process, multiple articles highlight the negative effects of implementing IoT, Big Data, and Cloud (Gensch et al., 2017; Lange et al., 2020; Sarkis et al., 2020). These papers suggest that the use of ICT technologies such as IoT and Big Data, has high energy demand and therefore increases energy consumption (Niehoff, 2022). With the expectation that the overall share of ICT-related will increase further over the next few years, GP performance could be heavily impacted (Gensch et al., 2017). The increasing use of IoT and Big Data could also result in possible rebound effects (Kunkel & Tyfield, 2021). This would mean that greater efficiencies in resources result in greater consumption and increasing pressures on the environment and the planet (Sarkis, 2019). Companies need to compare the positives and the negatives of the implemented technologies to see if the positives outweigh the negative impacts on GP.

Gensch et al. (2017) and Lange et al. (2020) and multiple other studies show that digital technologies related to the throughput stage could negatively affect GP performance (Beier et al., 2017; Itten et al., 2020; Soltovski et al., 2022). Implementing these technologies would lead to high energy consumption for production operations (Kunkel & Matthess, 2020; Soltovski et al., 2022), emission risks (Kayikci, 2018; Li et al., 2020) and increased electronic waste due to machinery replacement (Kayikci, 2018; Kunkel & Matthess, 2020). Due to new equipment, transportation, and the use of primary energy for technology operations, the consumption of digital technologies generates carbon emissions (Verma et al., 2022). Companies should take into consideration the negative effects related to this stage of the production process. When implementing too many non-useful digital technologies, negative GP performances will occur (Soltovski et al., 2022).

The articles of Braccini & Margherita (2019) and Li et al. (2020) suggested that IoT, Big Data, and Cloud contributed to the GP performances of a manufacturing company. These technologies generate and capture useful information for companies to reduce their resource and energy consumption (Isensee et al., 2020). Big data analysis affects innovative business practices in terms of green manufacturing, waste manufacturing, and efficient manufacturing (Xue et al., 2022). It forces companies to maximize the use of resources to reduce the possibility of environmental pollution and efficiently implement circular economy practices (Xue et al., 2022). IoT can impact GP through effective monitoring of used resources, transforming operations and processes, lowering costs and fostering efficiency, with the potential to benefit the natural environment (N. Xu et al., 2022). The effects of the interoperability and connectedness of IoT and Big Data technologies could compensate for the possible negative effects or rebound effects of the implemented digital technologies. IoT is mainly used to capture data by monitoring the production process through intelligent machines making use of embedded electronics. Big Data can use this data to analyse critical points for improvements to increase the current production process and GP performances.

The use of digital technologies such as Robotics, Digital Twins, 3D printing, AR, and VR have multiple benefits for the throughput stage of a production process. Implementing robots will offer a cost advantage and an excellent range of capabilities, performing most of the processes in the intelligent factory (Fengque et al., 2017). The benefits of Digital Twins applications include reduced production times and costs, hiding the complexity of integrating heterogeneous technologies, creating safer working environments, and establishing more environmentally sustainable operations (Pylianidis et al., 2021). Lastly, AR and VR can support workers with simulation of training, maintenance routines, and creating prototypes (Frank et al., 2019; Guo et al., 2018). These technologies optimise the production process mainly in the throughput stage by process optimisation, better supply chain management, and increased quality control. Therefore results in less energy consumption, reduced amount of waste, and ecological footprint contributing to better GP performances (Karuppiah et al., 2020). Accordingly, Wiegand & Wynn (2023) highlighted the importance of 3D printing, AR, and VR for creating a circular economy. This suggests that all digital technologies related to every stage of the production process are involved in creating fully recyclable products (Wiegand & Wynn, 2023).

In summary, the literature suggests a positive relationship between Digitalisation and Green Production in the various production stages. Therefore, we propose the following hypothesis to be tested in the empirical analysis section:

H1. *There is a positive relationship between Digitalisation and Green Production in all various production stages.*

2.3 Research and Development

2.3.1 Research and Development

R&D activities can be taken as a starting point for the analysis of innovative activities across firms (Mairesse & Mohnen, 2004). R&D activities, both external and internal, are widely recognised as being the drivers of technological advancements. The levels of growth of R&D expenditures are considered to be reliable indicators of innovative capacity (Martin & Nguyen-Thi, 2015). Innovation is a cumulative and interactive learning process, requiring more than firm-internal knowledge dynamics and therefore a combination of different resources and the involvement of a variety of actors (Grillitsch & Rekers, 2016).

Based on the article of Jensen et al. (2007), a clear distinction has been made between STI and DUI type of R&D approaches. STI (science-technology-innovation) is based on the creation and use of scientific and technical knowledge, that is usually codified and based on know-what and know-why (Alhusen & Bennat, 2021; Radicic & Petković, 2023). This type of knowledge is also known as analytical knowledge, which is mostly developed in private and public R&D departments and labs (Alhusen & Bennat, 2021; Jensen et al., 2007). Firms engage in internal R&D activities to exploit this type of knowledge, which is likely to result in superior product characteristics or a significant increase in production efficiency, thus leading to the successful commercialization of new products and processes (Rammer et al., 2009). The STI approach is generally associated with the production of radical innovations (Nunes & Lopes, 2015). Radical innovation is defined by Chandy & Tellis (2000) as: “a new product or process that incorporates a substantially different core technology and provides substantially higher customer benefits relative to previous products or services in the industry” (p. 2). The dependence of innovation on external sources increases as the complexity and radicalness of knowledge and processes increase (Kobarg et al., 2019).

The DUI (doing-using-interacting) innovation approach relies on the use of mostly tacit and synthetic knowledge with a focus on know-how and know-who (Alhusen & Bennat, 2021; Jensen et al., 2007). Learning is more informal and conducted through doing, using, and interacting as a holistic concept of innovating (Alhusen & Bennat, 2021). Studies aim to measure DUI innovativeness based on a firm’s internal or external interactions, using indicators of either learning-by-doing, -using and -

interacting as representative for the DUI mode of innovation (Alhusen et al., 2019; Parrilli & Alcalde Heras, 2016). Learning-by-doing results from work experience and increasing skills in production (Fergusson, 2022), using feedback from users and their involvement in improving products and services (Jensen et al., 2007). Innovation outputs are often incremental productivity gains, such as cost reductions or quality improvements (Fertig, 2018). Chandy & Tellis (1998) defined incremental innovations as: "innovations which involve relatively minor changes in technology and provide relatively low incremental customer benefits per dollar" (p. 476). Incremental innovations are less risky and involve lower uncertainties than radical innovation, thus reducing the need to share the risks and resources for innovation (Kobarg et al., 2019).

2.3.2 Impact of Research and Development on Green Production

The literature that focused on the relationship between R&D and the environment, thought that technological progress by R&D practices could eliminate resource scarcity (Shen & Lin, 2020). These studies mainly focused on R&D, technological knowledge spillovers, renewable energy, energy consumption, and CO2 emissions (Paramati et al., 2021). As already mentioned in section 2.1, CO2 emissions renewable- and energy consumption are elements contributing to and therefore stimulating GP. By analysing current literature and providing a theoretical background focusing on these elements of GP, the relationship between R&D and GP can become more clear.

In the article of Fei et al. (2014), the relationship between technological innovations and energy consumption was investigated. Their findings indicate that technological innovations have the least impact on reducing fossil fuel electricity consumption. Other studies claim that if the R&D technological innovations reduce energy consumption only marginally, this may not lead to any sizeable reduction in the share of energy in CO2 emissions (Paramati et al., 2021). Petrović & Lobanov (2020) found that the relationship between R&D and carbon emissions is neutral in the short run. Additionally, Koçak & Ulucak (2019) also found that R&D has no significant impact on reducing carbon emissions. In the research of Wang & Zhang (2020), the environmental regulation policy about GP was studied. No significant relationship between R&D and GP was found, which is in line with the outcomes of previously mentioned studies.

A reason for the negative or non-significant relationship would be the huge amount of R&D practices required for stimulating GP (Kamble et al., 2018; Kayikci, 2018; Verma et al., 2022). Moreover, Grover & Kohli (2013) suggested the existence of a minimum investment threshold. Within R&D, this is more related to the STI mode of innovation resulting in radical innovations. These 'high risk, high reward' innovations require more financial capital than the DUI mode innovations (Kobarg et al., 2019). The high amount of capital needed for R&D practices combined with the high risk is problematic for companies (Kamble et al., 2018), especially for SMEs due to often limited available financial resources (Seth et al., 2018). Another reason for negative or non-significant outcomes between R&D and GP is the inverted U-shape between R&D investments and innovation outcomes (Ravichandran et al., 2017). This U-shape relation highlights the diminishing returns to R&D investments. R&D can have an inverted U-shaped relationship with innovation because innovation from R&D may be increasing linearly, and the diseconomies or costs may escalate rapidly following an exponential curve (Ravichandran et al., 2017). Therefore, ending up with an inverted U-shaped relationship.

Besides a negative or non-significant relationship between R&D practices and GP, multiple studies show a positive relation between the two phenomena (Baek & Lee, 2024; Paramati et al., 2021; Shen & Lin, 2020). Research suggests that technological innovations help reduce electricity consumption significantly (Alam et al., 2019; Shen & Lin, 2020; Tang & Tan, 2013). The important channel through which R&D promotes renewable energy is technological knowledge development and spillovers (Miremadi et al., 2019). Therefore, the study underscores the importance of technological innovations toward decreasing fossil fuel consumption while ensuring environmental quality and stimulating GP performances. Multiple findings revealed that technological innovations make a significant contribution by increasing renewable energy consumption on one hand and minimizing CO2 emissions on the other hand (Baek & Lee, 2024; Fei, Rasiah, & Shen, 2014; Paramati et al., 2021). R&D investment reduces energy consumption through efficient production and promotes the development of new clean energy technologies that play a central role in the transition from energy systems to cleaner sources (Baek & Lee, 2024). Xu et al. (2020) revealed that R&D investment has a positive effect on green innovation performance and therefore stimulating GP outcomes.

In summary, the literature suggests a positive relationship between R&D and Green Production. Therefore, we propose the following hypothesis to be tested in the empirical analysis section:

H2. *There is a positive relationship between R&D modes and Green Production.*

2.3.3 Research and Development as moderator on relationship Digitalisation and Green Production

In the article of Xiong & Luo (2023), the moderating role of R&D intensity on digitalisation and green productivity has been investigated. The study concluded that R&D intensity positively influenced green productivity and suggested that companies need to increase R&D investments to boost technological innovation to support green productivity (Xiong & Luo, 2023). Ma et al. (2022) found a moderating effect of R&D on the increase in CO2 emission-inhibiting effects of digitalisation. They concluded that digitalisation alone cannot bring about a substantial decline in emission levels. If the digitalization strategies are integrated within the R&D-related policies then the development of green digitalization instruments can be expected to inflict higher reductions of CO2 emission (Ma et al., 2022). This can be linked with Zhang & Liang (2012), which recommended R&D practices that develop green ICT and therefore reduce emissions while creating GP.

Contrary, multiple studies suggest spin-offs of the role of R&D as moderator on digitalisation and GP (Adebayo & Kirikkaleli, 2021; Petrović & Lobanov, 2020; Zhao et al., 2021). Adebayo & Kirikkaleli (2021) found evidence of more R&D practices stimulating digitalisation, leading to higher emissions of CO2 in the long run rather than lower emission rates. In the article of Zhao et al. (2021) the analysis revealed that by the moderation effect of R&D, digitalisation is effective in reducing CO2 emissions in less-polluted nations. For relatively highly-polluted countries digitalisation stimulates higher CO2 emissions with R&D as moderator (Zhao et al., 2021).

As introduced in section 3.1, R&D has STI- and DUI-mode innovations (Alhusen & Bennat, 2021; Jensen et al., 2007). STI-mode innovations provide analytical knowledge that is codified in formulas or scientific laws and therefore is very abstract (Alhusen & Bennat, 2021). This can cause problems and challenges in the process of implementing this universal knowledge (Hooli et al., 2019). The knowledge is associated with high-technology industries and firms operating and therefore stimulating digitalisation innovations. These digital innovations often have a high impact if dealt with implementing challenges (Nunes & Lopes, 2015). These high-impact digital innovations would therefore result in stimulating GP (Dou & Gao, 2023). On the other hand, DUI-mode innovations are often based on learning-by-doing focusing on the operations of the specific company (Alhusen et al., 2019). These innovations are smaller but because of the practical not-universal knowledge, the innovations have little to no challenges for implementation (Apanasovich, 2016). Because of the smaller innovations, DUI has less than STI but still positive influence on digitalisation and thus the impact on GP (Radicic & Petković, 2023; Santos et al., 2022).

Relative to the R&D practices and their effect on the relationship between digitalisation and green production, optimising the throughput stage can make the most difference for manufacturing companies (Griffiths et al., 2016). With CPS, IoT, AI, Digital Twins, Robotics, and different machine tools, the most amount of digital technologies can be implemented in the throughput stage (Liu et al., 2023). Therefore, more R&D practices related to STI and DUI can be applied to the throughput stage. Because of this, the study will focus on the throughput stage because the role of R&D on digitalisation and GP can be better investigated.

In summary, the literature suggests a positive impact of R&D as moderator on the relationship between Digitalisation and Green Production. Therefore, we propose the following hypothesis to be tested in the empirical analysis section:

H3. *R&D positively impacts the relationship between Digitalisation and Green Production.*

2.4 Interoperability

2.4.1 Interoperability

As already mentioned in the introduction of this study, interoperability is the connectedness of machines, devices, sensors, technologies, and people (Hermann et al., 2016). Via these interconnected technologies and people, information sharing forms the basis for collaboration and reaching common goals (Giusto et al., 2010). Interoperability improves productivity, the quality of manufacturing, and waste reduction (Paritala et al., 2017). Related to the implementation of interoperability, Cohen et al. (2019) identified organisational challenges while Andreoni & Anzolin (2019) identified technological challenges. These technological challenges are the infrastructure with the right combination of hardware software and connectivity capabilities, the high number of operations requiring a high level of complexity, and data ownership in combination with software affordability (Andreoni & Anzolin, 2019). Organisational challenges are associated with a lack of knowledge, the need for another type of employee, dependency on technology, and changes in the infrastructure of the organisation (Cohen et al., 2019).

The operations management literature offers two main perspectives for organisations to deal with interoperability. These are the Business Process Re-engineering (BPR) or the continuous improvement philosophy (Martinez, 2019). BPR perspective argues the necessity to redesign the entire business from its fundamentals to take advantage of information and communication technologies possibilities, while aiming to optimise organizational resources for the most excellent result (Martinez, 2019). It refers to the acquisition of new technology and forgetting about the old technologies. While BPR suggests a “new beginning”, this approach is radical and controversial but also brings benefits in the short term (Bhaskar, 2018; Rigby, 2013). The continuous improvement perspective makes minor changes to obtain results in the long term (Iwao & Marinov, 2018). It prefers the evolution and the adoption of technologies based on specific needs (Martinez, 2019). The lean way of thinking generates improvements in factories every day, and these improvements in turn lead to better quality, improved production lead time, flexibility, and lower cost (Womack & Jones, 1997).

While in this study a clear distinction is made between R&D modes and the perspectives of managing interoperability, DUI and continuous improvement have similarities and therefore create overlap between the concepts. The most important factor both perspectives have in common is the focus on the innovations or improvements in the current existing production process (Santos et al., 2022; Singh & Singh, 2015). DUI is often characterized as learning-by-doing and focuses on the innovation of current processes by making use of experiences, experimentation, and iterative testing (Jensen et al., 2007). Continuous improvement is characterized by the Kaizen method and focuses on gradual and continuous progress, increase of value, intensification, and improvement of current processes (Karkoszka & Szewieczek, 2007). Besides keeping the current processes and innovating them, focusing on more incremental innovations is also a common factor. The DUI mode as well as the continuous improvement perspective, want to achieve long-term success by having incremental improvements and building advantages over time (Apanasovich, 2016; Parrilli & Alcalde Heras, 2016; Singh & Singh, 2015).

2.4.2 Interoperability as moderator on relationship Digitalisation and Green Production

Apart from the individual usage of the main technologies IoT and Big Data in the input stage, Dionisio & Paula (2024) identified the importance of the interoperability between these technologies. They concluded that the use of these combined technologies results in improved production, integrating supply chains, and reducing waste, carbon, and the ecological footprint (Dionisio & Paula, 2024). IoT monitors and captures data by making use of embedded electronics while Big Data analytics can use this data for identifying patterns and optimising the production process and GP. Furthermore, interoperability between the digitalisation between the input and throughput stages is also beneficial for sustainability in production (Horváth & Szabó, 2019). The data that is generated, captured, and analysed, can be implemented in the throughput stage of the process (Dionisio & Paula, 2024). Data from real-time tracking and monitoring could be immediately used by Robotics, 3D printing, or Digital Twins through the interoperability of these technologies (Verma et al., 2020). Bressanelli et al. (2022) highlighted that the collaboration and interoperability between multiple technologies in every production stage would result in higher GP outcomes. For example, digital technologies in the output stage can reveal information that could be implemented in the input and throughput stage leading to improved GP practices (Dionisio & Paula, 2024). It shows the importance of the connectedness and interoperability of multiple digital technologies across the production stages to practice GP (Bonilla et al., 2018).

Although interoperability as a moderator could positively impact the relationship, there are different impacts by using different perspectives to manage interoperability. For example, continuous improvement would fail to provide real signs of development in companies with outdated or obsolete technology (Martinez, 2019). For the BPR or radical change perspective, it needs large financial resources but also brings solutions that guarantee long-term performance (Bhaskar, 2018). The design of new facilities must ensure flexibility and easy implementation for optimal interoperability with this perspective (Sahno et al., 2015). The technology changes faster than before and therefore, flexibility must be an essential part of any new large technological investment (Martinez, 2019). Companies must know their capability to be flexible when choosing a perspective to manage their interoperability. The wrong way of managing interoperability would lead to a negative effect on the relationship between digitalisation and green production. Poor interoperability has detrimental effects such as inefficiencies, increased costs, energy consumption, emissions, and waste (Andreoni & Anzolin, 2019).

In summary, the literature suggests a positive impact of interoperability as moderator on the relationship between Digitalisation and Green Production. Therefore, we propose the following hypothesis to be tested in the empirical analysis section:

H4. *Interoperability positively impacts the relationship between Digitalisation and Green Production.*

2.5 Hypotheses Development

To finish the chapter providing the theoretical background of the main concepts in this study, the multiple hypotheses mentioned throughout the chapter are combined and will be tested. A visual representation of the theoretical framework as the conceptual model is shown below in Figure 1.

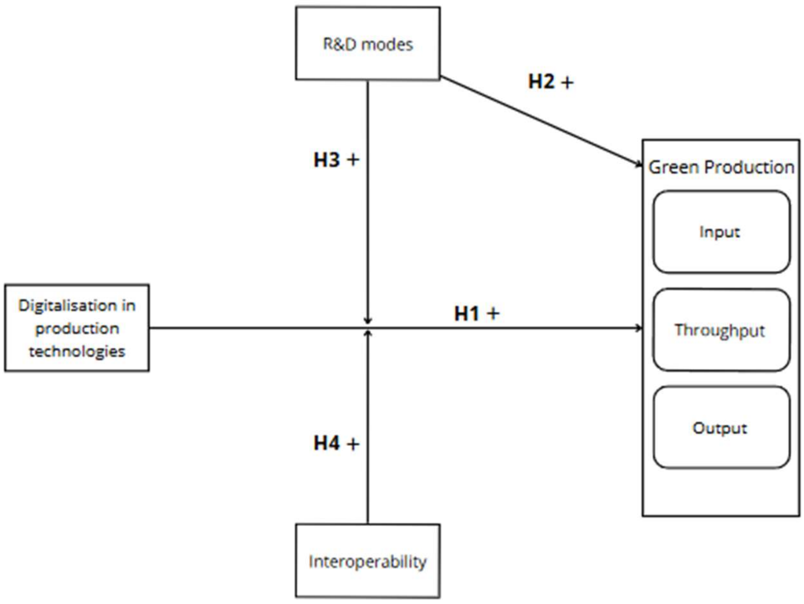

Figure 1: Illustration of the conceptual model

3. Methodology

This chapter will explain the design and choices made to get useful data for the study. First, the research design will be explained. Next, the research instruments will be described and explained to clarify the choices made for the reader. Finally, how validity, reliability and ethics will be ensured within the design of this study will be discussed.

3.1 Research Design

This study will make use of different approaches to gather data to test the hypothesis/hypotheses derived from the Theoretical Background. A mixed-method way of data collection will be used. This means that data will be generated by using a mix between quantitative and qualitative research (Matović & Ovesni, 2023). The type of the mixed-method will be the concurrent triangulation strategy (Creswell & Creswell, 2017). Both types of data will be collected concurrently and the two databases will be compared to determine if there is convergence, differences, or some combination between the two (Creswell & Creswell, 2017). The advantage of a mixed-method approach in research is the different insights it can provide to create a better overall understanding of the phenomenon being studied (Creswell & Tashakkori, 2007). As a result, mixed-method research provides more comprehensive and deeper information than just quantitative or qualitative research (Mejeh et al., 2023). Another advantage of using triangulation in research is the improvement in the generalisation of the study. When performing the data collection, there will be first a quantitative part with a database containing information about manufacturing companies. Through consulting this database, there will be clarification between digitalisation, R&D, and green production. In addition, by conducting interviews, data will be generated that will provide more detailed information to eventually answer the second sub-question. The qualitative part of this research ensures that in-depth knowledge about any relationship can be obtained (Matović & Ovesni, 2023). This specific gathered data and knowledge will help explain the influence of interoperability and R&D approaches on green production. By the use of triangulation in this study, all the necessary data can be obtained to provide an answer to the research question.

3.2 Research Instruments

The quantitative data will be based on a European Manufacturing Survey (EMS) which provides information about companies in the manufacturing industry. It contains questions regarding innovation, products, services, R&D, revenue, and general questions. The questions which relate to the concepts of this study are selected and summarised in an operationalisation table (Figure 2). The following concepts mentioned in Figure 2 are Digitalisation in production technologies, Green production, R&D, and Interoperability. Incorporating questions about these concepts gives insights that will answer the first part of the research question. It will show the influence of interoperability and R&D as moderators on the relationship between digitalisation and green production.

The operational table is based on questions used in earlier research for measuring the same concepts. Questions 11.1 and 11.2 related to the digitalisation concept, are valid through similar questions in digitalisation research (Benitez et al., 2020; Frank et al., 2019; Horváth & Szabó, 2019). Bai et al. (2020) also support question 12 of green production. R&D question 23.1 is a general question. Lastly, interoperability is partly covered by questions 8.1 and 8.7 focusing on continuous improvement (Ponsignon et al., 2019). This is related to a style of managing interoperability (Singh & Singh, 2015).

Table 1: Operationalisation Table

Operationalisation table		
Concept	Dimensions	Question (EMS database)
Digitalisation in the production process	Digital technologies	**Q11.1: Welke van de volgende technologieën worden momenteel in uw bedrijfsvestiging toegepast?** 11.1_1 Productiebeheersing: Mobiele/ draadloze apparaten voor programmering en bediening van installaties en machines (bijv. tablets) 11.1_2 Digitale oplossingen voor het direct beschikbaar maken van tekeningen, werkschema's en -instructies op de werkvloer 11.1_3 Digitale productieplanning en roostering (bijv. ERP- of ASP systeem) 11.1_4 Systemen voor geautomatiseerd management van interne logistiek en orderverzameling (e.g. RFID, warehouse management system) 11.1_5 Digitale uitwisseling van productieplanningsgegevens met toeleveranciers en/of klanten (elektronische data-uitwisseling (EDI)) 11.1_6 Product Lifecycle Management (PLM) systemen of product- of productieproces datamanagement 11.1_7 Bijna real-time productiemanagementsystem en (bijv. systemen voor gecentraliseerde besturing en machinemonitoring, MES) 11.1_8 Additive technologieën en simulatietechnieken3D printertechnologie voor prototypes, demonstratiemodellen, 0-series 11.1_9 3D printertechnologie voor de vervaardiging van producten,

		onderdelen, mallen, instrumenten, e.d. 11.1_10 Software voor simulatie van productontwerp (bijv. productprestaties, betrouwbaarheid van onderdelen) 11.1_11 Software voor simulatie van productieprocessen (bijv. op niveau van proces, productielijn, fabriek of toeleveringsketen) 11.1_12 Software voor geavanceerde berekeningen, simulaties en data analyse d.m.v. High Performance/Edge computing **Q11.2: Gebruikt u industriële robots in uw productieproces?** (Nee (1)/ Ja (2))
Green Production	Green technologies	**Q12: Welke van de volgende technologieën voor energie- en grondstoffenbesparing worden momenteel in uw bedrijfsvestiging toegepast?** 12.1 Technologiën die vanaf het begin resulteerde in een aanmerkelijk efficiënter materiaalgebruik (bijv. near net shape technologieën, introduceren van vormen i.p.v. ponsen) 12.2 Technologieën voor terugwinning van kinetische en procesenergie (bijv. terugwinnen afvalwarmte, energie opslag) 12.3 Technologieën voor recycling en hergebruik van water (bijv. water recirculatie systemen) 12.4 Installaties voor omschakeling van fossiele brandstoffen (olie, aardgas) naar andere energiebronnen (electriciteit, waterstof) 12.5 Technologieën voor eigen energie- en/of warmteopwekking door middel van zon-, wind-, waterkracht, biomassa of geothermische energie (bijv. zonnepanelen, windmolen, warmtepomp, etc) 12.6 Afschakelsystemen voor onderdelen, machines of installaties indien niet in gebruik (bijv. afschakeling luchttoevoer, aangepaste verlichtingssensoren) 12.7 Verbeteren van bestaande machines of installaties (bijv. hoogefficiënte motoren (IE3), aanbrengen isolatie, warmtewisselaar) 12.8 Worden gerecyclede metalen en kunststoffen gebruikt in het hoofdproduct van uw fabriek?
Research & Development (R&D)	R&D activity	**Q23.1: Heeft uw bedrijfsvestiging in 2021 Onderzoek en Ontwikkelingsactiviteiten (O&O, R&D) uitgevoerd al dan niet samen met of door externe partners (bijv. uitbesteed)?**
Interoperability		**Q8: Welke van de volgende organisatieconcepten en werkwijzen worden momenteel in uw bedrijfsvestiging toegepast?** 8.1 Organisatie van de productie Integratie van werkzaamheden (planning, bediening, en controle op niveau van machine operator) 8.7 Methoden om de kwaliteit van de productie te waarborgen (bijv. Total Quality Management, certificaten, continue verbetering van productieprocessen)

Control variables	Industry	**Q2_industry: In welke bedrijfstak is uw bedrijf actief?**
	Size	**Q22.1: Aantal werknemers (totaal in 2021)?**

As for the qualitative part of the research, a semi-structured interview script will be used to gather the data. The general themes which are included in this script are Digitalisation, Green Production, R&D, and Interoperability. Multiple questions are assigned to these themes to collect sufficient information to provide an answer to the research question. The respondent face questions about the digital technologies and green production activities in their company. These questions are based on the studies of Bai et al. (2020) and Braccini & Margherita (2019). Before the interview ends, questions are asked about R&D and interoperability in the specific companies. Furthermore, there will be some questions about the moderating role of R&D and interoperability on digitalisation and green production. These and their follow-up questions are based on research. The interview script which will be used, can be found in Appendix 1. The respondents will be directors, project managers, or employees with a supervision role in the production of a manufacturing company. Ultimately, this qualitative way of doing research will contribute to the study by mainly answering the second part of the research question. The interviews provide more and deeper information about the relationship between digitalisation and green production and the moderating effects of interoperability and R&D.

3.3 Methods of Analysis

After gathering all the data by using the database and interviews, it will be analysed before describing it in the results chapter. For the quantitative data based on the EMS Qualtrics, the descriptive statistics, the reliability statistics, and a regression analysis will be applied. Descriptive statistics will explain the more general information about the main concepts and can be seen in the results section. The Cronbach's Alpha (CA) of the concepts is used to test the reliability of the analysis and its results. After, the regression analysis will highlight the influence of the variables digitalisation, R&D, and interoperability on green production. With the analysis, the hypotheses formed in the conceptual model can be explained to provide the answer to the first part of the research question.

Coding will be used for the qualitative data following the interviews with the manufacturing companies. First thematic coding and after open/axial coding will be applied to analyse the interview transcript. Relevant quotes from the interview will be saved and linked to the core concepts of the study by making use of thematic and open coding. These quotes will be ranked from 1 to 3 based on their relevance to the results. In the results, a table with these quotes and their relevance can be seen for every core concept of the study (Digitalisation, Green Production, R&D, and Interoperability). The quotes and coding are combined to compare with the theoretical definitions of the concepts. Similarities and differences found by comparing will be discussed and lead to a conclusion. By analysing the qualitative data through coding, a deeper understanding of the main concepts and their relationships can be highlighted. It could show for example the reasoning why relationships exist and how this affects the results shown in the quantitative data analysis.

3.4 Validity, Reliability and Ethics

The validity of the study is safeguarded by the use of academic literature in the research instruments as shown in section 3.2 Research Instruments. For the operationalisation table multiple studies are used (Bai et al., 2020; Benitez et al., 2020; Frank et al., 2019; Horváth & Szabó, 2019; Ponsignon et al., 2019). The interview script has some overlap with other earlier conducted qualitative research (Alhusen et al., 2019; Bai et al., 2020; Braccini & Margherita, 2019; Koçak & Ulucak, 2019). The validity of both the operationalisation table and the interview script is fundamental for answering the research question.

To ensure reliability within this study, multiple actions will be executed to realise this. An action related to the quantitative results will be the support of an associate professor who has access to the data. The support will be in selecting the right data and output to analyse for the results section. It ensures that the results from the analysis are reliable and, when performed repeatedly, the same conclusions are formed. For the qualitative part of the study, reliability will be ensured as much as possible by having a similar company's industry and number of employees. By having similarities in both control variables, the data can be easily compared which improves the reliability of the results.

Besides making sure that valid and reliable data and results will be obtained for the study, it is also important that certain ethical choices will be made about the study. To conduct an ethical study, mutual consent will be held at all times. In addition, the privacy and anonymity of respondents will be maintained. Thus, no information will be shared in the interview transcripts that can be directly traced back to the respondent or company in question. This will be done by identifying respondents and the specific companies as: respondent/company A,B,C. Also, after transcribing, the audio file will be destroyed immediately to eliminate the chance of leaving any unwanted traces. Contact with the company and the respondent will remain respectful at all times. Finally, the agreements which are made with the company and respondents will be kept.

4. Results

In this chapter, the results of the mixed-method research will be shown. The results are split up into quantitative and qualitative parts. The quantitative results will be presented first and consist of descriptive statistics, reliability, and regression analyses. The data is shown in tables and what this entails for the study. After, the qualitative results will be presented which consist of data coming from interviews. These data are coded and the most relevant quotes will be selected and presented in tables. To finalise the chapter, both quantitative and qualitative results are compared to accept or reject the hypotheses previously shown in the conceptual model.

4.1 Quantitative Results

4.1.1 Descriptive Statistics Analyses

Starting with the control variables "Number of employees" and "Industry sector", the database contains 186 participating companies. The variable "Number of employees" has a kurtosis of 184,571 and therefore is transformed into a log variable. The log variable gives an average of 3,928 number of employees per company. The median of the non-transformed variable was 45, which gives a better indication of the size of the participating companies. For the industry sector, in Table 2 we can see the percentages of the companies that are manufacturing. With a percentage of 20.4 or above, both the metal and chemical sectors are well-represented in the data. The food, electronic, and construction sectors are the least represented with a percentage of 7.5 or below.

The first independent variable "digital technologies" as tested with the questions in the operationalisation table consists of 14 digital technologies which could be implemented in the production process. With a mean score of 3,9624 as shown in Table 2, four digital technologies are on average implemented by the participating manufacturing companies. The minimum amount of digital technologies is 0 and the maximum of implemented digital technologies is 10.

The independent variable "Research and Development" is tested by the indicator if the participating companies did activities related to R&D. This yes-or-no question has resulted in a mean score of 0,4731. This concludes that 47.3% of the participating companies engaged in R&D activities. The last independent variable "Interoperability" consists of two indicators as seen in the operationalisation table. As well as the R&D indicator, both indicators for interoperability are yes-or-no questions to show the application of the integration of tasks and the application of methods to assure the quality of the production. The integration of tasks scores a mean of 0,6682 and is therefore being applied in 66.8% of the companies. For the methods of assuring quality in the production, the score of the mean is 0,7213 and this shows an application of 73.1% in the companies.

The dependent variable "Green production" consists of seven technologies that are related to sustainable production. The variable gives a mean score of 1,8817 therefore meaning that the average is two sustainable technologies within companies. The descriptive statistics also show that the minimum amount of sustainable technologies is 0 and a maximum of 6.

Table 2: Descriptive statistics *(N = 186)*

	Description	Mean	Std. Deviation	Minimum	Maximum	Median	Frequency (%)
FirmSize	*Number of employees*	246,89	161,133	10,00	30000,00	45,00	
FirmSize (log)	*Number of employees*	3,77	1,073	2,30	8,41	3,81	
Industry sector							
	Metal and metal products		*0,442*				*26.3*
	Food, bevarage and tobacco		*0,265*				*7.5*
	Textile, leather, paper and board		*0,369*				*16.1*
	Construction, furniture		*0,203*				*4.3*
	Chemicals (energy and non-energy)		*0,404*				*20.4*
	Machinery, equipment transport		*0,392*				*18.8*
	Electrical and optical equipment		*0,246*				*6.5*
Digital technologies	*Count implemented digital technologies*	3,9624	2,558	0,00	10,00	4,00	
Green production	*Count implemented sustainable technologies*	1,8817	1,637	0,00	6,00	2,00	
Research and Development	*Count present R&D activities*	0,4731	0,501	0,00	1,00		*47,3*

Interoperability	*Count present interoperability activities*	-	-				
	Integration of tasks	*0,6682*	*0,464*				*66,8*
	Methods of assuring quality in production	*0,7312*	*0,445*				*73,1*

4.1.2 Measurement Models and Reliability Analyses

When analysing the statistics for the measurement model of the variable Digital Technologies, two technologies are mostly applied within the participating companies. Software for production planning and scheduling has a mean of 0,6344 and digital solutions on the shopfloor have a mean of 0,5054. Based on this statistic, both technologies are implemented in more than half of the companies participating. With a mean score of 0,16 or less, the following four digital technologies are the least implemented: Software for simulating production, Software for advanced computations and data analysis, Additive manufacturing 3D for product components, and Product-Lifecycle-Management systems. These technologies are implemented in 10.8% to 16.1% of the companies participating in the database.

To finish the measurement model section, Green Production, and Interoperability are being analysed. For the variable Green Production, the technologies generating own-fossil energy (mean = 0,43) and upgrading technologies or equipment for sustainability (mean = 0,33) are used in one-third of the respondent companies. One of the two least applied sustainable technologies is the technology for recycling and re-use of water with a mean score of 0,1667. The other least applied sustainable technology is the one where the technology is switched to a non-fossil energy resource with a mean score of 0,1398. For Interoperability, there are only two items to indicate the variable. For both Integrating of tasks (mean = 0,66) and Methods of assuring quality in production (mean = 0,73), these implemented actions are in two-thirds of the respondent companies used.

The reliability will be measured by making use of Cronbach's Alpha (CA) as a statistical score. The coefficient value ranges from 0.00 to 1.00, where 1.00 indicates the higher internal consistency. The measurement process is reliable if the obtained coefficient value is greater than 0.6 (Verma et al., 2022). In the article of Sharma (2016), the reliability score of $0.6 \geq \alpha \geq 0.7$ would make the model questionable. Furthermore, it stated that a score of $\alpha \geq 0.7$ would be sufficient. The CA coefficients related to this study are shown below in Table 3. By looking at these coefficients, it can be concluded that the reliability is questionable for digital technologies with a CA of .652.

For the other variable of "green production", the CA coefficient has a score of .513 of all the eight indicators taken into account in the operationalisation table. To improve this CA score, one item is removed and the CA therefore improved to the highest possible score of .565. A coefficient in this range would be not sufficient but can still be used (Sharma, 2016). In addition, acceptance of the norm of the CA score is also dependent on the type and purpose of the study (Sharma, 2016). In this case, exploratory research is taking place where the model is used as an index for a theory. In that case, the CA score of 0.565 is acceptable and therefore usable.

The last CA coefficient is related to the variable "interoperability". The variable has a reliability score of .325 which means that the variable is not meeting the required score of 0.7. The variable containing two items is not reliable for the study. To tackle this, the regression analysis has been done with both items used separately from each other in the regression analysis to see if there is a significant effect on the dependent variable. An advantage of this is that there is more clarity in the relationship between the individual items and the dependent variable. These results would provide a better understanding and insights because it is directly related to the specific items.

Table 3: Measurement model and reliability

	Mean	Std. Deviation	CA
Digital Technologies			.652
***Mobile/wireless devices for programming and operation*	*0,3763*	*0,48578*	
***Digital solutions for providing drawings, work schedules or work instructions directly on the shopfloor*	*0,5054*	*0,50132*	
***Software for production planning and scheduling*	*0,6344*	*0,48290*	
***Systems for automation and management of internal logistics*	*0,2957*	*0,45759*	
***Digital Exchange of product/process data with suppliers / customers*	*0,3333*	*0,47268*	
***Product-Lifecycle-Management-System*	*0,1613*	*0,36879*	
***Near real-time production control system*	*0,2419*	*0,42941*	
***Industrial robots for manufacturing processes*	*0,2258*	*0,41924*	
***Industrial robots for handling processes*	*0,2742*	*0,44731*	
***Additive manufacturing 3D for prototyping*	*0,2204*	*0,41566*	
***Additive manufacturing 3D for products components etc*	*0,1559*	*0,36375*	
***Software for product design simulation*	*0,2796*	*0,45000*	

***Software for advanced computations, data analysis High-Performance Edge computing*	*0,1505*	*0,35856*	
***Software for simulating production processes*	*0,1075*	*0,31062*	
Green Production			.565
****Sustainable technologies - resulted in a significantly more efficient use of materials*	*0,2151*	*0,41197*	
****Technologies to recuperate kinetic and process energy*	*0,1989*	*0,40027*	
****Technologies for recycling and re-use of water*	*0,1667*	*0,37368*	
****Technologies generating their own non-fossil energy*	*0,4301*	*0,49643*	
****Technologies being switched to non-fossil energy source*	*0,1398*	*0,34770*	
****Technologies switching off components*	*0,2581*	*0,50062*	
****Upgrading technologies or equipment for sustainability*	*0,3333*	*0,43875*	
Interoperability			.325
*****Integration of tasks*	*0,6682*	*0,46449*	
*****Methods of assuring quality in production*	*0,7312*	*0,44454*	
** Types of digital technologies *** Types of sustainable production technologies **** Interoperability measures			

4.1.3 Structural Model and Regression Analyses

When analysing the Model Fit statistics, the conclusion is that the R^2 for Model 2 is .210 and Model 3 is .222. It means that these models with the included variables explain 21,0% and 22,2%. A R^2 of .09 shows a medium score and a R^2 of .25 would be considered as great (Cohen, 1988). Therefore the R^2 for both models can be interpreted as sufficient. In the ANOVA table by using $\alpha = 0.05$, the conclusion can be made that all models are significant (p = <.001). The R Square and the F statistic with the corresponding significance score (ANOVA) are shown in Table 4. It includes the scores of the three different models, whereas Model 3 includes all the variables and interactions.

As seen in Table 5, the variable digital technologies have a significant effect on green production with a significance of $p < 0.05$ (p = .03). The regression coefficient is 0,258 which means that it is positively related to green production. Therefore, H1 is accepted.
H1. *There is a positive relationship between Digitalisation and Green Production in all various production stages.*

For the variable R&D, it can be concluded that this has also a significant effect on green production with a significance of $p < 0.1$ ($p = 0.096$) because of a one-sided hypotheses testing. The effect is thus significant as well as positive with a coefficient of 0,391. Therefore, R&D has a positive significant effect on green production and H2 is accepted.
H2. *There is a positive relationship between R&D modes and Green Production.*

When analysing the interaction effect of R&D on the relationship between digitalisation and green production, the table shows a not significant interaction effect. Therefore, R&D doesn't have a significant impact on the relationship and H3 needs to be rejected.
H3. *R&D positively impacts the relationship between Digitalisation and Green Production.*

The interaction effect of interoperability on the relationship between digitalisation and green production is split up into two separate items (Integration tasks and Quality measures). In Table 5 both of the separate items show a negative coefficient as well as a not significant p-value. This means that interoperability doesn't have a significant interaction effect and H4 needs to be rejected.
H4. *Interoperability positively impacts the relationship between Digitalisation and Green Production.*

To finalise this section, the control variables for the regression table can be analysed. For the variable Number of employees (log) the coefficient is non-significant with a $p > 0.05$. The industry sector statistics vary in significance and direction of the regression coefficient. The following industry sectors are shown to be significant ($p < 0.05$): Food ($p = 0.047$) and Chemical ($p = 0.031$). The regression coefficients are for both industries positive and therefore show that these industries have a positive effect on green production. All other industry sectors have a non-significant effect on the green production of manufacturing companies.

Table 4: Model fit

Model	R square	F	Significance
1*	.116	3,332	.002
2**	.210	4,216	<.001
3***	.222	3,485	<.001
a. Dependent variable: Green production			
* Variables included: Number of employees (log) and Industry sector			
**Variables included: Number of employees (log), Industry sector, Integration of tasks, Quality measures, R&D activities and Digitalisation in production			
***Variables included: Number of employees (log), Industry sector, Integration of tasks, Quality measures, R&D activities, Digitalisation in production, DigitalisationXR&D, DigitalisationXIntegrationtasks, DigitalisationXQualitymeasures			

Table 5: Regression statistics

	B	*Std. Error*	*Sig.*	*VIF*
Control Variables				
Constant	0,281	0,589	0,634	
Number of employees (log)	0,110	0,121	0,364	1,376
Food	0,951	0,476	0,047	1,301
Textile	0,204	0,355	0,566	1,404
Construction	0,926	0,576	0,110	1,128
Chemical	0,736	0,339	0,031	1,536
Machinery	-0,149	0,334	0,656	1,402
Electronic	-0,805	0,485	0,099	1,172
Independent Variables				
Digital technologies	0,258	0,118	0,030	7,494
R&D activities	0,391	0,234	0,096	1,122
Integration tasks	0,244	0,258	0,345	1,177
Quality measures	-0,169	0,287	0,557	1,331
DigTech*RD	0,106	0,094	0,259	2,443
DigTech*IntTasks	-0,098	0,103	0,346	3,850
DigTech*QualMeasures	-0,092	0,112	0,415	4,797

4.2 Qualitative Results

4.2.1 Introduction

As for the qualitative results, semi-structured interviews are conducted to gather useful insights about the relationship between digitalisation and green production and the moderating role of R&D and interoperability. In total, there are six interviews conducted with (operation) managers and/or employees with a supervisor role in the production process of Dutch manufacturing companies. The participating companies were all active in the Machinery or Electrical industry. The company size, based on the number of employees, was measured between 11 and 2300. Four of the companies had between 120 and 300 employees. The exact statistics of the participating companies can be seen in Table 6. Because of the similar characteristics of the companies, the results of this study can be generalised for companies specific in the Machinery and Electrical industry.

Based on the transcription of the interviews, relevant quotes are highlighted which provide information about the concepts themselves or the relationship between the specific concepts. First thematic coding is applied to categorise the important quotes to specific concepts. After, the quotes are open-coded to discuss in the results section. Besides the specific open code, every quote has an ID label. The first digit indicates the respondent of the quote (1= interview A, 2= interview B, etc.), the second digit indicates the specific concept, and the last digit shows if the quote is related to the concept or the relation between other concepts (based on the hypotheses and conceptual model). In this case, a 1 indicates the information about the concept and a 2 indicates information about the relationship of concepts. Section 4.2.2 will discuss every concept with the corresponding hypotheses. Every concept will start with the definition, then the quotes will be discussed, and ending with the acceptance or rejection of the hypotheses.

Table 6: Control variables of participating companies

	Type of industry	Number of employees
Company A	Machinery	2300
Company B	Machinery	140
Company C	Electrical	11
Company D	Machinery	250
Company E	Electrical	300
Company F	Machinery	120

4.2.2 Results Core Concepts

4.2.2.1 Digitalisation

In this study, digitalisation is defined by Brennen & Kreiss, (2016) as: “The adoption or increase in the use of digital or computer technology by an organization, industry, country, etc.” (p. 6). The digitalisation is focused on the production process and contains digital technologies such as CPS, IoT, IoS, cloud, AI and big data.

Manufacturing companies are not using many different digital technologies for their production processes. A reason for this is the amount of assembly work which is mostly manual and customer-specific products (ID 1.1). Therefore, companies with these problems are struggling to digitalise these continuously changing operations and stick with the digitalisation of supply chain activities (ID 1.1). The main type of technology is digital software for production and planning (ID 1.1; 2.1; 3.1). Also, 3D printing is used as a main technology in production (ID 3.1) or as a tool to test prototypes (ID 4.1). Also, wireless devices for operations and shopfloor are implemented technologies (ID 2.1). Reasons for implementing digital technologies are according to the respondents increasing efficiency and predictability (ID 4.1), shortening the lead time, and the decreasing chance of mistakes (ID 2.1). Another positive consequence of applying digitalisation is the increase in transparency of certain activities and operations in the company (ID 5.1). When monitoring correctly, the data that is provided always tells some part of the truth. A disadvantage of digital software related to planning or production is the cooperation and the dependency it requires on different systems (ID 1.1). Besides that, it requires more trust and transparency with your customers as well as suppliers (ID 1.1).

Table 7: Relevant quotes of the concept ‘Digitalisation’

ID label	Quote	Open Code
2.1	"We hebben sowieso een ERP en een WMS pakket. We hebben een datamanagementsysteem. We proberen nu een PLM systeem te bouwen. Op de werkvloer werken we met shopfloor, waar alle informatie voor de monteurs digitaal beschikbaar is."	Types digitalisation
3.1	"Wij hebben hier 3D printers staan. En dan heb je daarnaast ook heel veel hoofdprocessing apparatuur nodig. Dat zijn apparaten die je nodig hebt om uiteindelijk een eindproduct bij de klant dan in halffabricaten te kunnen leveren. Als software gebruiken we een MES systeem."	Types digitalisation
4.1	"Onze Transport-Productie-Distributie structuur is digitaal, maar een geautomatiseerd productieproces voor het bouwen van onze machines hebben we niet. 3D printen doen we wel, maar dat is voor af en toe wat prototypes.	Types digitalisation
4.1	"Digitalisering doe je vaak vanuit efficiency. Natuurlijk heb je ook minder kans op fouten. Je hebt wel kans dat je soms aanpassingen moet doen met software en security beheer kost veel aandacht."	Efficiency

2.1	"Uiteindelijk gaat het allemaal om efficiënter werken. Het gaat dan ook om de beheersbaarheid van een groot assortiment van artikelen, de doorlooptijd inkorten en dat de organisatie wat voorspelbaarder wordt."	Efficiency
1.1	"Het bouwen van een robot is bijna allemaal handwerk, dus we gebruiken nauwelijks machines om die robots in elkaar te zetten. Daar valt niet heel veel in te digitaliseren, maar wij kunnen wel veel digitaliseren In de aansturing van onze supply chain."	Supply chain
1.1	"Het is voor ons eenvoudiger wordt om de supply chain te sturen omdat je minder afhankelijk bent van mensen. Het gevolg is ook dat de voorraden in de keten omlaag gaan en de leverbetrouwbaarheid omhoog."	Independency
1.1	"Een nadeel is echt de samenwerking met leveranciers en de afstemming van systemen op elkaar. Er moet een bepaalde mate van vertrouwen zijn. Je moet veel meer transparantie geven."	Cooperation
5.1	"De gevolgen van digitalisering is dat we een beter beeld hebben van wat er nou precies gebeurd. Als je op basis van data kijkt, dat je altijd wel een kern van waarheid te pakken hebt."	Transparancy

4.2.2.2 Green Production

Green production is defined by D'Angelo et al. (2022) as: "environmental consciousness in production and related interventions, … " (p. 2). Additionally, other research gave specified these activities which would be part of green production: reducing toxins, waste, pollution, optimising use of raw material and energy … " (Toke & Kalpande, 2019). Thus, green production can be viewed as having environmental consciousness in production and supply chain by reducing toxins, waste, pollution, and energy use and optimise material use and energy.

From the interviews, multiple manufacturing companies that participated are not actively engaging in the concept of green production (ID 6.2.1; 2.2.1 (1); 2.2.1 (2)). This can be due to some reasons as a lack of priority by the top managers (ID 2.2.1 (1)). In this case, there is no clarity as to what extent green production is present. As a result, there is no insight into what can be improved for better GP results. Another reason given in the interview is that the manual practices the company performs, can't be improved concerning green production (ID 2.2.1 (2)). On the contrary, other participating companies do engage on purpose in green production activities. An example is actively looking for ways to produce more sustainably by using less energy (ID 4.2.1; 5.2.1). The company that implemented 3D printing is having better performances related to green production due to this specific type of digital technology (ID 3.2.1). According to the respondent (ID 3.2.1), 3D printing creates way less and sometimes zero waste. Comparing this with other machines that other companies are using in production processes, 3D printing is one of the best technologies for the concept of green production. As one of the respondents mentioned, their active participation in green production creates only positive aspects and no negative ones (ID 1.2.1 (1)). It shows that green production can be a good way of producing to stimulate performance.

Table 8: Relevant quotes of the concept 'Green Production'

ID label	Quote	Open Code
6.2.1	"We scheiden ons afval maar voor de rest hebben we niet heel bewust gekozen voor minder afval of iets dergelijks."	Lack of priority
2.2.1 (1)	"Er wordt nu vanuit de directie ook geen prioriteit aan gegeven. En ja, de vraag is hoeveel er echt aan gedaan kan worden. Wij meten onze voetprint nu niet, dus dat zou je eerst al moeten gaan doen. Dan weet je waar veel ruimte zit om nog te verbeteren."	Lack of priority
2.2.1 (2)	"Wij zijn een montagebedrijf en daar is dus veel arbeid. Het is moeilijk om daarin te vergroenen. We doen niet echt iets actiefs met het letten op afvalvermindering."	Lack of priority
1.2.1 (1)	"Wij zien eigenlijk alleen maar positieve effecten van groene productie."	Positive effects
1.2.1 (2)	"Wij focussen op lean en het wegnemen van verspillingen."	Focus
4.2.1	"We proberen een zo licht mogelijk product te maken waardoor er zoveel mogelijk energie bespaard kan worden. De assemblage is handwerk dus daar verbruiken we geen energie. Daarnaast hebben we nog sensoren voor verlichting, zonnenwering en zonnenpanelen."	Sustainability
5.2.1	"We zijn bewust bezig om op een andere manier te produceren waardoor we duurzaamer zijn. Het heeft niet per se met digitalisering te maken. Daarnaast maken we onze eigen stikstof voor het optimaliseren van onze eigen processen."	Ways of producing
3.2.1	"In principe 3D printen in de basis zorgt ervoor dat je alleen materiaal gebruikt wat je nodig hebt. Je hebt dus weinig tot geen afval in tegenstelling tot bij andere machines. Daarnaast kunnen we in gesprek met de klant het ontwerp zelf ook nog verduurzamen."	3D printing

4.2.2.3 Research and Development

The definition used In this article is mentioned by Kainulainen (2014) as: "systematic activities to increase knowledge and use of this knowledge when developing new products, processes, or services" (p. 5516). R&D activities can be split up into two categories: STI (science, technology, and innovation) and DUI (doing, using, and interacting). STI mode can be seen as more external and DUI as more of an internal learning-by-doing approach.

From the conducted interviews, it can be concluded that more than half of the companies use or see the combination of both R&D modes as the best possible option (ID 1.3.1 (1); 2.3.1; 5.3.1; 6.3.1). It is mentioned that there needs to be awareness of the possibilities outside of the firm to know the latest changes and opportunities (ID 3.3.1 (2)). This can be done by cooperation with suppliers or other companies (ID 3.3.1 (2); 5.3.1). Besides making use of the STI mode (ID 4.3.1), the combination with the DUI mode is important to keep making improvements to the current production processes (ID 1.3.1 (1); 6.3.1). Additionally, other companies are mainly focusing on the DUI mode by having more of a learning-by-doing-based approach for their internal processes (ID 3.3.1 (1); 1.3.1 (2)). Overall, the companies use a mix of both or only a DUI mode approach for their R&D activities. There wasn't any participating company which make use only of the STI mode.

Table 9: Relevant quotes of the concept 'Research and Development'

ID label	Quote	Open Code
5.3.1	"In het verleden is heel erg een interne focus geweest. Heel erg op eigen ervaringen, eigen manier van werken en daarin verbeteren. Langzaam zijn staan we steeds meer open voor kennis. Een goed voorbeeld is dus die zusterbedrijven. Daar is juist aan de productiekant, onze digitalisatie van productieproces, veel van geleerd."	Combination R&D modes
1.3.1 (1)	"Het beste is een combinatie van beide. Je moet af en toe ook buiten kijken voor een technology scan. Daarnaast zal je altijd nog bezig moeten zijn met continu verbeteren."	Combination R&D modes
2.3.1	"Ik denk niet dat er een beste manier is, maar dat het zit in de combinatie van beide. Er is ook nog wel voor bedrijven te winnen door meer op STI te richten omdat veel informatie voor bedrijven ontsloten wordt."	Combination R&D modes
6.3.1	"Ik denk dat je niks hebt aan de theorie als je niet praktisch probeert. Dus ik ben zelf ook meer van gewoon dat proberen. Alleen, je komt door de theorie wel tot nieuwe ideeën om te proberen. Dus ik denk dat ik het op 40% procent STI zou zetten en 60% DUI."	Combination R&D modes
3.3.1 (1)	"Het is echt learning-by-doing, vallen en opstaan en verbeteren van processen. Dat is een continu proces en elke dag ben je er mee bezig."	DUI mode
1.3.1 (2)	"Bij ons is het met name gefocust op learning-by-doing."	DUI mode
4.3.1	"Je moet de technologische ontwikkeling In de markt In de gaten houden, kijken of jij daar of jij die kunt gebruiken. Het mooiste is als je zelf iets ontwikkeld wat anderen niet hebben en daar patent op aanvraagt, want dan kun je er ook meer geld voor vragen."	STI mode
3.3.1 (2)	We houden natuurlijk wel onze ogen en oren open, maar dat is nou eenmaal inherent aan onze markt. Wij laten ons heel goed informeren door allerlei leveranciers die ons kunnen overtuigen dat iets sneller of goedkoper kan.	Consciousness

4.2.2.4 Interoperability

Interoperability is defined by Verma et al. (2022) as: "the ability of different devices and technologies to communicate and connect (sensors, devices, machines, etc.) and have meaningful human/machine interpretation performance" (p. 12). New implemented technologies and therefore interoperability can be managed in two ways: radical changes perspective or a continuous improvement perspective. Radical changes perspective is implementing more technologies in a short period. The continuous improvement perspective is implementing one technology at a time.

Based on the quotes of the respondents, there are mixed results on which perspective is the best approach regarding interoperability. A continuous improvement perspective is been applied by multiple companies (ID 5.4.1; 4.4.1). The smaller and slower implementation of the technologies is more beneficial because of the lower complexity (ID 4.4.1). In quote 1.4.1, the respondent sees the radical change perspective as best. Lastly, another respondent mentioned the use of both as ideal (ID 2.4.1). Overall, interoperability has its benefits which are brought to light in the interviews. One of them is the amount of extra and useful data that is created by the implementation of interoperability (ID 3.4.1). This would result in more and better insights to help with decision-making situations.

Table 10: Relevant quotes of the concept 'Interoperability'

ID label	Quote	Open Code
2.4.1	"Het is ook weer een combinatie van beide. Je doet een grote implementatie als radical change, en daartussen doe je kleine verbeterstapjes."	Radical & Continuous
5.4.1	"Je kan best meerdere technologieën tegelijk doen. Alleen het probleem wat je hebt is, als er iets niet goed gaat, weet je niet meer waar je het moet zoeken. Algemeen als wij veranderingen doen, in onze productie doen we dat ook. Één voor één bewust om de juiste conclusie te kunnen trekken."	Radical vs Continuous
1.4.1	"Ik zou het invoeren van digitale technologiën als radical changes invoeren. En daarna kun je deze gaan optimaliseren."	Radical changes
4.4.1	"Nee ik zou stap voor stap en dan de blokjes op elkaar zetten. Als je te groot begint te worden wordt het te complex. "	Continuous improvement
3.4.1	"De verbondenheid van digitale technologieën niet, maar de inzicht die het geeft wel. De verbondenheid heb je alleen wel nodig om die inzichten te genereren. Ik merk dat als je iets verbindt, dan komt er een enorme hoeveelheid data opgang."	Data increase

4.2.3 Results Relationships and Interaction Effects

4.2.3.1 Digitalisation and Green Production

Looking at the quotes which give insights into the relationship between digitalisation and green production, there can be concluded that all the relevant quotes show a positive relationship (ID 1.2.2; 2.2.2; 3.2.2; 5.2.2; 6.2.2). As a respondent (ID 2.2.2) mentioned, digitalisation increases the efficiency of the production process of companies. This would result in the usage of less energy (ID 2.2.2), paper, and other materials (ID 5.2.2), and create less waste by two of the companies (ID 3.2.2; 1.2.2). One respondent (ID 6.2.2) specifically talks about the 'ERP system' as a digital technology that has a big influence on green production together with digital work instructions. This corresponds with another quote (ID 1.2.2), which mentions that online portals with suppliers lead to a reduction of material waste.

Given the findings related to green production and the relationship between green production and digitalisation. The hypothesis of H1 can be accepted:

H1. *There is a positive relationship between Digitalisation and Green Production in all various production stages.*

Table 11: Relevant quotes of the relationship 'Digitalisation and Green Production'

ID label	Quote	Open Code
2.2.2	"Op het moment dat je processen efficiënter verlopen. Ja goed, daar zal ook minder energie gebruikt worden. Dus in die zin zou er dan een relatie zijn."	Efficiency
5.2.2	"Door digitalisatie gebruiken we bijvoorbeeld wel geen papier meer. We doen bijna niks meer analoog."	GP practices
3.2.2	"Het genereert ieder geval stuk inzicht. En groen produceren, daar kom je achter door naar de data te kijken en dat doen we eigenlijk niet anders. Het zorgt ervoor dat wij eind van de rit veel minder afval genereren."	Insights data
1.2.2	"Digitalisering is niet specifiek opgezet voor groene productie. Wat natuurlijk wel helpt, zijn de digitale portals die we hebben met onze leverancier. Deze materiaalsturing helpt ons om verspillingen te voorkomen."	Waste limitation
6.2.2	"Het ERP systeem gaat dat bij ons heel veel invloed hebben op groene productie. En het digitaliseren van bepaalde werkinstructies. "	Influence

4.2.3.2 R&D and Green Production, and R&D as moderator on Digitalisation and Green Production

According to the quotes in Table 12, it can be concluded that R&D has a direct influence on the sustainability and green production of a manufacturing company (ID 2.3.2; 6.3.2). This is mainly based on the growing demand for greener (produced) products and sustainability. This is thus based on the wishes of the specific customer (ID 6.3.2). When looking at quotes related to R&D as a moderator (ID 1.3.2 (1); 1.3.2 (2); 4.3.2), different answers are given. Quote 4.3.2 initiates a positive interaction effect of R&D based on the growing data-driven developments. Another respondent mentioned that there is not really for production a significant role, although he mentioned a significant impact on the whole supply chain (ID 1.3.2 (1)). The other relevant quote shows the difference in effect R&D can have on different types of companies (ID 1.3.2 (2)). According to this respondent, the main characteristic for different effects should be the amount of machinery there is present in the production process. The more machinery, the better the effect would be on the relationship. This theory can clarify the different opinions shown above. Overall, R&D would have a positive moderation effect on digitalisation and green production.

Given the findings related to green production and the relationship between green production and digitalisation. The hypothesis of H2 and H3 can be accepted:

H2. *There is a positive relationship between R&D modes and Green Production.*

H3. *R&D positively impacts the relationship between Digitalisation and Green Production.*

Table 12: Relevant quotes of the relationship 'R&D and Green Production' and R&D as moderator

ID label	Quote	Open Code
1.3.2 (1)	"Ja R&D en digitalisering heeft dan voor het stuk productieverbetering niet een hele grote rol. Maar wel in de hele keten denken. Ik zie productie als één stap in de keten. De keten is van leveranciers tot aan de boeren en die moet je slim besturen en dan heb je veel aan digitalisering. Dat helpt daar heel erg bij."	Supply Chain
2.3.2	"Ik denk wel dat er een invloed is want uiteindelijk de machines die wij morgen bouwen of de machine concepten die we morgen bouwen en die R&D vandaag aan het ontwikkelen is. Daarbij wordt er wel sterk gekeken naar de vraagstelling van de klant die ook steeds complexer wordt met meer digitalisering en duurzaamheid."	Interaction R&D
1.3.2 (2)	"Het productie stukje an sich is vooral fysiek waarbij het niet een hele grote rol speelt bij ons. Als jij gaat als jij naar bijvoorbeeld bedrijf gaat kijken, die plaatmaterialen maken of las samenstellingen, daar heb je veel meer machines en daar is digitalisering speelt daar gewoon een grotere rol."	Difference between companies
6.3.2	"Als de klant erom vraagt. Ja, wij ontwikkelen altijd een product voor de klant. Dus als een klant een groen product wil om het even zo te noemen, dan zullen zij daar de materialen bij uitzoeken en daar ook verder over nadenken."	Customer specification
4.3.2	"Alles wordt met heel veel met data gedreven dan heb je dan heb je automatisering of computertechnologie nodig. Ik denk dat het antwoord "ja" is."	Interaction R&D

4.2.3.3 Interoperability as moderator on Digitalisation and Green Production

From the quotes about interoperability as a moderator, the majority see positive effects of connectivity or interoperability with multiple digital technologies (ID 1.4.2; 2.4.2; 3.4.2; 4.4.2; 5.4.2). Implementing interoperability would increase efficiency (ID 2.4.2), production rate, and decrease in stock (ID 3.4.2). Important conditions are information sharing (4.4.2) and monitoring (ID 5.4.2) to maximize the use of the connectivity (ID 1.4.2). One respondent saw no effects of interoperability in the production (ID 6.4.2). The positive benefits would be only from the digitalisation itself and not the interoperability.

Given the findings related to the interaction effect of interoperability on the relationship between digitalisation and green production. The hypothesis of H4 can be accepted:

H4. *Interoperability positively impacts the relationship between Digitalisation and Green Production.*

Table 13: Relevant quotes of the relationship 'Interoperability' as moderator

ID label	Quote	Open Code
2.4.2	"Ja dat is omdat je efficiënter kan werken en dan gooi je misschien minder materialen weg of voorkom je fouten."	Efficiency
5.4.2	"Ja zeker wel. Met die verbondenheid en monitoring kun je dit soort dingen wel eruit halen en verbeteren."	Monitoring
1.4.2	"Ik denk dat die verbondenheid heel veel helpt. Ik denk dat het op een goede manier aan elkaar knopen van die van digitale hulpmiddelen, dat dat echt gaat helpen."	Connectivity
6.4.2	"Ik denk dat de koppeling op zich niet van invloed gaat zijn, maar het gaat digitaliseren opzich gaat van invloed zijn. Ik denk dat de koppeling meer het gebruikersgemak vergroot."	Convenience
4.4.2	"Het sharen van digitale informatie scheelt een hoop papier, dus dat is sowieso een milieu boost. Dat is denk ik wel een winstpunt."	Information sharing
3.4.2	"We verbruiken dan minder, kunnen sneller produceren en de voorraad kan omlaag."	Positive effects

4.3 Summary of the Results

Comparing quantitative and qualitative results, there are similarities and differences in the concepts measured in the qualitative and quantitative parts. In both types of research, digitalisation is measured by the implementation rate of different technologies. For green production, a similarity is the tested sustainable technologies. A difference in green production is the addition of efficiency in the qualitative research. This efficiency can be stimulated by specific ways of working or producing related to the manufacturing company. R&D activities are part of the concept of R&D in both research, although the different R&D modes are included in the qualitative part. Lastly, the concept of interoperability is tested differently in the quantitative and qualitative parts. The qualitative part focused on the specific connection between digital technologies and the different approaches to managing this interoperability. The quantitative part focused on two items which are practices for creating interoperability.

Besides the differences in the formulated hypotheses, there are some differences in accepting or rejecting the formulated hypothesis. The quantitative results show that R&D doesn't have a positive interaction effect whereas the qualitative results do show a positive interaction effect. Furthermore, analysing the quantitative statistics concluded also a rejection of the fourth hypothesis. According to this, Interoperability doesn't have a positive interaction effect on the relationship between digitalisation and green production. Contrary to these statistics, the relevant quotes from the qualitative results do show a positive interaction effect and thus this hypothesis needs to be accepted. The other hypotheses of the relationship between digitalisation and green production and R&D and green production are accepted in both results. An overview of the acceptance or rejection of the hypotheses is shown in Table 14 and applied to the conceptual model in Figure 2.

Table 14: Summary of the formulated hypotheses

Description hypothesis	Result quantitative	Result qualitative
H1. There is a positive relationship between Digitalisation and Green Production in all various production stages.	Accepted	Accepted
H2. There is a positive relationship between R&D modes and Green Production.	Accepted	Accepted
		Accepted
		Accepted

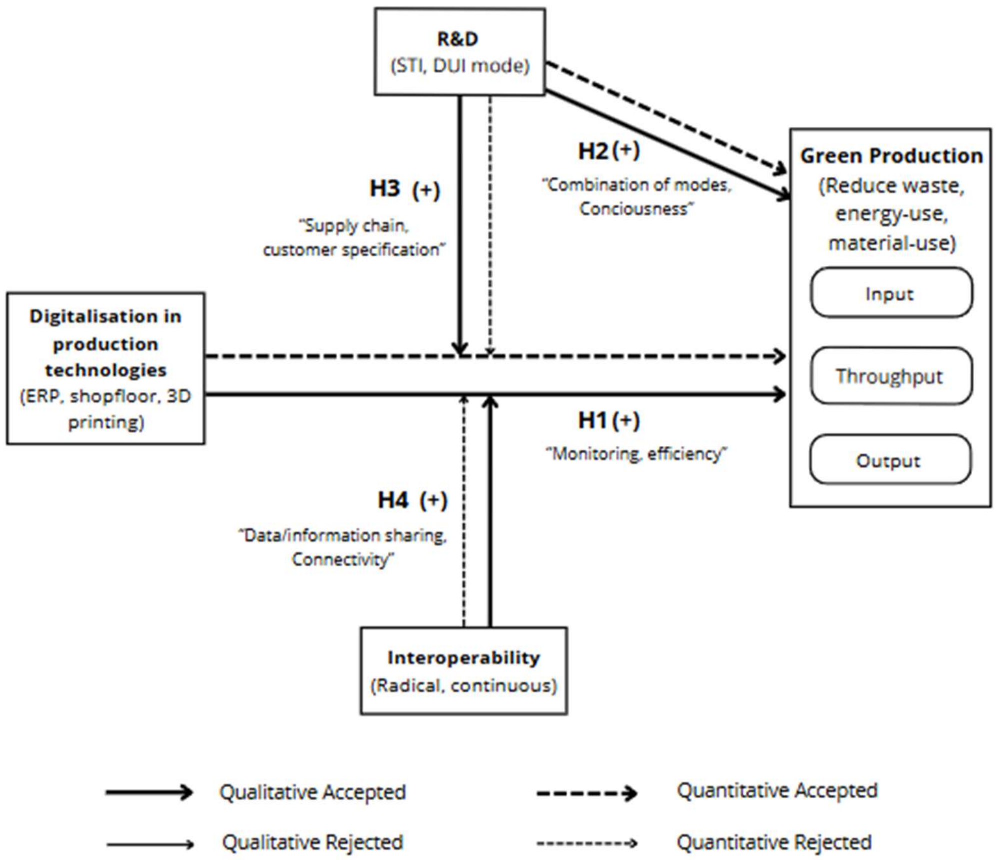

Figure 2: Illustration of the conceptual model with the final conclusions

5. Conclusion

This section will provide a summary of the findings which are derived from the triangulation method to get an answer to the following research question:

"What is the impact of digitalisation, interoperability, and R&D on green production? And how could interoperability and R&D best be organised?"

As already mentioned, this study used a triangulation method to get useful insights and conclusions. To further explain the core concepts of this study, a literature search has been done. Based on the available and found literature, a conceptual model and hypotheses are formulated to test in a quantitative and qualitative part. In the quantitative part, the concepts are measured by the constructs related to theory. These constructs and relations between constructs are tested with the regression model. In the qualitative part, the main concepts are tested based on six semi-structured interviews at Dutch manufacturing companies. These interviews were thematically and open-coded to get a deeper understanding of the relationships between the main concepts.

In the literature search, there were only positive relations found between the concepts of digitalisation, R&D, and interoperability with green production. Digitalisation and R&D would have on itself have a positive impact on green production. Simultaneously, interoperability and R&D have a positive mediation effect on the relationship between digitalisation and green production. Literature also suggested the distinction in R&D between an STI- or DUI-mode. For managing interoperability, a radical change approach and a continuous improvement approach were found that could be implemented. The distinctions of both concepts were tested in the qualitative part for insights into how to organise R&D and interoperability.

The quantitative part of this study showed partly different outcomes and insights than the literature study suggested. The direct relations of digitalisation and R&D on green production were positive and similar as highlighted in the literature section. It implies that an increase in both digitalisation and R&D has a positive stimulating effect on green production performance within Dutch manufacturing companies. The moderating roles of R&D and interoperability on green production showed a non-significant and negative impact. This would mean that the presence of R&D and interoperability are not impacting the relationship between digitalisation and green production.

The qualitative part showed outcomes that are aligned with the literature search. The results mention that the conceptual model only consists of positive relationships. The direct effects of R&D and digitalisation on green production are found positive. As well as the indirect moderation effects of

R&D and interoperability. The results from the interviews also show that for R&D, a mixture of both STI- and DUI-mode approaches are the most desirable for achieving success. The main reason is that both approaches complement each other and can be executed simultaneously. For interoperability, a continuous improvement approach would be for the majority of the respondents the ideal approach. A radical change approach would be too complex to deal with and create difficulties in finding potential bottlenecks.

6. Discussion & Implications

In this section, the discussion is presented based on the findings of the study. The main findings will be discussed and linked to previous academic literature. Additionally, future research directions are given following the discussion of the main findings.

The first finding of the study supported by both quantitative and qualitative research is the positive effect of digitalisation on green production. In the interviews, it has been shown that digitalisation stimulates green production performances by creating the ability to monitor production processes. Monitoring would result in efficiencies in the use of materials and energy and reduce the risk of errors, leading to a higher level of green production (Niehoff, 2022). Besides monitoring, research shows more benefits of digitalisation concerning green production such as value creation, factory layout, smart manufacturing, and optimal planning (Beier et al., 2017). These benefits are not been mentioned in the interviews because of the limited use of digitalisation. A reason for this is the lack of possibilities for implementing digital technologies due to product-specific assembly operations in between the production process. More knowledge of digitalisation and specific technologies could help deal with this problem (Malacina & Teplov, 2022). Multiple studies show that the lack of knowledge is a barrier to digital implementation (Ghazilla et al., 2015; Jabbour et al., 2016; Karuppiah et al., 2020). Thus to stimulate more digitalisation and green production, research should investigate and provide knowledge on which digital technologies are best for assembly operations and how these can be best implemented.

Furthermore, this study investigated the direct effect of R&D on green production and the moderating effect of digitalisation and green production. The direct effect is positive and supported by quantitative and qualitative research. The interviews suggested that applying R&D results in improved and efficient production processes, thus promoting green production. An example given by a respondent is a new way of producing which is found through R&D and increasing sustainability by less pollution. For the moderating effect, quantitative research shows no effect and the qualitative part shows a positive effect. A reason for the difference which is given in the interviews, is the amount of implemented digitalisation in these specific companies. R&D is increasingly focusing on improving and implementing digitalisation as a problem-solver for the specific needs of the company or its customers (Ben Khalifa, 2023). The more digitalisation is applied in the production process, the more impact R&D can have on the relationship between digitalisation and green production (Ma et al., 2022). Overall, R&D needs to be prioritised by manufacturing companies to stimulate green production performance (Baek & Lee, 2024).

In the analysis of the different R&D modes from the qualitative results, respondents mainly saw a combination of both STI- and DUI-modes as the best option for practicing R&D. They mentioned that both R&D modes complement each other. This is aligned with other research that shows the effectiveness of this combination (Jensen et al., 2007; Santos et al., 2022). It can trigger innovation activities beyond R&D and supports the building of technology platforms in less research-intensive companies (Isaksen & Nilsson, 2013). Contrary to this, articles by Apanasovich (2014) and Peña et al. (2012) found that combining STI and DUI modes is not more effective in generating organisational innovation than companies relying only on the DUI mode. This is aligned with the conducted interviews while some respondents see only the DUI mode as the main R&D mode. They see DUI as the easiest and fastest way to innovate within their company. The literature review of Apanasovich (2016) showed that current literature on R&D modes is mostly applied to product innovation rather than process innovation, while (production) process innovation is the main focus of this study. Because of the absence of literature on the R&D modes and process innovation, future research should focus on this on a larger scale to gain more knowledge.

Additionally, this study shows the moderating role of interoperability on digitalisation and green production. The quantitative part shows a non-significant effect while the qualitative part shows a positive effect. This is mainly due to the lack of internal consistency and the low number of items for interoperability. It resulted in a less valid result and non-significant relationship because the items don’t measure the full construct of interoperability. The interviews show that interoperability influences the impact digitalisation has on green production. Interoperability boosts the information-sharing process and the ability to monitor the production process. It leads to less use of materials and energy, storage, and faster production. These benefits that are seen by respondents are also supported by literature (Dionisio & Paula, 2024; Frank et al., 2019). Thus, more digitalisation and interoperability increase green production performance. On the contrary, Lange et al. (2020) stated that the more digitalisation and interoperability are used, the more energy is consumed during this process. Energy use, emission risks, and electronic waste are often overlooked (Kayikci, 2018; Kunkel & Matthess, 2020). Although digitalisation requires more use of energy, the benefits of digitalisation and interoperability are not been taking into account in these above-mentioned articles. This study shows that the benefits outweigh the negative effects of digitalisation on green production.

Finally, this study has participating Dutch manufacturing companies which are not very active in digitalisation. Most current manufacturing companies have not applied much digitalisation (Ligthart & Vaessen, 2020), showing that the participating companies are a reliable sample for Dutch manufacturing companies. Dionisio & Paula (2024) showed that companies with more digital implementation could have increasingly more benefits in green production than companies with less digitalisation. Therefore, the results and insights can differ when other manufacturing companies participate. Future studies should focus on manufacturing companies that have implemented more digital technologies to gain insights into how the different approaches in R&D and interoperability apply to a high level of digitalisation.

6.1 Theoretical Implications

The literature reveals that previous digitalisation and green production studies focus on basic concepts and relations. There is a lack of reliable and valid empirical studies which entail factors such as R&D and interoperability. The scarcity of empirical studies regarding these topics was identified in the literature, and hence this study makes a significant theoretical contribution to the literature in the form of explaining how R&D and interoperability influence the relationship between digitalisation and green production.

Previous studies investigated the role of R&D on general green performance (Baek & Lee, 2024; Paramati et al., 2021), as opposed to this study focusing only on the production process. Additionally, other studies didn't make a distinction in R&D between the STI and DUI mode (Xiong & Luo, 2023; Xu et al., 2020). Therefore, this study provides in both ways specific knowledge about R&D and green production. Within this study, the findings show that R&D has a direct positive impact on green production and a positive moderating effect on digitalisation and green production. A combination of STI and DUI modes would be best for practicing R&D, while only the DUI mode can work for some companies as well. These results have a significant theoretical value because they can explain the results of other studies that are investigating the role of R&D in green production.

Furthermore, this study found that interoperability has in combination with digitalisation a stimulating effect on green production. The continuous improvement approach is seen as the best managerial way to implement digitalisation while creating interoperability. This study builds upon the need for empirical studies related to the interoperability of digital technologies as mentioned by Dionisio & Paula (2024). There is still very little research on the impact of interoperability on sustainability aspects (Beier et al., 2017). Interoperability and digitalisation provide large opportunities for the ecological dimension of sustainability and this transformation should receive more attention within the currently existing literature (Beier et al., 2017). This study focuses on this transformation by giving insights into how companies can implement the transformation and therefore have a significant impact.

6.2 Practical Implications

The results derived from this study are relevant for mainly managers in Dutch manufacturing companies. These insights can be used to advise these managers about digitalisation and its effect on green production including R&D and interoperability as moderators.

Firstly, this study highlights the positive influence of digitalisation on green production. Digitalisation can be a great tool for managers to make their production process more sustainable and green. Respondents concluded that digitalisation results in increased efficiency, predictability, and decreased chance of mistakes (Table 11). For the optimisation of certain digital technologies, companies need to focus on building trust, cooperation, and transparency with other members of the supply chain (Table 7). An important aspect that should be considered by managers, is the interoperability and the interconnectedness of digital technologies stimulating more green production. To introduce more digital technologies to create interoperability, managers need to implement them making use of a continuous approach. This approach ensures that the implementation is relatively slow but smooth and is used successfully by the majority of the participating companies. A radical change approach would be faster but increases the risk of errors in the production process, as stated by the respondent from quote 5.4.1 (Table 10).

When managers want to maximise their green production in their manufacturing company, they should consider the role of R&D in their company. This study acknowledges the importance of R&D with a direct positive effect on green production, as well as a positive moderating effect with digitalisation on green production. According to the respondents (Table 9), R&D should be executed by using a combination of STI and DUI mode approaches. Participants are successful in an STI approach by making use of cooperation while having an internal development focus as the DUI mode. Cooperation is present in the participating companies by aligning with universities, customers, suppliers, or sister companies. These ways of cooperation in combination with the DUI mode, for optimal results. Another important highlight for managers is the fact that R&D has a greater effect if there is also a greater degree of digitalisation. Especially in Dutch manufacturing companies, the average degree of digitalisation present in the production process is relatively low. Therefore it is important to implement more digital technologies while making use of R&D. This is also mentioned by a respondent highlighting the minimal impact R&D has because of the lack of implemented digital technologies.

6.3 Limitations

Given the mixed-method research design of this study, the results are valid and reliable. As already mentioned, this is because of the applied triangulation to create valuable insights and an answer to the specific research question of this study. Still, this study has some limitations which are presented in this section.

The first limitation is the low reliability score when measuring the constructs in the quantitative part of this study. Considering the normal acceptable value of Cronbach's Alpha ($\alpha \geq 0.7$), the constructs 'digitalisation', 'green production', and 'interoperability' are all not meeting the score and therefore showing a low internal consistency. Although this low internal consistency is a limitation of this study, a positive consequence is the high heterogeneity of the constructs.

A second limitation is related to the regression analyses used for the quantitative research part. The regression technique shows only an association between certain tested concepts. It doesn't show causality between or more constructs. In this study, it is the assumed relation between digitalisation and green production. The results are perceived in a way that digitalisation has an impact on green production. Because of the limitation of this regression technique, it could in reality be the opposite. In that case, green production would be the independent variable and digitalisation would be stimulated as the dependent variable.

Another limitation is the construct validity of the concepts in the quantitative part. There is an assumption being made that the number of different technologies implemented, shows a high rate of digitalisation. The construct 'digitalisation' includes 14 technologies, while maybe other technologies implemented by manufacturing companies are left out. Also, the scope of digital technologies is not mentioned and can have an impact on the results. For example, some technologies can be used more than others or are implemented in the main or side production line. This is also relatable to the construct of 'green production', which consists of several green production technologies. Manufacturing companies participating could have different green production technologies than mentioned in the EMS-Qualtrics. While the included technologies are the most relevant ones on both concepts, the same assumption related to the construct of 'digitalisation' is also relevant to 'green production'. For the construct 'interoperability', the EMS-survey doesn't provide clear questions that cover this concept. Although covering some characteristics of interoperability, the two items are not sufficient and can be considered as a limitation of the study.

Lastly, the respondents who participated in the interviews didn't always have the information that could have created more and better insights into the concepts. It resulted in sometimes general answers and more specific information would have increased the relevancy of the insights for this study. Respondents with a function working on the production floor could have had more specific and direct information which would have been more helpful for the study.

6.4 Ethical Reflection

To ensure ethical behaviour while conducting this research, multiple specific actions are taken. Firstly, concerning the interviews, agreements have been met between the researcher and the participating companies and respondents. The interviews are recorded and the audio is after the transcription is deleted. In the transcripts, the respondent and company neem are made anonymous by using tags like Company A, Respondent A, etc. Academic literature has been used and referenced ethically by using the Zotero program. The use of ChatGPT is minimised to the extent of only using it for creating similar search terms related to the core concepts. Moreover, a popular program has been used to translate valuable information from the interviews. Additionally, an integrity statement is signed and can be seen in Appendix 4.

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8. Appendixes

Appendix 1: Interview script

Thema	Open hoofdvragen (+ doorvraag vragen)	Geschatte tijd
Introductie	Ik ben Tom Kessels, student aan de Radboud Universiteit. Op dit moment ben ik bezig met het masterprogramma Strategic Management. Hiervoor schrijf ik mijn masterscriptie en daar draagt dit interview aan bij. Ik doe onderzoek naar de relatie tussen digitalisering en groene productie, met daarbij tussen factoren als R&D en de samenwerking/verbinding tussen de digitale technologieën. Voordat we beginnen, kan ik de audio van het interview opnemen voor transcriptie naderhand? Naderhand wordt het audiofragment verwijderd en in het transcript worden alle namen etc anoniem gemaakt zodat er niks traceerbaar of te identificeren is. Het interview zal ongeveer een uur duren. Heeft u zelf richting mij nog vragen of dingen die u wilt weten?	**5 min.**
Oriënterende vragen voor de respondent	**Wat is uw functie/rol in het bedrijf?** (Taken, ervaring in het algemeen, binnen bedrijf)	**5 min.**
	Wat is … voor een bedrijf? (Grootte, producten, aanvullende diensten, opererende markt)	
	Ondernemingsstrategie: Wat is het doel van het bedrijf in 5 jaar? (Kernactiviteiten, wat onderscheidt bedrijf van anderen?)	
	Op welke manier bent u betrokken bij innovatie activiteiten in uw bedrijf? (Productie?, productontwikkeling? Focus op werkzaamheden/ activiteiten)	
Digitalisering in het productieproces	Dan wil ik het nu graag hebben over de digitale technologieën die zijn toegepast in het productieproces in uw bedrijf. Hierbij kunnen we denken aan technologieën zoals: Internet, AI, Big Data, bepaalde machines, robots, 3D-printer, VR etc.	**10 min.**
	Welke digitale technologieën zijn er in uw bedrijf aanwezig in het productieproces? (bijv. machines, installaties, gereedschappen)	
	Wat vormt vooral de aanleiding tot het invoeren van de digitale technologieën? (aanbod leveranciers; verandering product; makrtvraag; suggesties personeel/concurrenten; voorbeelden?)	
	Wat zijn de gevolgen van deze digitalisering voor het productieproces en het gehele bedrijf? (voordelen, nadelen, implementatie, barrieres, toen vs nu vergelijken)	

Groene productie	Dan wil ik het nu graag hebben over de groene productie/ duurzaamheid in uw bedrijf. Groene productie is op een duurzame manier produceren waarbij er zo min mogelijk afval en energie etc verbruikt wordt. Dit kan in de verschillende fases van de productie (input, throughput en output) toegepast worden. Voornamelijk richten we ons in dit interview op de throughput van het productieproces.	**10 min.**
	Welke activiteiten die uw bedrijf uitvoerd, vallen onder groene productie / duurzaamheid? (voorbeelden, bewustzijn van groene activiteiten, prioriteiten, neveneffecten)	
	Hoe zou de mate van groene productie nog meer verbeterd/gestimuleerd kunnen worden binnen uw bedrijf? (Investeringen, kennis, aandacht, personeel, cursussen/trainingen)	
	Inhoeverre zijn digitale technologieën betrokken bij groene productie activiteiten in uw bedrijf? (Voorbeelden, algemeen, verschillen in impact van technologieën)	
R&D	Research and Development is een afdeling of een activiteit in een bedrijf die zich richt op innovatie/vernieuwingen van producten of processen. Dit kan vanuit de literatuur onder andere op twee verschillende manieren, namelijk meer gericht op wetenschap en technologische innovatie, en meer door learning-by-doing (dus door ervaringen van uitvoeren, gebruiken of communiceren)	**10 min.**
	Inhoeverre speelt R&D een rol in uw bedrijf? (Welke activiteiten, welke innovaties door R&D, aandacht voor R&D, betrokken afdelingen, belang van R&D)	
	Is R&D of innovaties in uw bedrijf vooral gericht op STI en/of DUI mode? Waarom? (Gevolgen, beste optie (en in algemeen?))	
	Inhoeverre heeft R&D invloed op de digitalisering en daarmee groene productie? (voorbeelden, activiteiten, verschillen in invloed door wel/geen focus op groene productgie, STI of DUI)	
Interoperability	Interoperability is de verbondenheid van verschillende digitale technologieën. Bijvoorbeeld een ERP-systeem die directe data doorstuurt naar een 3D-printer etc. Dit kan gemanaged/geïmplementeerd worden door radical changes (grote veranderingen in het productieproces mbt verbondenheid) of continuous improvements (kleinere veranderingen in proces mbt verbondenheid)	**10 min.**
	Inhoeverre is er interoperability aanwezig in het productieproces van uw bedrijf? (Voorbeelden, voordelen, nadelen/kwetsbaarheden, verschillende impact, ondersteunende factoren)	
	Hoe wordt de interoperability vooral 'gemanaged' in uw bedrijf? Continuous improvement of radical changes? (Voorbeelden, beste manier, voordelen, nadelen/risico's)	

	Inhoeverre heft de toepassing van interoperability op digitalisering invloed op groene productie? (positief of negatief, voorbeelden, radical of continuous changes, hindernissen, risico's)	
Outro	Dan zijn we aan het einde gekomen aan de vragen en het interview. Heel erg bedankt dat u deel heeft genomen aan het onderzoek en het interview. Nogmaals u blijft geheel anoniem in het transcript.	**5 min.**

Appendix 2: Output SPSS-data

Model Summary[d]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics					Durbin-Watson
					R Square Change	F Change	df1	df2	Sig. F Change	
1	,340[a]	,116	,081	1,56926	,116	3,332	7	178	,002	
2	,459[b]	,210	,161	1,49990	,095	5,211	4	174	<,001	
3	,471[c]	,222	,158	1,50191	,012	,845	3	171	,471	1,899

a. Predictors: (Constant), Electronic, lnSize number of employees 2017 (log), Construction, Textile, Food, Machinery, Chemical

b. Predictors: (Constant), Electronic, lnSize number of employees 2017 (log), Construction, Textile, Food, Machinery, Chemical, oi_IntegrationTasks Organizational concepts - Integration of tasks, dRD performing research and development (R&D) or award R&D contracts to external partners in 2021, oi_QualityMeasures Organizational concepts - Methods of assuring quality in production, Digi_Production index of digitalization process innovations used

c. Predictors: (Constant), Electronic, lnSize number of employees 2017 (log), Construction, Textile, Food, Machinery, Chemical, oi_IntegrationTasks Organizational concepts - Integration of tasks, dRD performing research and development (R&D) or award R&D contracts to external partners in 2021, oi_QualityMeasures Organizational concepts - Methods of assuring quality in production, Digi_Production index of digitalization process innovations used, i_cDiProXdRD, i_cDiProXIntTask, i_cDiProXQual

d. Dependent Variable: Sust_Production index of sustainable production technologies

Statistics

		Sust_Production index of sustainable production technologies	Digi_Production index of digitalization process innovations used	dRD performing research and development (R&D) or award R&D contracts to external partners in 2021	oi_IntegrationTasks Organizational concepts - Integration of tasks	oi_QualityMeasures Organizational concepts - Methods of assuring quality in production
N	Valid	186	186	186	186	186
	Missing	0	0	0	0	0
Mean		2,1505	3,9624	,4731	,6882	,7312
Std. Error of Mean		,12003	,18758	,03671	,03406	,03260
Median		2,0000	4,0000	,0000	1,0000	1,0000
Mode		1,00	3,00	,00	1,00	1,00
Std. Deviation		1,63705	2,55823	,50062	,46449	,44454
Variance		2,680	6,545	,251	,216	,198
Skewness		,428	,446	,109	-,819	-1,051
Std. Error of Skewness		,178	,178	,178	,178	,178
Kurtosis		-,635	-,516	-2,010	-1,344	-,904
Std. Error of Kurtosis		,355	,355	,355	,355	,355
Range		6,00	10,00	1,00	1,00	1,00
Minimum		,00	,00	,00	,00	,00
Maximum		6,00	10,00	1,00	1,00	1,00
Sum		400,00	737,00	88,00	128,00	136,00

Descriptive Statistics

	Mean	Std. Deviation	N
Sust_Production index of sustainable production technologies	2,1505	1,63705	186
lnSize number of employees 2017 (log)	3,9287	1,07349	186
Food	,0753	,26454	186
Textile	,1613	,36879	186
Construction	,0430	,20343	186
Chemical	,2043	,40428	186
Machinery	,1882	,39190	186
Electronic	,0645	,24633	186
Digi_Production index of digitalization process innovations used	3,9624	2,55823	186
dRD performing research and development (R&D) or award R&D contracts to external partners in 2021	,4731	,50062	186
oi_IntegrationTasks Organizational concepts - Integration of tasks	,6882	,46449	186
oi_QualityMeasures Organizational concepts - Methods of assuring quality in production	,7312	,44454	186
i_cDiProXdRD	,3189	1,84453	186
i_cDiProXIntTask	,3216	2,10030	186
i_cDiProXQual	,3393	2,15248	186

b

Correlations

		Sust_Production index of sustainable production technologies	lnSize number of employees 2017 (log)	Food	Textile	Construction	Chemical	Machinery	Electronic	Digi_Production index of digitalization process innovations used	dRD performing research and development (R&D) or award R&D contracts to external partners in 2021	oi_IntegrationTasks Organizational concepts - Integration of tasks	oi_QualityMeasures Organizational concepts - Methods of assuring quality in production	i_cDiProXdRD	i_cDiProXIntTask	i_cDiProXQual
Pearson Correlation	Sust_Production index of sustainable production technologies	1,000	,252	,148	-,058	,078	,125	-,061	-,158	,301	,209	,190	,138	,254	,206	,224
	lnSize number of employees 2017 (log)	,252	1,000	,201	-,045	-,053	,046	-,040	-,055	,411	,207	,136	,249	,370	,384	,367
	Food	,148	,201	1,000	-,125	-,060	-,145	-,137	-,075	-,044	,097	,060	,081	-,001	-,040	-,050
	Textile	-,058	-,045	-,125	1,000	-,093	-,222	-,211	-,115	-,114	-,093	-,083	-,130	-,065	-,084	-,017
	Construction	,078	-,053	-,060	-,093	1,000	-,107	-,102	-,056	-,049	,011	,028	-,051	-,035	-,030	-,031
	Chemical	,125	,046	-,145	-,222	-,107	1,000	-,244	-,133	-,123	-,053	,024	,127	-,170	-,148	-,178
	Machinery	-,061	-,040	-,137	-,211	-,102	-,244	1,000	-,126	,136	,067	-,003	-,018	,109	,129	,097
	Electronic	-,158	-,055	-,075	-,115	-,056	-,133	-,126	1,000	,012	,014	,035	,011	,017	,005	,003
	Digi_Production index of digitalization process innovations used	,301	,411	-,044	-,114	-,049	-,123	,136	,012	1,000	,250	,272	,300	,743	,840	,862
	dRD performing research and development (R&D) or award R&D contracts to external partners in 2021	,209	,207	,097	-,093	,011	-,053	,067	,014	,250	1,000	,150	,210	,183	,191	,190
	oi_IntegrationTasks Organizational concepts - Integration of tasks	,190	,136	,060	-,083	,028	,024	-,003	,035	,272	,150	1,000	,194	,156	,103	,186
	oi_QualityMeasures Organizational concepts - Methods of assuring quality in production	,138	,249	,081	-,130	-,051	,127	-,018	,011	,300	,210	,194	1,000	,161	,197	,096
	i_cDiProXdRD	,254	,370	-,001	-,065	-,035	-,170	,109	,017	,743	,183	,156	,161	1,000	,693	,713
	i_cDiProXIntTask	,206	,384	-,040	-,084	-,030	-,148	,129	,005	,840	,191	,103	,197	,693	1,000	,779
	i_cDiProXQual	,224	,367	-,050	-,017	-,031	-,178	,097	,003	,862	,190	,186	,096	,713	,779	1,000
Sig. (1-tailed)	Sust_Production index of sustainable production technologies	.	<,001	,022	,214	,145	,045	,203	,015	<,001	,002	,005	,031	<,001	,002	,001
	lnSize number of employees 2017 (log)	,000	.	,003	,270	,237	,265	,294	,230	,000	,002	,032	,000	,000	,000	,000
	Food	,022	,003	.	,044	,206	,024	,031	,155	,277	,094	,208	,136	,492	,295	,248
	Textile	,214	,270	,044	.	,103	,001	,002	,059	,061	,102	,129	,039	,190	,128	,409
	Construction	,145	,237	,206	,103	.	,072	,083	,225	,254	,439	,351	,246	,320	,344	,336
	Chemical	,045	,265	,024	,001	,072	.	,000	,035	,047	,237	,370	,042	,010	,022	,007
	Machinery	,203	,294	,031	,002	,083	,000	.	,043	,032	,181	,486	,402	,070	,040	,095
	Electronic	,015	,230	,155	,059	,225	,035	,043	.	,433	,424	,317	,440	,411	,473	,485
	Digi_Production index of digitalization process innovations used	,000	,000	,277	,061	,254	,047	,032	,433	.	,000	,000	,000	,000	,000	,000
	dRD performing research and development (R&D) or award R&D contracts to external partners in 2021	,002	,002	,094	,102	,439	,237	,181	,424	,000	.	,021	,002	,006	,004	,005
	oi_IntegrationTasks Organizational concepts - Integration of tasks	,005	,032	,208	,129	,351	,370	,486	,317	,000	,021	.	,004	,017	,080	,006
	oi_QualityMeasures Organizational concepts - Methods of assuring quality in production	,031	,000	,136	,039	,246	,042	,402	,440	,000	,002	,004	.	,014	,003	,097
	i_cDiProXdRD	,000	,000	,492	,190	,320	,010	,070	,411	,000	,006	,017	,014	.	,000	,000
	i_cDiProXIntTask	,002	,000	,295	,128	,344	,022	,040	,473	,000	,004	,080	,003	,000	.	,000
	i_cDiProXQual	,001	,000	,248	,409	,336	,007	,095	,485	,000	,005	,006	,097	,000	,000	.
N	Sust_Production index of sustainable production technologies	186	186	186	186	186	186	186	186	186	186	186	186	186	186	186
	lnSize number of employees 2017 (log)	186	186	186	186	186	186	186	186	186	186	186	186	186	186	186
	Food	186	186	186	186	186	186	186	186	186	186	186	186	186	186	186
	Textile	186	186	186	186	186	186	186	186	186	186	186	186	186	186	186
	Construction	186	186	186	186	186	186	186	186	186	186	186	186	186	186	186
	Chemical	186	186	186	186	186	186	186	186	186	186	186	186	186	186	186
	Machinery	186	186	186	186	186	186	186	186	186	186	186	186	186	186	186
	Electronic	186	186	186	186	186	186	186	186	186	186	186	186	186	186	186
	Digi_Production index of digitalization process innovations used	186	186	186	186	186	186	186	186	186	186	186	186	186	186	186
	dRD performing research and development (R&D) or award R&D contracts to external partners in 2021	186	186	186	186	186	186	186	186	186	186	186	186	186	186	186
	oi_IntegrationTasks Organizational concepts - Integration of tasks	186	186	186	186	186	186	186	186	186	186	186	186	186	186	186
	oi_QualityMeasures Organizational concepts - Methods of assuring quality in production	186	186	186	186	186	186	186	186	186	186	186	186	186	186	186
	i_cDiProXdRD	186	186	186	186	186	186	186	186	186	186	186	186	186	186	186
	i_cDiProXIntTask	186	186	186	186	186	186	186	186	186	186	186	186	186	186	186
	i_cDiProXQual	186	186	186	186	186	186	186	186	186	186	186	186	186	186	186

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	57,445	7	8,206	3,332	,002[b]
	Residual	438,340	178	2,463		
	Total	495,785	185			
2	Regression	104,338	11	9,485	4,216	<,001[c]
	Residual	391,447	174	2,250		
	Total	495,785	185			
3	Regression	110,056	14	7,861	3,485	<,001[d]
	Residual	385,729	171	2,256		
	Total	495,785	185			

a. Dependent Variable: Sust_Production index of sustainable production technologies

b. Predictors: (Constant), Electronic, lnSize number of employees 2017 (log), Construction, Textile, Food, Machinery, Chemical

c. Predictors: (Constant), Electronic, lnSize number of employees 2017 (log), Construction, Textile, Food, Machinery, Chemical, oi_IntegrationTasks Organizational concepts - Integration of tasks, dRD performing research and development (R&D) or award R&D contracts to external partners in 2021, oi_QualityMeasures Organizational concepts - Methods of assuring quality in production, Digi_Production index of digitalization process innovations used

d. Predictors: (Constant), Electronic, lnSize number of employees 2017 (log), Construction, Textile, Food, Machinery, Chemical, oi_IntegrationTasks Organizational concepts - Integration of tasks, dRD performing research and development (R&D) or award R&D contracts to external partners in 2021, oi_QualityMeasures Organizational concepts - Methods of assuring quality in production, Digi_Production index of digitalization process innovations used, i_cDiProXdRD, i_cDiProXIntTask, i_cDiProXQual

Coefficients[a]

Model		Unstandardized Coefficients B	Unstandardized Coefficients Std. Error	Standardized Coefficients Beta	t	Sig.	Collinearity Statistics Tolerance	Collinearity Statistics VIF
1	(Constant)	,720	,481		1,495	,137		
	lnSize number of employees 2017 (log)	,336	,110	,221	3,053	,003	,952	1,051
	Food	,705	,484	,114	1,458	,147	,812	1,231
	Textile	-,071	,364	-,016	-,194	,846	,739	1,353
	Construction	,799	,599	,099	1,334	,184	,897	1,115
	Chemical	,479	,340	,118	1,409	,161	,706	1,417
	Machinery	-,068	,347	-,016	-,197	,844	,718	1,392
	Electronic	-,800	,506	-,120	-1,581	,116	,858	1,166
2	(Constant)	,509	,479		1,061	,290		
	lnSize number of employees 2017 (log)	,107	,119	,070	,897	,371	,746	1,340
	Food	,969	,475	,157	2,039	,043	,769	1,300
	Textile	,180	,353	,041	,510	,611	,718	1,393
	Construction	,906	,576	,113	1,574	,117	,887	1,127
	Chemical	,740	,335	,183	2,206	,029	,661	1,512
	Machinery	-,138	,333	-,033	-,415	,679	,716	1,396
	Electronic	-,793	,484	-,119	-1,637	,103	,854	1,171
	Digi_Production index of digitalization process innovations used	,174	,053	,273	3,297	,001	,663	1,507
	dRD performing research and development (R&D) or award R&D contracts to external partners in 2021	,395	,233	,121	1,693	,092	,891	1,122
	oi_IntegrationTasks Organizational concepts - Integration of tasks	,296	,251	,084	1,180	,240	,897	1,115
	oi_QualityMeasures Organizational concepts - Methods of assuring quality in production	-,101	,272	-,027	-,372	,711	,834	1,199
3	(Constant)	,281	,589		,476	,634		
	lnSize number of employees 2017 (log)	,110	,121	,072	,911	,364	,727	1,376
	Food	,951	,476	,154	1,997	,047	,769	1,301
	Textile	,204	,355	,046	,575	,566	,712	1,404
	Construction	,926	,576	,115	1,606	,110	,887	1,128
	Chemical	,736	,339	,182	2,175	,031	,651	1,536
	Machinery	-,149	,334	-,036	-,447	,656	,713	1,402
	Electronic	-,805	,485	-,121	-1,659	,099	,853	1,172
	Digi_Production index of digitalization process innovations used	,258	,118	,403	2,183	,030	,133	7,494
	dRD performing research and development (R&D) or award R&D contracts to external partners in 2021	,391	,234	,120	1,675	,096	,891	1,122
	oi_IntegrationTasks Organizational concepts - Integration of tasks	,244	,258	,069	,947	,345	,849	1,177
	oi_QualityMeasures Organizational concepts - Methods of assuring quality in production	-,169	,287	-,046	-,588	,557	,751	1,331
	i_cDiProXdRD	,106	,094	,119	1,132	,259	,409	2,443
	i_cDiProXIntTask	-,098	,103	-,125	-,946	,346	,260	3,850
	i_cDiProXQual	-,092	,112	-,121	-,818	,415	,208	4,797

a. Dependent Variable: Sust_Production index of sustainable production technologies

Appendix 3: Research Integrity

Name: Tom Kessels	Student number: S1062052
RU e-mail address: Tom.kessels@ru.nl	Master specialisation: Strategic Management

Thesis title: **Connecting Digitalisation and Research and Development to Green Production: A Green Link?**
Brief description of the study: This study focuses on the relationship between digitalization and green production including R&D and interoperability as moderators. This study also investigates whether R&D has a direct effect on green production. Different approaches in R&D and managing interoperability are studied to gain insights into are best ways to practice both concepts. A mixed-method approach is being applied within this study, meaning that there is a quantitative and qualitative research method used. Besides using a database from the European Manufacturing Survey, six interviews were conducted targeting Dutch manufacturing companies. The results show that digitalization in itself positively stimulates green production. For R&D and interoperability as moderators, results in quantitative and qualitative research differ. Although for the direct impact of R&D, both types of research show a positive relationship. Additionally, qualitative research made clear that a combination of both R&D approaches is best for performance. A continuous improvement as a management style for interoperability seemed preferable over a radical change approach. This research contributes to the academic literature by adding R&D and interoperability and focusing on their approaches to stimulate green production. The results call attention to how managers need to perceive R&D and interoperability for practicing green production.

It is my responsibility to follow the university's code of academic integrity and any relevant academic or professional guidelines in the conduct of my study. This includes:

- providing original work or proper use of references;
- providing appropriate information to all involved in my study;

- requesting informed consent from participants;
- transparency in the way data is processed and represented;
- ensuring confidentiality in the storage and use of data;

If there is any significant change in the question, design or conduct over the course of the research, I will complete another Research Integrity Form.

Breaches of the code of conduct with respect to academic integrity (as described / referred to in the thesis handbook) should and will be forwarded to the examination board. Acting contrary to the code of conduct can result in declaring the thesis invalid

Student's Signature: ______________________________ **Date:** 17-6-2024

To be signed by supervisor

I have instructed the student about ethical issues related to their specific study. I hereby declare that I will challenge him / her on ethical aspects through their investigation and to act on any violations that I may encounter.

Supervisor's Signature: ______________________________ **Date:**