Working Paper Sustainability and Innovation
No. S 07/2019

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# Environmental product innovations and the digital transformation of production –

Analysing the influence that digitalising production has on generating environmental product innovations

Fraunhofer ISI

**Acknowledgements**

This paper is based partially on results of the European project "***Access to I4MS — XS2I4MS".*** This project has received funding from the European Union's **Horizon 2020** research and innovation programme under **grant agreement No 678860**.

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# 1 Introduction

## 1.1 Background and problem

The invention, market introduction and diffusion of innovations with improved environmental impacts play a special role in achieving the goal of sustainable development because they can support ecological sustainability and the competitiveness of the national economy to a large extent (cf. Rennings et al. 2008, p. 1; Frenken and Faber 2009, p. 449). Environmental innovations harbour a multitude of social and economic potentials that go beyond the purely ecological dimension. For instance, they can lead to increased competitiveness, productivity and a better economic situation even in individual enterprises (cp. Chiou et al. 2011, p. 822f.; Chen et al. 2006, p. 331; Ar 2012, p. 861).

A large number of empirical studies are therefore attempting to identify the conditions that give rise to environmental innovations by examining the determinants or factors influencing their generation and adoption (cf. Horbach 2008; Jansson et al. 2010; Wagner 2008; Wagner and Llerena 2011; Del Río González 2009; Horbach et al. 2012; Frondel et al. 2008, among others). However, detailed case studies and empirical approaches are still missing that focus on the different ecological effects of environmental product innovations (cf. Yang and Chen 2011, p. 998f.; Hojnik and Ruzzier 2016, p. 39; Díaz-García et al. 2015, p. 8ff.; Medeiros et al. 2014, p. 78f.). Existing studies usually focus on obvious factors that are mostly taken from classical innovation theory and the current environmental policy agenda and generally avoid indirect or less obvious factors that could make a valuable contribution to understanding how environmental innovations develop. Furthermore, very few studies clearly refer to the manufacturing sector in particular or to environmental product innovation rather than environmental process innovation in the initiation phase (cf. Medeiros et al. 2014, p. 78).

The digital transformation of the production environment in the manufacturing sector represents a comparatively new and potentially enabling factor. To date, however, the study of the ecological sustainability effects can mostly been reduced to direct resource efficiency improvements (cf. Beier et al. 2017, p. 227ff.; Börjesson Rivera et al. 2014, p. 105ff.; Hilty 2011, p. 3f., among others.). However, as a sub-phenomenon of one of the most important megatrends of the 21st century (cf. Collin et al. 2015, p. 29), we need to study its indirect ecological sustainability implications in more detail as well. In particular, so far, research is mostly restricted to induced environmental process innovations and has largely ignored the possible existence of correlations between the increased used of Internet and communication technologies in the digital transformation and the realisation of environmental innovations (cf. Cainelli et al. 2012, p. 704).

## 1.2 Objective

In this study, we therefore attempt to gain first insights into the digital transformation as a potential enabler of environmental product innovation, both conceptually and empirically. We strive for a holistic view that considers organisational, individual and technological aspects of the digital transformation. We start by examining the mechanisms based on current research through which we can establish a conceptual cause-effect relationship between the digital transformation of the production environment and environmental product innovation.

Another objective is to examine the potential cause-effect relationships empirically in the context of the manufacturing sector. We aim to examine both descriptive correlations and the impacts of the digital transformation of production by controlling other factors in a suitable multivariate model. This is based on an operationalisation of digital transformation in the form of an index that reflects the readiness for networked production in the sense of Industry 4.0.

## 1.3 Approach

After introducing the problem, objective and approach in chapter 1, Chapter 2 presents the theoretical background to environmental product innovation. In particular, we give a clear definition of this within innovation research and an overview of its potential determinants that have been identified in previous studies. In the following, we explain the concept and theoretical background of digital transformation in the production environment of the manufacturing sector in more detail. The focus here is on a definition and classification within the megatrend of digitalisation, an introduction to the ICTs used in the production environment that we examine in this study, and a presentation and systematisation of its possible environmental effects according to the latest research.

Based on current research, Chapter 3 presents a conceptual framework that can explain the influence that the digital transformation of the production environment has on environmental production innovation activities. In particular, we address how the digital transformation can potentially enable new business models and the generation of environmental product innovation by improving the company-internal and company-external integration of the innovation process.

Chapter 4 describes the empirical approach and the database used and gives a theoretical introduction to the multivariate logistic regression model used. Chapter 5 then provides a detailed description of the operationalisation of the variables and regression models used in the study.

In this study, we evaluate the empirical data both descriptively (Chapter 6) and econometrically (Chapter 7). We begin by presenting findings on environmental product innovation activity and the current status of the digital transformation of the production environment in Germany's manufacturing sector and then conduct a bivariate analysis of the group differences between these two constructs. The multivariate analysis in Chapter 7 compares the role of the digital transformation of the production environment with other potential determinants in regression models to explain the generation of substantial environmental product innovations and general product innovations.

Based on the hypotheses in the previous chapters, Chapter 8 evaluates the descriptive and econometric analyses with regard to the role of the digital transformation of the production environment in the conceptual framework of innovation activity. This is followed by a final review of the main findings, a critical appraisal of the work conducted and a suggestion for further studies of this subject.

# 2 Literature analysis

This chapter aims to illustrate and define our understanding of the characteristics and conditions under which environmental product innovations evolve. We begin by defining environmental product innovation in the context of innovation research. This is followed by presenting the results of a literature search for the most relevant determinants generating environmental product innovations in Germany’s manufacturing sector. We address the influence of policy framework conditions, market-, technology- and sector-related influencing factors as well as potential company-specific determinants.

## 2.1 Defining environmental product innovation

Environmental product innovation is the main focus of this study, i.e. tangible environmental innovation that affects the product. We understand environmental innovations as those that reduce or even avoid the environmentally-harmful impacts of using, adapting or disposing of an innovation object (cf. Klemmer et al. 1999, p. 5ff.; Rennings 2000, p. 322; Fussler and James 1996, p. 3ff.; Carrillo-Hermosilla et al. 2010, p. 1074, among others). These include both the reduction of environmentally-harmful emissions and waste as well as a reduction in resource consumption over the innovation’s entire life cycle (cf. Kemp and Pearson 2007, p. 5ff., among others). An innovation can be classified as an environmental innovation based on an actually achieved effect or the initiator’s intended effect (cf. Carrillo-Hermosilla et al. 2010, p. 1073f.). The survey evaluated in this study records the intention and therefore the conscious decision to realise environmental product innovations.

Research uses the terms *eco-innovation* and *green innovation* alongside *"environmental innovation"* that largely refer to the same kind of innovation (cf. Schiederig et al. 2012, p. 180; Díaz-García et al. 2015, p. 32). The only term that cannot be used within the scope of this study is *"sustainable innovation"*, because the common definition of this explicitly refers to social impacts as well as ecological and economic ones (cf. Schiederig et al. 2012, p. 188). Since this study focuses almost exclusively on the ecological impacts of product innovations, we made a deliberate decision to use the term environmental product innovation.

## 2.2 Determinants of environmental product innovation

A large part of the existing literature on environmental innovations focuses on identifying and examining key factors that influence the generation of environmental innovations by organisations. The term ‘determinant’, which is neutral in terms of describing the direction of impact, is primarily chosen to describe these factors (cf. Horbach 2008; Horbach et al. 2012). On the other hand, the term ‘driver’ is frequently used if the analysed factors are attributed the effect of enhancing and reinforcing this generation (cf. Díaz-García et al. 2015; Cuerva et al. 2014; Hojnik and Ruzzier 2016).

To understand this better, it is useful to document the influences of the potential determinants of environmental innovation at different levels of observation (Díaz-García et al. 2015, p. 11). For instance, the macro-level examines the influence of political framework conditions and regulations; the meso-level looks at the innovation system focusing on technology-push and market-pull effects; and the micro-level captures the influence of company-specific factors (cf. Cuerva et al. 2014, p. 105ff.; Díaz-García et al. 2015, p. 12). The next section reports the current research on the determinants at different levels. The focus here is on the company-specific factors of the micro-level that form the main object of our empirical studies.

### 2.2.1 Regulatory determinants

On the macro-level, the generation of environmental innovations is mainly influenced by a targeted regulatory framework (cf. Doran and Ryan 2012, p. 16; Horbach et al. 2012, p. 119). It is of the utmost importance that environmental policy displays a high degree of stringency (cf. Frondel et al. 2008, p. 158). Especially companies that are otherwise less innovative require very stringent regulations for effective support (Kesidou and Demirel 2012, p. 868). We can distinguish push and pull effects in the design of the regulatory framework; the former are oriented towards rules and the latter towards incentives (cf. Rennings 2000, p. 325f.; Del Río González 2009, p. 869). Earlier studies already observed the very promising effects on companies’ environmental innovation activities of individual policy instruments such as environmental standards, tax benefits, recycling fees, voluntary commitments and subsidies (cf. Hojnik and Ruzzier 2016, p. 36f.; Brouillat and Oltra 2012, p. 237ff.).

### 2.2.2 Market and technology-related determinants

The role played by market dynamics that spans across companies is also captured at the meso-level. Of particular importance here are changing customer requirements (cf. Horbach et al. 2012, p. 113), financing options (cf. Johnson and Lybecker 2012, p. 8), pressure from market stakeholders (cf. Yalabik and Fairchild 2011, p. 519) and sector-specific characteristics (cf. Peiró-Signes et al. 2011, p. 4ff.) (cf. Díaz-García et al. 2015, p. 14). The influencing factors on this level can also be roughly divided into market-pull and technology-push determinants (cf. Horbach et al. 2012, p. 113f.).

The suppliers and customers of enterprises also exert a clear **market-pull** effect on the generation of environmental innovations (cf. Wu 2013, p. 548). Above all, customer perceptions and requirements can contribute to the corporate decision for environmental innovation (cf. Doran and Ryan 2012, p. 436; Grunwald 2011, p. 676; Wagner and Llerena 2011, p. 760ff.). In particular, private end-consumers in many sectors are increasingly environmentally conscious and some even hope their attitude will influence the development of new products by manufacturing companies (cf. Tsai et al. 2012, p. 4442ff.).

The **technology-push** effect at the meso-level describes the pressure on organisations to come up with product innovations caused by the emergence of new technology solutions, usually without explicit customer pressure (cf. Paul 1987, p. 59f.). Numerous studies have identified technology-push as a relevant influencing factor, above all in the initiation phase of environmental innovation (cf. Hojnik and Ruzzier 2016, p. 38). The possibility for environmental innovation is closely linked to the possibilities for financing research and development on the technological meso-level (cf. Cuerva et al. 2014, p. 110). A distinction must be made between private and public financing whose effectiveness with regard to environmental innovation varies widely (cf. Johnson and Lybecker 2012, p. 3ff.). According to Halila and Rundquist (2011, p. 294), it is apparent to some extent that environmental innovators have to overcome more barriers and difficulties when acquiring capital for new developments than other innovators.

### 2.2.3 Company-specific determinants

In the context of environmental innovations, strategic and organisation-specific characteristics also have a significant effect at company level. A large number of determinants have therefore been analysed empirically at the level of individual companies. The following section gives an overview of the analysed company-specific aspects that are considered to be a factor for generating environmental innovation.

***Environmental management***

Environmental management is frequently seen as a deciding factor for the tendency towards environmental innovation. For instance, **management interest** in environmental matters is often seen as one of the most important drivers for introducing green practices in different industries (cf. Qi et al. 2010, p. 1364). The definition of **concrete company-internal environmental targets** appears especially important here (cf. Jakobsen and Clausen 2016, p. 138; Wagner and Llerena 2011, p. 760ff.).

Numerous studies have demonstrated the potential significance of various **environmental management systems and certificates** for generating environmental innovation (cf. Horbach 2008, p. 172; Horbach et al. 2012, p. 117; Jakobsen and Clausen 2016, p. 138; Rehfeld et al. 2007, p. 97). In particular, the ISO 14001 certification seems an effective lever that fosters the production of end-of-pipe solutions and ecological R&D (cf. Demirel and Kesidou 2011, p. 1554f.). An increased output of environmental innovations has also been observed in companies that have implemented a quality management system in line with ISO 9001 certification (cf. Leenders and Chandra 2013, p. 203ff.).

***Design of research and development***

Successfully integrating both internal and external stakeholders in the product development process is generally thought to play a significant role in generating environmental innovations (cf. Medeiros et al. 2014, p. 81; Carrillo-Hermosilla et al. 2010, p. 1081, among others). Improving the **interfunctional collaboration** between different company departments is necessary to integrate internal stakeholders (cf. Medeiros et al. 2014, p. 81). It is assumed that well-developed interfunctional synergies are an important enabler of environmentally-friendly sustainable product innovation (cf. Byrne and Polonsky 2001, p. 1524). Previous studies have shown that continuous and proactive exchanges between functional areas within a company can potentially create better conditions for a higher environmental innovative capacity (cf. Gonzalez-Benito 2008, p. 7030ff.) and improve the integration of a company-wide ecological, sustainable vision into product development (cf. Hallstedt et al. 2010, p. 709f.).

Integrating external stakeholders into the product development process takes place by engaging in **R&D cooperation**. According to several studies, cooperations with other companies in the value chain (especially with suppliers), administrations and research institutes are particularly important for generating environmental product innovations (cf. Cainelli et al. 2015, p. 218; Klewitz and Hansen 2014, p. 67ff.; Petruzzelli et al. 2011, p. 292ff.; Triguero et al. 2013, p. 26).

***General company characteristics***

The literature is inconclusive about the influence that **company size** has on the capacity for environmental innovation (cf. Hojnik and Ruzzier 2016, p. 36; Díaz-García et al. 2015, p. 16). First of all, many studies show that large enterprises frequently produce both general product innovations and innovations that improve the environment (cf. Kesidou and Demirel 2012, p. 867). This can be explained by the advantages that large enterprises have concerning financing, systematised research and development, and the greater influence by and visibility for stakeholders (cf. Kesidou and Demirel 2012, p. 866). On the other hand, there are also studies indicating that smaller enterprises focus more on green initiatives (cf. Revell et al. 2010, p. 283) and therefore generate almost all the forms of environmental impact that environmental innovations have to a greater extent than large enterprises (cf. Walz 2016, p. 20), or that they are generally more strongly inclined towards environmental innovation (cf. Aragón-Correa et al. 2008, p. 98f.; Bos-Brouwers 2010, p. 431).

The influence of **company age**, the possible significance of the **position in the value chain**, **employee qualification** and the **complexity of the product portfolio** could also be correlated with generating innovations that have a positive effect on the environment. So far, the utilization of ICTs in the manufacturing sector as an indicator of **digital transformation** has only been analysed as an influencing factor for the adoption of environmental process innovation and confirmed to some extent (cf. Cainelli et al. 2011, p. 718). It is analysed as a potential determinant of generating environmental product innovation for the first time in the section below.

## 2.3 Defining the digital transformation of production

**Digitisation** is defined as the conversion of information from analogue to digital storage using digitisation tools (cf. Bounfour 2016, p. 21). **Digitalisation** is making use of this digitised information to create revenue, improve business and transform processes. The more precise concept of **digital transformation** goes beyond this and describes the continuous changes that our daily lives, society and the economy are subject to due to the increasing use of digital technologies and the effects this has (cf. Bounfour 2016 p. 22; Pousttchi 2017, p. 1). In the concrete case of companies, this means the partial or complete transition of products, services or business processes into a digital representation using information systems. The goal in doing so is mostly to improve productivity, enhance or improve existing products and services and create new business models (cf. Maedche 2017, p. 22; Pousttchi 2017, p. 1).

In the specific case of the **digital transformation of manufacturing**, the main focus is on the further development of operational areas in the production environment, i.e. especially production, assembly, intralogistics, supply chain management and product development (cf. Bechtold et al. 2014, p. 4ff.). The aim is to improve these operations in particular by the targeted and widespread use of ICTs, mostly from the domains of sensor technology, automation, machine learning, big data storage and processing, human-computer interaction and mobile communications (cf. Blanchet et al. 2014, p. 9ff.). However, this is also based on the targeted use of more common ICT solutions from the digital factory, such as production planning and product life cycle management systems (cf. Lerch et al. 2016, p. 4f.). Especially in the German discourse, this process is referred to as **Industry 4.0** and is understood as a paradigm shift that represents a fourth industrial revolution in its significance (cf. Kagermann et al. 2013, p. 13). The transformation into Industry 4.0 is expected to bring the benefits of significant productivity improvements, resource savings and increased flexibility and adaptability (cf. Kagermann et al. 2013, p. 13ff.).

## 2.4 Impacts of the digital transformation of production on the environment

It is assumed that the digital transformation in manufacturing will have huge impacts on the social, economic and ecological development in the 21st century. However, our study does not focus on all these far-reaching effects, but rather on the potential influence on the ecological sustainability dimension and the organisational skills **at company level**. Because the concept of Industry 4.0

is so new and the public sphere is focusing on industrial digital transformation, there are only a few studies to date that deal explicitly with its impacts on environmental aspects (cf. Herrmann et al. 2014, p. 84f.; Beier et al. 2017, p. 227f.). When looking at the environmental effects of digital transformation due to the use of ICTs, we can distinguish **three order levels** that make it possible to define and investigate both positive and negative impacts: (cf. Horner et al. 2016, p. 4; Hilty et al. 2006, p. 1619)

**First order impacts**, or primary or direct effects, describe the influence on the environment of producing, using and disposing of the ICTs, i.e. during their life cycles (cf. Hilty et al. 2006, p. 1619; Hilty and Aebischer 2015, p. 27; Berkhout and Hertin 2004, p. 905f.). This influence on the environment is by definition usually negative overall if the entire life cycle of ICTs is regarded (cf. Berkhout and Hertin 2004, p. 905f.). A negative effect on the environment is also initially expected with regard to the **digital transformation of the production environment**, because the greater use of complex ICT solutions is expected to lead to considerable increases in energy consumption for manufacturing, using and disposing of the systems (cf. Fettweis and Zimmermann 2008, p. 2).

**Second order impacts**, or secondary or indirect effects, cover impacts on the environment that go beyond the direct consequences of ICT adoption and therefore represent enabling influences (cf. Hilty et al. 2006, p. 1619; Berkhout and Hertin 2004, p. 906). Following Hilty and Aebischer (2015, p. 28f.), we distinguish three types of enabling influence: (1) Process optimisation by replacing a material resource with an intangible one, (2) Media substitution, where material resources are replaced by other material resources and (3) the externalization of control, in which purely intangible resources are substituted. In the context of the digital transformation in manufacturing, it is expected that especially productivity but also energy and material efficiency will increase due to the optimisation of production processes (cf. Berkhout and Hertin 2004, p. 906; Beier et al. 2017, p. 232). However, the **digital transformation of the production environment** is expected to have other enabling influences on how organisations are designed and how the entire company and individual areas behave that potentially imply ecological sustainability effects. For example, how work is organised in the production environment may become more flexible or there may be changes in behavior in the interaction between functional areas (cf. Börjesson Rivera et al. 2014, p. 110ff.; Hilty and Aebischer 2015, p. 31). New sustainable business models may also be enabled (cf. Kagermann 2015, p. 23ff.).

**Third order impacts**, or tertiary or structural effects, include medium- to long-term changes in behaviour and economic structures caused by the digital transformation (cf. Hilty et al. 2006, p. 1619; Berkhout and Hertin 2004, p. 906). These include effects that improve the environment, such as the shift in the industrial economy towards a less energy-intensive service economy, but also rebound effects that describe a situation where positive environmental effects, such as efficiency improvements based on the use of ICTs, are partially compensated or even overcompensated by the increased demand from end consumers (cf. Berkhout and Hertin 2004, p. 906). A structural change in consumer behaviour in the economy is potentially an especially significant third-order ecological sustainability effect of the **digital transformation of the production environment**. This is expected, for example, due to the far-reaching effects that ICT adoption will have on employment structures (cf. Rüßmann et al. 2015, p. 6). In the context of third-order environmental effects, a structural change in the ecological sustainability of the economy can also be expected due to the emergence of new, sustainable business models, e.g. increased level of service due to innovative product-service systems in the manufacturing sector (cf. Lerch and Gotsch 2015a, p. 77f.; Kagermann 2015, p. 23ff.).

# 3 Development of a conceptual framework for the digital transformation of production as a determinant of environmental innovation

## 3.1 Potentially enabling effects of the digital transformation of the production environment

When examining the ecological impacts of the digital transformation of the production environment towards Industry 4.0, the focus up to now has mainly been on possible efficiency improvements in existing processes due to the adoption of environmental process innovations (cf. Cainelli et al. 2012, p. 704, among others). However, increased activities with regard to the generation of product innovations are also expected, because these are often only possible due to technical process innovations, which is what the digital transformation of the production environment basically represents (cf. Klemmer et al. 1999, p. 28; Som 2012, p. 236). Conversely, conceptually possible product innovations usually require new kinds of processes (cf. Kraft 1990, p. 129f.; Bönte and Dienes 2013, p. 502f.). The use of and investment in emerging technologies is also generally regarded as an important driver of sustainability improvements and ecological change (cf. Cainelli et al. 2012, p. 704; Blum-Kusterer and Hussain 2001, p. 311f., among others). At its core, the digital transformation of the production environment in the manufacturing sector basically represents the development of technological skills in the field of ICT. We can therefore assume that digital transformation in the manufacturing sector functions as an indirect enabler, generating not only product innovations but also specifically environmental product innovations. Based on the latest research, it is therefore necessary to understand how and through which enabling second-order effects the digital transformation of the production environment can influence this. In the following, we analyse three potentially enabling effects in more detail:

- Improved company-internal integration of the innovation process
- Enabling new business models
- Improved company-external integration of the innovation process.

### 3.1.1 Improved company-internal integration of the innovation process

Far-reaching changes in how manufacturing companies are organised are expected as a result of the digital transformation of the production environment (cf. Börjesson Rivera et al. 2014, p. 111ff.). In particular, efficiency increases due to ICT adoption should improve interfunctional collaboration and increase the flow of knowledge between departments (cf. Hilty and Aebischer 2015, p. 31). Product life cycle management systems are expected to have an especially strong enabling effect. These systems are implemented technically using shared platforms and should enable the cooperation of all the relevant operational areas and support the product throughout its entire life cycle in a product-centred environment (cf. Maedche 2017, p. 22). Once successfully implemented, these systems can destroy functional silos and interconnect all the relevant stakeholders in the company and above all in production and development; this makes it possible to apply a sustainable corporate strategy to a large extent (cf. Ameri and Dutta 2005, p. 582ff.).

Innovation research has already identified a higher degree of interfunctional collaboration and interfunctional knowledge flows between different company areas as a driver of environmental product innovation. This is made possible by ICTs in the production environment (cf. Medeiros et al. 2014, p. 81). Several studies have shown that continuous and proactive exchanges between functional areas within an enterprise potentially create better conditions for increased environmental innovation capacity (cf. Gonzalez-Benito 2008, p. 7030ff.) and for better integration of a company-wide ecologically sustainable vision into product development (cf. Hallstedt et al. 2010, p: 709f.).

### 3.1.2 Enabling new business models

Business models describe the decision basis used by companies to generate, deliver and use value added (cf. Chesbrough 2007, p. 12). It can therefore be assumed that the megatrend of digitalisation will also influence how business models are designed. It may well be the case that new business models are needed to successfully manage networked industry and customer integration into company processes within the framework of the digital transformation. (cf. Stock and Seliger 2016, p. 540; Kagermann 2015, p. 23ff.; Prause 2015, p. 164).

Companies' development towards product-service systems with an increasing number of service components is one example of a change in business models in the manufacturing sector that is fostered and accelerated by the digital transformation of the production environment among other things (cf. Lerch and Gotsch 2015b, p. 76f.). These product-service systems have emerged quite recently and can potentially deliver very customer-oriented and adapted solutions. They therefore have major implications for a company's value added process, especially the innovation process (cf. Lerch and Gotsch 2015a, p. 49f.). Open Innovation, intrapreneurship and company fragmentation are examples of other innovative business model tendencies in the manufacturing sector that are strongly supported by the digital transformation (cf. Prause 2015, p. 161ff.).

The potentially ecological sustainability character of many of the innovative business models is already apparent due to the improved utilization of large amounts of data on products and users (cf. Stock and Seliger 2016, p. 540). A large proportion of the business models are expected to be ecologically sustainable ones that generate positive environmental impacts to a substantial extent or at least reduce negative ones (cf. Bocken et al. 2016, p. 308f.), or contribute fundamentally to solving an ecological or social problem (cf. Schaltegger et al. 2012, p. 112). A study by Boons and Lüdeke-Freund (2013, p. 12ff.) identified a positive conceptual influence of these more sustainable business models on the generation of environmental innovation.

### 3.1.3 Improved company-external integration of the innovation process

The digital transformation in manufacturing companies can continue the integration of horizontal and vertical value chains (cf. Koch et al. 2014, p. 7). Many businesses expect they will be able to better meet the requirements of customers and other stakeholders by vertical cooperation, in particular, or by integrating and optimising the flows of information and materials with other companies in the value chain (cf. Stock and Seliger 2016, p. 539f.). Integrating external companies of the value chain (especially suppliers) is generally recognised in the research as an important general driver of environmental innovation activity (cf. Cainelli et al. 2015, p. 218; Klewitz and Hansen 2014, p. 67ff.; Petruzzelli et al. 2011, p. 292ff.; Triguero et al. 2013, p. 26).

The digital transformation of the production environment also makes it increasingly possible to integrate customers into product design and development processes (cf. Lacy 2015, p. 13f.). In this regard, among other things, it is expected that the latest developments in the field of ICT will make it possible to improve the integration of the external perspective within the framework of open innovation concepts (cf. Prause 2015, p. 164; Prause and Thurner 2014, p. 19). Better integration of customer requirements into the product innovation process may be accompanied by customer relevance exerting a strong supporting influence on the individual company's innovation activity (cf. Stock and Seliger 2016, p. 539).

Customer perceptions and requirements are a potentially decisive aspect of a company's decisions to engage in environmental innovation (cf. Doran and Ryan 2012, p. 436; Grunwald 2011, p. 676; Wagner and Llerena 2011, p. 760ff.). Private end consumers, in particular, are increasingly environmentally-conscious in many sectors and some even hope their attitude will influence the development of new products by manufacturing companies (cf. Tsai et al. 2012, p. 4442ff.). It is therefore probable and conceptually logical that environmental product innovation activities will increase due to the enabling effect of digitalisation through improved integration of customer requirements into the innovation process.

## 3.2 Conceptual framework

The three potentially enabling effects of the digital transformation of the production environment as determinants of environmental innovation can be summarised in a conceptual framework, which is illustrated in Figure 1.

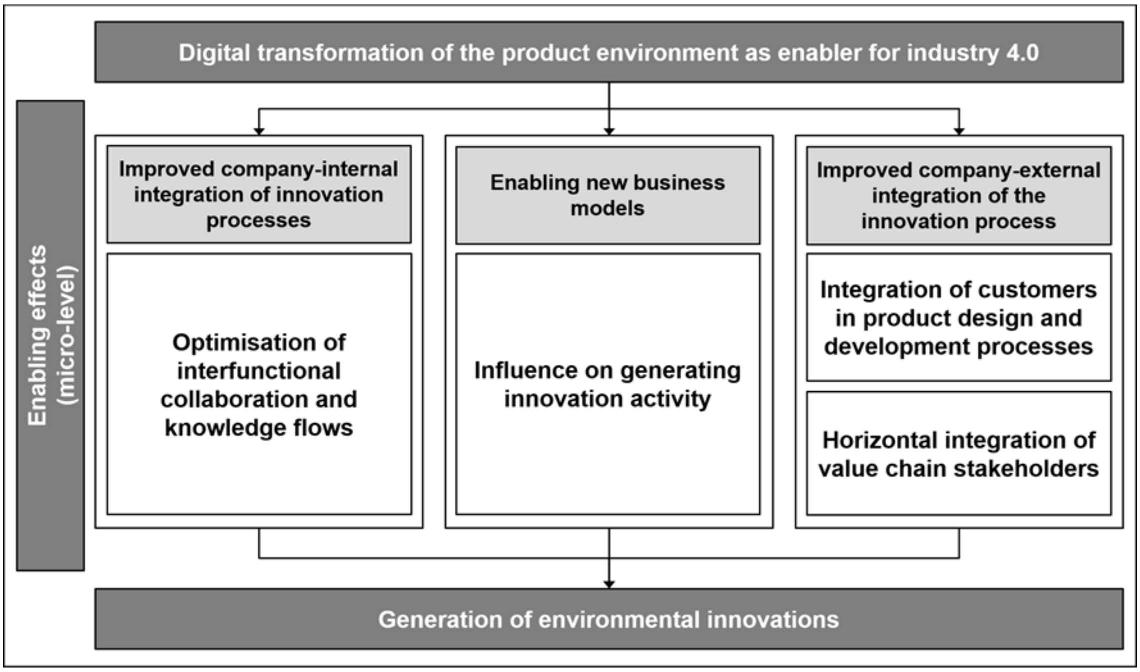


Figure 1: The enabling influence that the digital transformation of the production environment has on environmental product innovation activity (own diagram)

In the following, we test the conceptual model presented here using quantitative-empirical methods. These make it possible to quantify, describe and statistically verify the correlations between environmental product innovation and the digitalisation of the production environment as well as other potential influencing factors in the manufacturing sector.

# 4 Research method of the empirical analyses

## 4.1 Database

We use the *German Manufacturing Survey* from 2015 as the database for the descriptive and econometric analyses. This postal survey has been conducted regularly by Fraunhofer ISI since 1993 and covers various current topics on the diffusion and use of different process, organisational and product innovations in the manufacturing sector in Germany as well as numerous performance data and company characteristics.

Of the manufacturing companies in Germany with at least 20 employees, one in three was randomly selected for the survey. After deducting all the companies that no longer manufacture in Germany and those that no longer exist, this yielded a total net random sample of 15,720. 1282 usable questionnaires were returned, which is equivalent to a response rate of 8 % (cf. Jäger and Maloca 2015, p. 8). The questionnaire was completed by the production manager or technical management and the information given related to 2014, the financial year just ended (cf. Jäger and Maloca 2015, p. 7ff.).

Comparing the sample with the total population shows that the participating companies cover a comprehensive spectrum of the manufacturing sector in terms of size, industry structure and regional distribution (cf. Jäger and Maloca 2015, p. 9ff.). The random selection performed means we can draw conclusions from this study for the whole of the manufacturing sector.

## 4.2 Methodology

We start by operationalising the model parameters and analysing the relevant bivariate group differences descriptively, considering suitable significance tests. In the subsequent chapter, we present and evaluate several multivariate logistic regression models to test the bivariate group differences in relation to different influencing factors, especially the digitalisation of the production environment in the context of explaining the generation of environmental product innovation and achieving individual impacts. We can exclude spurious relationships caused by other relevant influencing variables by applying these multiple steps of analysis. As a result, the influences of the different factors can be checked simultaneously and independently of each other (cf. Hair et al. 1998, 341ff.).

A binary logistic regression analysis is suitable for modelling the influence of several explanatory variables on a dichotomous dependent variable (see, e.g. Hair et al. 1998, p. 355f.). This method makes it possible to deduce potential causal relationships with greater certainty because it examines the isolated effect of a change in an explanatory variable while controlling for other variables (cf. Hair et al. 1998, p. 341ff.).

Using logistic regression, we can estimate the probability that environmental product innovations with at least two effects are initiated (P(Y=1)) or not initiated (P(Y=0)) (cf. Backhaus et al. 2015, p. 284). The chances of an event occurring (Y=1), also referred to as the odds, play an important role in the interpretation. These can be calculated by the ratio of the probability of the event occurring P(Y=1) to the probability of it not occurring (1-P(Y=1). When calculating probability, if the value of an explanatory variable $X_i$ is increased by one, the odds increase or decrease by the factor $e^b$. This factor is referred to as the odds ratio or impact coefficient and offers a very intuitive way of interpretation and a simple graphic clarity with regard to the effects of individual influencing factors. For instance, an odds ratio of $X_i$ with the value 2 represents a doubling of the chances of an event occurring (Y=1), if $X_i$=1 and not $X_i$=0 (cf. Backhaus et al. 2015, p. 311).

The Wald test is usually applied to check the statistical significance of individual factors in logistic regression models. According to McFadden, Cox & Snell and Nagelkerke, pseudo R-squareds ($R^2$) are suitable to assess the model’s accuracy, alongside the $\chi^2$ test (cf. Backhaus et al. 2015, p. 317ff.). To screen for multicollinearity of the explanatory variables, the variance inflation factor (VIF) is used in accordance with Mansfield and Helms (1982). It makes sense to use the Kruskal-Wallis test for descriptive analyses of group differences between three or more groups that are not normally distributed, as is the focus in the bivariate analyses (cf. McKnight and Najab 2010a, p. 1). For two groups, the Mann-Whitney-U-Significance test is more suitable (cf. McKnight and Najab 2010b, p. 1). The significance level for both tests is set at 5 %.

# 5 Operationalisation of the variables and model design

## 5.1 Dependent variable: Environmental product innovation

The construct **generation of product innovations ($Y_1$)** describes the product innovation activity of a company in the period between 2012 and 2015 as a dichotomous variable. In concrete terms, we rate those market introductions as product innovations that are new to the company or feature a major technical improvement. This operationalisation of product innovation is in line with the common practice of empirical studies of product innovation activities (cf. Horbach 2008; Horbach et al. 2012).

In the bivariate and multivariate analyses, the **generation of environmental product innovations ($Y_2$)** is operationalised as the achievement of at least two of the environmentally-relevant impacts considered when using and disposing of the product innovations using a dichotomous variable. Six ecological impacts of the environmental product innovation were considered:

- reduced health risks during use
- reduced energy consumption during use
- simpler maintenance/retrofitting
- prolonged product lifespan
- reduced environmental pollution due to use
- improved recycling, take-back and disposal

In our study, the operationalisation of environmental product innovation in the empirical analyses is based on the assumption that, apart from being the unintended result of favourable circumstances, the generation of environmental innovations represents first and foremost a conscious decision by the company. However, it is questionable whether such a conscious decision is made if only one of the possible impacts is achieved. In our study, we therefore regard a conscious decision for environmental innovation as given only if at least two of the impacts considered are achieved.

## 5.2 Explanatory variable

### 5.2.1 Digital transformation of the production environment

We need to develop a digitalisation index that is as meaningful as possible to accurately represent the function of the **digital transformation of the production environment ($X_1$)** in manufacturing companies as a shift towards Industry 4.0. In our empirical analyses, we operationalise the I4.0 readiness index following Lerch et al. (2016) as a categorical variable. This has already been used in earlier studies examining the diffusion and effects of the digital transformation of the production environment (cf. Lerch et al. 2016; Dachs et al. 2017).

The “2015 German Manufacturing Survey” recorded the diffusion of various forms of production-related ICT. In particular, it explored the diffusion of the following forms of ICT in manufacturing companies in Germany (cf. Lerch et al. 2016, p. 5):

- Digital management systems (IT-related)
  - Software systems for **production planning and control** (e. g. ERP systems)
  - **Product life cycle management systems** (PLM) or product process data management
- Wireless human-machine communication (IT-related)
  - Digital solutions to **provide and use drawings, diagrams, work plans or work instructions** directly at the employee’s workplace (e.g. tablets, smartphones)
  - **Mobile/ wireless devices** to program and operate systems and machines (e.g. tablets)
- Cyber-physical systems (CPS-related)
  - **Real-time production control systems** (e.g. systems with centralised machine/process data records, MES)
  - **Digital exchange** of disposition data with suppliers and customers (supply chain management systems)
  - Technologies **to automate and control internal logistics** (e.g. warehouse management systems, RFID)

The I4.0 Readiness index first splits these ICTs into the three fields of technology listed that differ especially with regard to the type of processes supported and their proximity to networked production in the sense of Industry 4.0.

Companies can be classified into six levels of readiness for Industry 4.0 based on their use of the different ICTs. None of the analysed ICTs are used at readiness level 0, while ICTs from one or two IT-related technology fields are used at levels 1 and 2. ICTs from all three fields of technology are used at levels 3 to 5. Distinctions here are based only on the number of ICTs used from the CPS-related field of technology (cf. Figure 2). In addition, in the context of our study, it makes sense to apply an aggregated classification into non-users with no readiness for Industry 4.0 (level 0), a basic group with limited readiness for Industry 4.0 (levels 1 to 3) and a leading group (levels 4 and 5) that act as trendsetters for Industry 4.0 (cf. Lerch et al. 2016, p. 13).

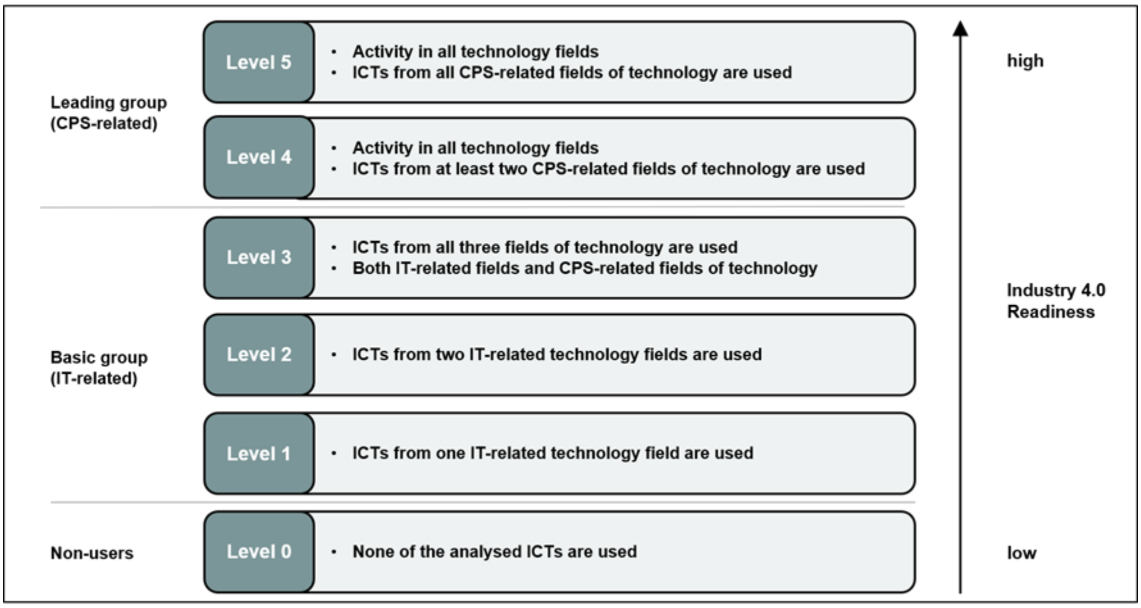


Figure 2: Levels of the I4.0 readiness index (own diagram based on Lerch et al. 2016, p. 13)

The digital transformation is bringing about far-reaching changes in how companies are organised that also have potential impacts on their innovative capacity. This functions as one driver for the generation of product innovations and especially of environmental product innovations by enabling new sustainable business models and the company-internal and company-external integration of the innovation process. We therefore expect that the explanatory variable digital transformation of the production environment ($X_1$) will show a positive correlation with the generation of both product innovations ($Y_1$) and environmental product innovations ($Y_2$) when comparing the group of non-users with higher levels of the I4.0 readiness index.

### 5.2.2 Control variables I: Environmental management

An important control variable, the use of **environmental management certificates and systems ($X_2$)** is operationalised as a dichotomous variable in the logistic regression models. In the questionnaire used in this study, the EU ecolabel, cradle-to-cradle certification and compliance with ISO 14020 are given as explicit examples. Earlier studies observed the high importance of environmental management for generating environmental innovations, especially systems based on ISO certification (cf. Demirel and Kesidou 2011, p. 1554f.; Leenders and Chandra 2013, p. 203ff.; Horbach et al. 2012, p. 117). We therefore expect a strong positive correlation with the generation of environmental product innovations ($Y_2$).

### 5.2.3 Control variables II: Research and development

The following variants are distinguished with regard to the process of **product development ($X_3$)**:

- product development according to customer specifications
- product development as a basic standardised program within which customer-specific variants are realised
- product development for a standard program from which the customer can make a selection
- the company does not develop products

It is conceivable that customer specifications exert a pressure to generate product innovations with aspects that improve the environment, but also that involving customers has an inhibiting effect on the freedom of scope when designing environmentally-related aspects. We therefore assume a correlation between the process of product development and the realisation of environmental product innovations ($Y_2$), in particular. However, whether this correlation is positive or negative is not obvious a priori. Further, we assume that the generation of both environmental product innovations and product innovations ($Y_1$) is severely impeded if the company does not have its own product development capacities.

The indicator **R&D activity ($X_4$)** is a dichotomous variable that is measured based on whether the company conducted research and development in 2014 or outsourced this to an external partner. R&D activity is an important basis for realising both general product innovations ($Y_1$) (cf. Cuerva et al. 2014, p. 110) and environmental product innovations ($Y_2$) (cf. Cainelli et al. 2011, p. 723) and is therefore an essential component of the regression models controlling the research questions. We expect a strong positive correlation with the dependent variables in both models.

Other dichotomous variables operationalised in the models are **R&D cooperation with companies ($X_{5a}$)** and **R&D cooperation with research organisations ($X_{5b}$)**. Numerous studies have already observed the special relevance of these forms of cooperation with companies, authorities and research institutes for realising product innovation ($Y_1$) and environmental product innovations ($Y_2$) (cf. Cainelli et al. 2015, p. 218; Klewitz and Hansen 2014, p. 67ff.; Petruzzelli et al. 2011, p. 292ff.; Triguero et al. 2013, p. 26). The access to external knowledge sources, and especially the regional proximity to research centres and universities seems even more important for environmental innovations than for many other kinds of innovation (cf. Horbach 2014, p. 30ff.; Triguero et al. 2013, p. 28ff.; Belin et al. 2011, p. 13ff.). We therefore anticipate a positive correlation of both indicators with the generation of both general product innovations ($Y_1$) and environmental product innovations ($Y_2$).

### 5.2.4 Control variables III: General company characteristics

We control for the influence of **company size ($X_6$)** by introducing an indicator that reflects this construct in the form of the number of employees in 2014 (excluding temporary workers). In line with earlier studies (cf. Horbach 2008), we assume that the impacts of this indicator are not linear, but decrease as the number of employees increases. It is easy to operationalise this decrease in logistic regression models by transforming the values into logarithms (cf. Hair 2009, p. 77ff.). There are studies that regard smaller enterprises as stronger environmental innovators (cf. Aragón-Correa et al. 2008, p. 98f.; Bos-Brouwers 2010, p. 431), as well as others that assign this attribute to large enterprises (cf. Segarra-Oña et al. 2011, S, 428) or discern no influence of company size at all ($X_6$) (cf. Wagner 2008, p. 397f.; Pereira and Vence 2012, p. 81f.).

**Company age ($X_7$)** is operationalised in the regression models as a dichotomous variable. We explicitly distinguish companies that were founded pre- and post-2000. We set the company age to 15 years before the survey because we assume that this represents a suitable division into companies founded in the digital age and those founded in the pre-digital age. It is assumed that both older (cf. Hojnik and Ruzzier 2016, p. 38; Rehfeld et al. 2007, p. 96f.) and younger companies (cf. Acs and Audretsch 1990, p. 79ff.; Díaz-García et al. 2015, p. 16; Keskin et al. 2013, p. 58) have their own respective advantages when generating product innovations ($Y_1$) and environmental product innovations ($Y_2$). Therefore, we did not formulate a final hypothesis here concerning the correlation with the dependent variables.

When operationalising the **position in the value chain ($X_8$),** we use a categorical variable to distinguish companies that are either predominantly a final producer for consumers, a final producer for companies or not a final producer for consumers or companies.

The shares of specific qualification levels in the total number of employees in the company are used as metric variables to operationalise **employee qualification ($X_9$)**. This value is also logarithmised to implement the assumption of non-linearity. We use the percentage shares of **graduates from universities and universities of applied sciences ($X_{9a}$)** as well as those of **technicians and master craftsmen ($X_{9b}$)**. We expect a positive correlation between higher employee qualification ($X_9$) and the generation of product innovations ($Y_1$) and environmental product innovations ($Y_2$).

With regard to **product complexity ($X_{10}$)**, we use a categorical variable to distinguish between companies with simple products, products with average complexity and complex products. We expect a potentially positive correlation between higher product complexity and the generation of both product innovations ($Y_1$) and environmental product innovations ($Y_2$).

We operationalise the companies' **industry affiliation ($X_{11}$)** as an essential control variable when studying the determinants of realising innovation using the NACE industry classification as dichotomous variables. We consider the following manufacturing industries:

- Food and beverages (NACE 10-11)
- Chemicals including pharmaceuticals (NACE 20-21)
- Rubber and plastics (NACE 22)
- Metal manufacture and processing, manufacture of fabricated metal products (NACE 24-25)
- Computer, electronic and optical products (NACE 26)

- Electrical equipment (NACE 27)
- Machinery and equipment (NACE 28)
- Manufacture of motor vehicles, trailers and semi-trailers, ships and boats (NACE 29-30)

Other industries in the manufacturing sector (NACE 12-19, 23, 31-33) are summarised as “other industries”. The manufacture of computer, electronic and optical products (NACE 26) is used as a reference group in the regression models, because this has average values based on its descriptively observed environmental innovation activity.

Table 1 provides a descriptive overview of the model parameters.

| Indicator | | Category | n | % (all companies) |
|---|---|---|---|---|
| **Digital transformation of the production environment** | | | | |
| $X_1$ | Digitalisation index (I4.0 readiness index) | (1) Non-users | 279 | 22.9% |
| | | (2) Basic group | 752 | 61.6% |
| | | (3) Leading group | 190 | 15.6% |
| **Control variables I: Environmental management** | | | | |
| $X_2$ | Environmental management certificates and systems | (0) No use of intruments for life cycle assessments | 1126 | 94.1% |
| | | (1) Use of intruments for life cycle assessments | 70 | 5.9% |
| **Control variables II: Research and development** | | | | |
| $X_3$ | Product development: Customer specifications | (0) Unchecked | 643 | 51.2% |
| | | (1) According to customer specifications | 612 | 48.8% |
| | Product development: Standardised program | (0) Unchecked | 691 | 55.1% |
| | | (1) Standardised program or standardised program enabling variants | 564 | 44.9% |
| | Product development: Non-existant | (0) Unchecked | 1140 | 90.8% |
| | | (1) Non-existant | 115 | 9.2% |
| $X_4$ | R&D activity | (0) None conducted or outsourced R&D in 2014 | 700 | 55.2% |
| | | (1) Conducted or outsourced R&D in 2014 | 569 | 44.8% |
| $X_{5a}$ | R&D cooperation: Companies | (0) No R&D cooperation with other companies | 633 | 50.1% |
| | | (1) R&D cooperation with other companies | 631 | 49.9% |
| $X_{5b}$ | R&D cooperation: Research organisations | (0) No R&D cooperation with other research organisations | 685 | 54.2% |
| | | (1) R&D cooperation with research organisations | 580 | 45.8% |
| **Control variables III: General company characteristics** | | | | |
| $X_6$ | Company size (ln) | metric | 4.34 (AM) | 1.13 (SD) |
| $X_7$ | Company age | (0) Company founded post 2000 | 174 | 14.4% |
| | | (1) Company founded pre 2000 | 1037 | 85.6% |
| $X_8$ | Value chain: Final producer | (0) No final producer (consumers or companies) | 508 | 39.9% |
| | | (1) Final Producer | 766 | 60.1% |
| | Value chain: Final producer for consumers | (0) No final producer for consumers | 988 | 77.6% |
| | | (1) Predominantly final producer for consumers | 286 | 22.4% |
| | Value chain: Final producer for companies | (0) No final producer for consumers | 710 | 55.7% |
| | | (1) Predominantly final producer for companies | 564 | 44.3% |
| $X_{9a}$ | Employee qualification: Shares of graduates (ln) | metric | 2.79 (AM) | 1.11 (SD) |
| $X_{9b}$ | Employee qualification: Shares of technicians and master craftsmen (ln) | metric | 2.06 (AM) | 0.86 (SD) |
| $X_{10}$ | Product complexity: Simple products | (0) Unchecked | 1025 | 81.4% |
| | | (1) Simple products (reference group) | 234 | 18.6% |
| | Product complexity: Products with average complexity | (0) Unchecked | 600 | 47.7% |
| | | (1) Products with average complexity | 659 | 52.3% |
| | Product complexity: Complex products | (0) Unchecked | 866 | 68.8% |
| | | (1) Complex products | 393 | 31.2% |
| $X_{11}$ | Industry affiliation | (1) Food and beverages | 109 | 8.5% |
| | | (2) Chemicals including pharmaceuticals | 69 | 5.4% |
| | | (3) Rubber and plastics | 102 | 8.0% |
| | | (4) Metal manufacture and processing, manufacture of fabricated metal products | 294 | 22.9% |
| | | (5) Computer, electronic and optical products (reference group) | 83 | 6.5% |
| | | (6) Electrical equipment | 67 | 5.2% |
| | | (7) Machinery and equipment | 223 | 17.4% |
| | | (8) Manufacture of motor vehicles, trailers and semi-trailers, ships and boats | 57 | 4.4% |
| | | (9) Other industries | 278 | 21.7% |

Table 1: Descriptive overview of the model parameters (own representation)

# 6 Evaluating the bivariate analyses

We begin with the descriptive analysis of the relevant parameters. The focus is a bivariate analysis of the research questions on the relationship between the digital transformation of the production environment and environmental product innovation in the manufacturing sector.

## 6.1 Environmental product innovation activity in Germany's manufacturing sector

55 %, i.e. more than half the companies in the manufacturing sector, introduced innovative products to the market between 2012 and 2015 that were new to the respective firm or featured major technical improvements (**generation of product innovation ($Y_1$)**). According to the companies themselves, 29 % of all those surveyed or 53 % of product innovators also achieved an improved environmental impact during use and disposal (see Figure 3; Walz 2016b, p. 18). This means about one in two product innovators functioned simultaneously as an environmental product innovator.

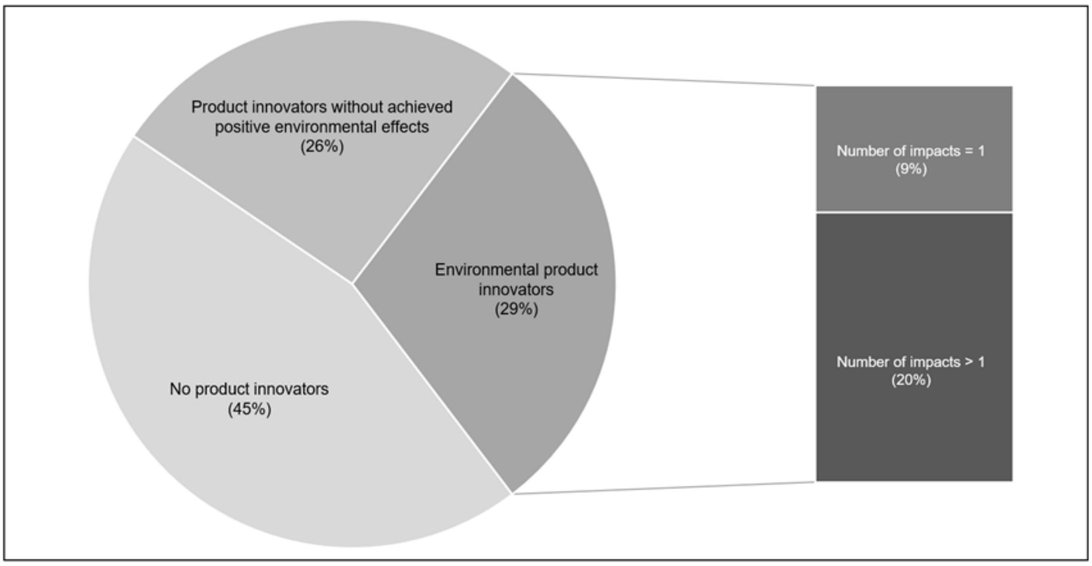


Figure 3: Shares of product innovators and environmental product innovators in manufacturing companies in Germany (own diagram based on Walz 2016b, p. 18). Environmental product innovators are further distinguished by the number of environmental impacts achieved.

When evaluating the impacts, it is striking that a majority (69 %) of the environmental product innovators not only achieved positive environmental effects but actually realised two or more of these impacts (**generation of environmental product innovation ($Y_2$)**) (see Figure 3). In addition, it is apparent that **achieving the different effects ($Y_{3...8}$)** occurs with a very different relative frequency (see Figure 4).

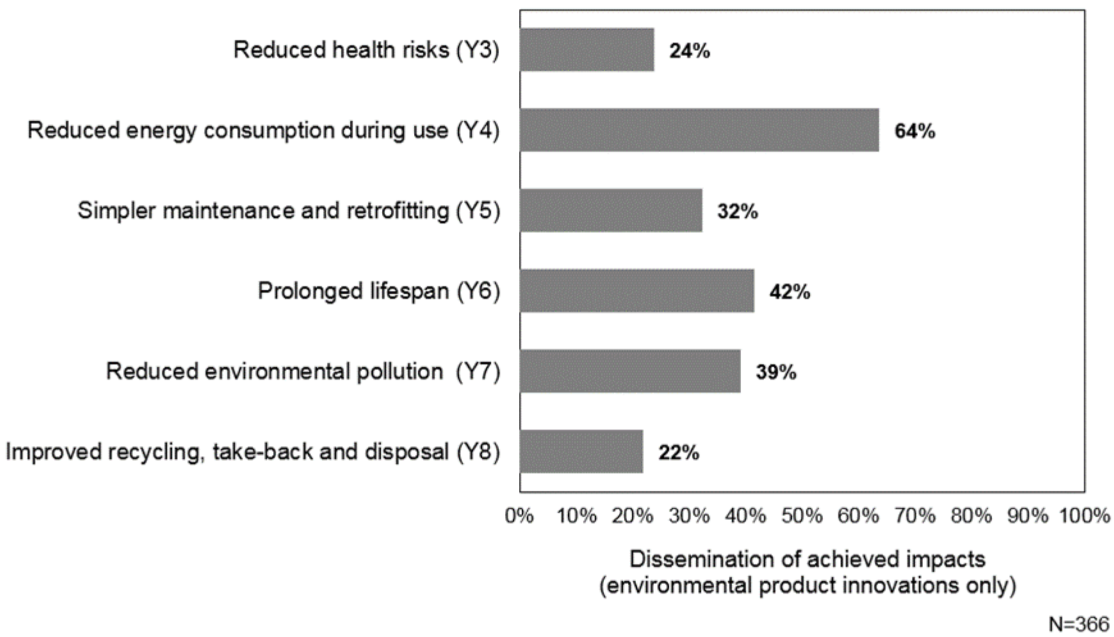


Figure 4: Dissemination of achieving individual ecological impacts among environmental product innovators in Germany's manufacturing sector (cf. Walz 2016b, p. 19)

With 64 %, the biggest share of environmental product innovators by far achieved a reduction of **energy consumption during use ($Y_4$)** with their products. This makes it clear that environmental product innovators make a significant contribution to achieving energy efficiency targets for their customers, possibly due to the pressure of rising energy prices (cf. Walz 2016b, p. 18f.). A significant share of the environmental product innovators in the manufacturing sector in Germany (42 %) also **prolonged the lifespan ($Y_6$)** of products compared to previous ones, while 39 % of environmental product innovators achieved a **reduction of environmental pollution ($Y_7$)**, e.g. in terms of emissions or physical pollution. **Simpler maintenance and retrofitting ($Y_5$)** was only the top priority for the industrial environmental product innovators in 32 % of the products introduced during the analysed period. **Reduced health risks ($Y_3$)** with a share of 24 %, and **improved recycling, take-back and disposal ($Y_8$)** with a share of approx. 22 %, played a subordinate role in the manufacturing sector in Germany in the context of the effects of environmental innovations (cf. Walz 2016b, p. 19).

## 6.2 Current state of the digital transformation of the production environment

The use of the ICTs analysed in our study varies widely in Germany's manufacturing sector (cf. Figure 5). For example, only 11 % of the companies use product life cycle management systems, while software systems for production planning and control have already been introduced in about two thirds of the surveyed companies (67 %) (cf. Gotsch 2016, p. 9f.). The study also reveals that a significant share of the companies (23 %) use none of the analysed ICTs. Only one or two of the technologies are used in almost half of the digitalised companies (38 %) (cf. Lerch et al. 2016, p. 6f.).

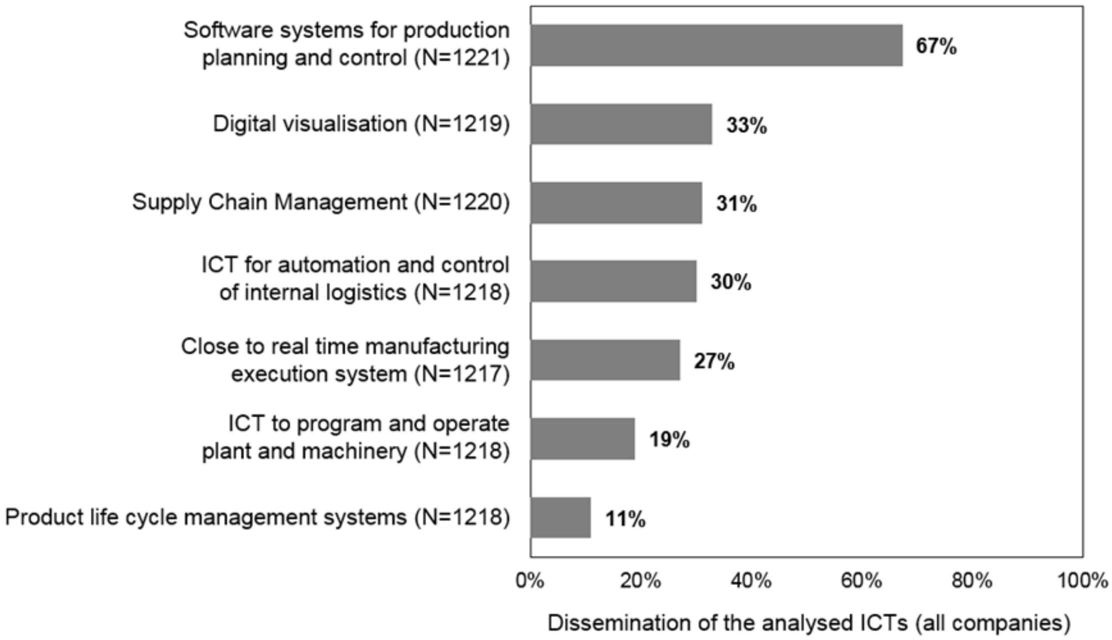


Figure 5: Dissemination of the analysed ICTs in Germany's manufacturing sector in 2015 (cf. Lerch et al. 2016, p. 6)

To show the state of the **digital transformation of the production environment ($X_1$),** we can group companies based on operationalising the use of the analysed ICTs in the I4.0-Readiness index (cf. 5.2.1). When looking at these digitalisation levels, we can clearly identify a leading group in Germany's manufacturing sector with a share of 15 % that has already taken a decisive step towards networked production in the sense of Industry 4.0. However, the relative majority of companies (62 %) belong to the group that is still hesitant about digitalisation, while 23 % of companies are non-users, i.e. do not use any of the analysed ICTs (cf. Figure 6; Lerch et al. 2016, p. 14).

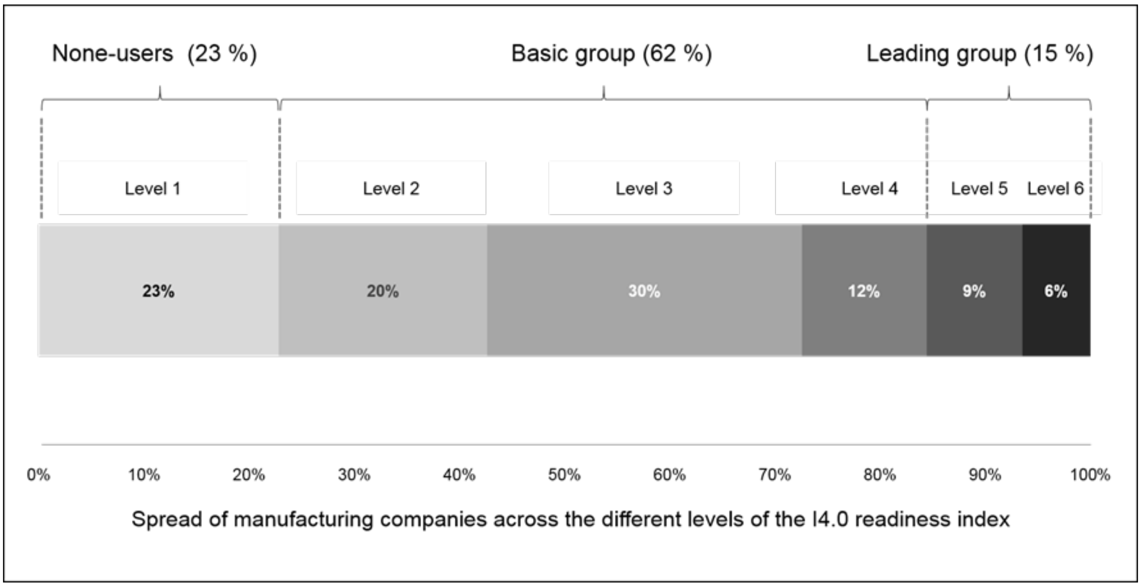


Figure 6: Spread of manufacturing companies in Germany across the different levels of the I4.0 readiness index (own diagram based on Lerch et al. 2016, p. 14)

## 6.3 Linking digital transformation and environmental product innovation

When we look at the co-occurrence of the **digital transformation of the production environment ($X_1$)** operationalised using the I4.0 readiness index described, and the **generation of environmental product innovation** with one or **at least two impacts ($Y_2$)** by manufacturing companies in Germany, it becomes clear that companies with greater I4.0 readiness also generate a larger share of the environmental product innovations (cf. Figure 7).

The share of substantial environmental product innovators achieving at least two impacts (29 %) is about three times higher in the leading group of industrial digitalisation than in the group of non-users of ICTs in the production environment (10 %). There is also a marked difference (11 percentage points) when comparing the share of substantial environmental product innovators among non-users of the analysed ICTs (10 %) with this share in the large number of still hesitant ICT users in the basic group (21 %). We found a statistically significant difference between the three groups using the Kruskal-Wallis test ($p < 0.05$). We also observe a positive group difference between the levels of digitalisation when looking at environmental product innovators that achieve only one impact. However, when related to the differences between the groups, this is less marked compared to substantial environmental product innovators.

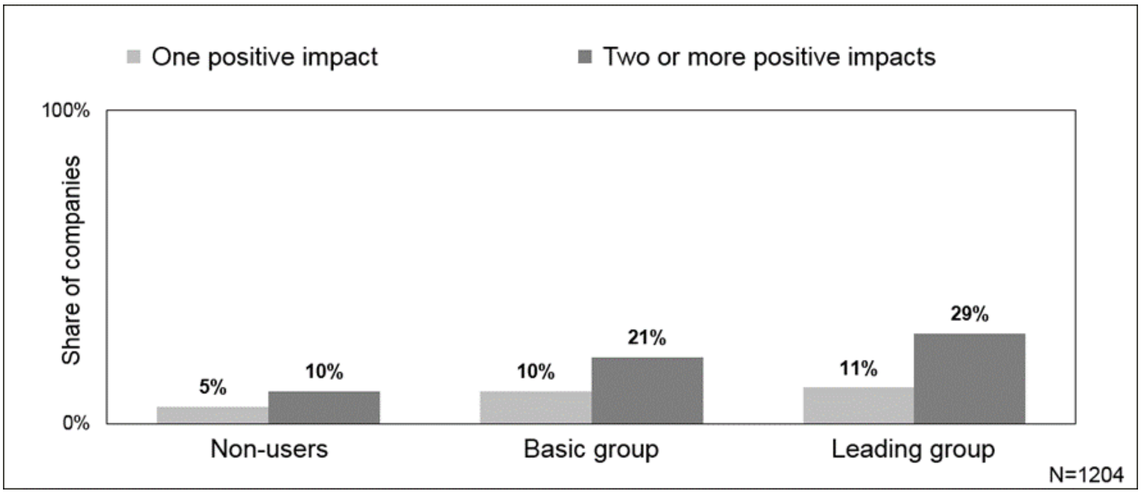


Figure 7: Share of environmental product innovators in the different digitalisation groups of the I4.0 readiness index in Germany's manufacturing sector (own diagram)

When looking at the group differences between the three main groups of the I4.0 readiness index in the context of the respective environmental product innovators **achieving different impacts ($Y_{3...8}$)**, it becomes clear that there is no homogeneous direction or strength for all the environmental dimensions (cf. Figure 8).

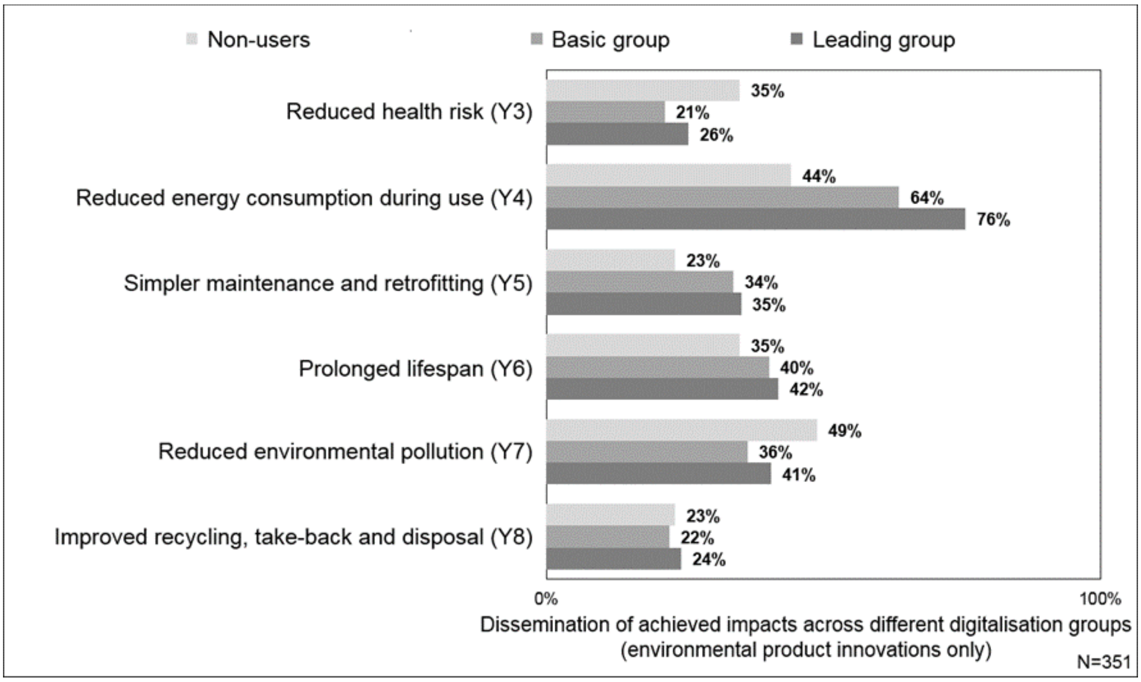


Figure 8: Achievement of individual impacts by the different digitalisation groups of the I4.0 readiness index (own diagram)

On the one hand, there are impacts, especially the **reduction of health risks ($Y_3$)** during use and the **reduction of environmental pollution ($Y_7$)** that are more prevalent among non-users of ICTs than among the companies in the leading group. On the other hand, we can identify impacts such as the **reduction of energy consumption ($Y_4$)** during use, **simpler maintenance and retrofitting ($Y_5$)** and **prolonged product lifespan ($Y_6$)**, for which the share of companies is higher with an increasing level of digitalisation. We find no group difference with regard to the analysed effects between the digitalisation levels for **improved recycling, take-back and disposal ($Y_8$)**. The leading group (24 %) and non-users (23 %) are almost identical here.

When comparing the differences between non-users and the leading group with regard to achieving the respective impact, they are noticeably large for the **reduction of energy consumption ($Y_4$)** (group difference of 33 percentage points) and **simpler maintenance and retrofitting ($Y_5$)** (group difference of 12 percentage points). This corresponds to a statistically significant group difference based on the Mann-Whitney U test ($p < 0.05$).

It is also noticeable that there seems to be no monotonically rising or falling group difference for the impacts **improved recycling, take-back and disposal ($Y_8$)**, **reduction of environmental pollution ($Y_7$)** and **reduced health risks**

**($Y_3$)**. An increase in the level of digitalisation that, in this context, corresponds to a switch into the next higher group of I4.0 readiness is not always linked to a group difference in the same direction.

# 7 Evaluating the multivariate analyses

## 7.1 Logistic regression model on generating product innovation and environmental product innovation

We apply the following logistic regression model to explore which company-specific factors influence the probability of **generating environmental product innovations in the manufacturing sector to a substantial extent ($Y_2$)**. We start by examining the probability of introducing at least two effects that improve the environment among all the companies that took part in the survey. The results of this regression model are compared with the results of a further regression model to **explain the probability that companies play the role of product innovator ($Y_1$)** (cf. Table 2). We used IBM SPSS Statistics for the estimations.

| Indicator* | | General product innovation (Y1) | | | Substantial environmental product innovation (Y2) | | |
|---|---|---|---|---|---|---|---|
| | | Regression coefficient b (standard error) | Odds ratio | Model test ($\chi^2$ value) | Regression coefficient b (standard error) | Odds ratio | Model test ($\chi^2$ value) |
| **Digital transformation of the production environment** | | | | | | | |
| $X_1$ a) | Digitalisation index: Basic group | 0.382 (0.191) | **1.46 **** | 4.249 | 0.568 (0.269) | **1.76 **** | 5.537 * |
| | Digitalisation index: Leading group | 0.437 (0.28) | 1.55 | | 0.727 (0.342) | **2.07 **** | |
| **Control variables I: Environmental management** | | | | | | | |
| $X_2$ | Environmental management certificates and systems | -0.164 (0.334) | 0.85 | 0.24 | 0.614 (0.337) | **1.85 *** | 3.188 * |
| **Control variables II: Research and development** | | | | | | | |
| $X_3$ b) | Product development: Customer specifications | -0.215 (0.166) | 0.81 | 11.161 ** | -0.382 (0.188) | **0.68 **** | 15.799 ** |
| | Product development: Non-existant | -0.96 (0.297) | **0.38 **** | | -2.15 (0.745) | **0.12 **** | |
| $X_4$ | R&D activity: Company spending on R&D in 2014 | 0.862 (0.168) | **2.37 **** | 26.288 ** | 0.722 (0.206) | **2.06 **** | 12.617 ** |
| $X_{5a}$ | R&D cooperation: Companies | 0.403 (0.174) | **1.5 **** | 17.099 ** | 0.084 (0.216) | 1.09 | 4.706 * |
| $X_{5b}$ | R&D cooperation: Research organisations | 0.442 (0.187) | **1.56 **** | | 0.416 (0.224) | **1.52 *** | |
| **Control variables III: General company characteristics** | | | | | | | |
| $X_6$ | Company size | 0.142 (0.087) | 1.15 | 2.721 * | -0.051 (0.085) | 0.95 | 0.364 |
| $X_7$ | Company age (pre 2000) | 0.07 (0.213) | 1.07 | 0.107 | -0.197 (0.264) | 0.82 | 0.548 |
| $X_8$ c) | Value chain: Final producer for consumers | 0.339 (0.209) | 1.4 | 3.384 | 0.037 (0.267) | 1.04 | 0.95 |
| | Value chain: Final producer for companies | 0.189 (0.161) | 1.21 | | 0.179 (0.184) | 1.2 | |
| $X_{9a}$ | Employee qualification: Shares of graduates | 0.166 (0.08) | **1.18 **** | 4.307 ** | 0.032 (0.104) | 1.03 | 0.097 |
| $X_{10}$ d) | Product complexity: average | -0.056 (0.207) | 0.95 | 2.882 | 0.014 (0.298) | 1.01 | 1.979 |
| | Product complexity: high | 0.252 (0.242) | 1.29 | | 0.287 (0.322) | 1.33 | |
| $X_{11}$ e) | Food and beverages | -0.766 (0.475) | 0.46 | 28.815 ** | -2.341 (1.078) | **0.1 **** | 36.559 ** |
| | Chemicals including pharmaceuticals | -0.134 (0.495) | 0.87 | | 0.624 (0.454) | 1.87 | |
| | Rubber and plastics | -0.96 (0.445) | **0.38 **** | | -0.426 (0.532) | 0.65 | |
| | Metal manufacture and processing, manufacture of fabricated metal products | -1.076 (0.4) | **0.34 **** | | 0.151 (0.398) | 1.16 | |
| | Electrical equipment | 0.161 (0.486) | 1.18 | | 0.655 (0.445) | 1.92 | |
| | Machinery and equipment | -0.177 (0.409) | 0.84 | | 1.035 (0.358) | **2.81 **** | |
| | Manufacture of motor vehicles, trailers and semi-trailers, ships and boats | -1.364 (0.518) | **0.26 **** | | 0.726 (0.523) | 2.07 | |
| | Other industries | -0.671 (0.404) | **0.51 *** | | 0.285 (0.394) | 1.33 | |
| | Constant | -1.145 (0.592) | **0.32 *** | | -2.582 (0.635) | **0.08 **** | |

***Reference group: a)** Digitalisation index: Non-users **b)** Standardised program or standardised program enabling variants **c)** No final producer **d)** Simple products **e)** Computer, electronic and optical products

Table 2: Logistic regression models to explain the generation of general product innovation and substantial environmental product innovation (own calculation)

**Significance level:** * $p < 0.1$, ** $p < 0.05$

**Model accuracy (general product innovation (all companies)):** N=1021, Model $\chi^2$ value = 279,551 ($p < 0.05$), Cox and Snell-$R^2$ = 0.241, Nagelkerkes-$R^2$ = 0.324

**Model accuracy (substantial environmental product innovation (all companies)):** N=1005**,** Model $\chi^2$ value = 159.874 ($p < 0.05$), Cox and Snell-$R^2$ = 0.147, Nagelkerkes-$R^2$ = 0.233

## 7.2 Assessing the model's accuracy

To verify the usability of the two logistic regression models, we first check the **independence of the explanatory variables,** and the accuracy of the model. To maintain the premise of independence, no collinearity between the independent variables is permitted because otherwise individual regression coefficients could be over- or underestimated (cf. Backhaus et al. 2015, p. 107). We check for collinearity by examining the correlation matrix.

The highest positive correlation based on Pearson is approx. 0.54 between **R&D cooperation with companies ($X_{5a}$)** and **R&D cooperation with research institutions ($X_{5b}$)**. We observe the highest negative correlation with a value of approx. -0.68 for the two forms of the explanatory variable **product complexity ($X_{10}$)** (products of average complexity and complex products). In general, only a value above 0.9 or below -0.9 is regarded as a high correlation among the explanatory variables (cf. Hair 2009, p. 230). Therefore, the regression models with the defined set of independent variables seem reliable. We also assume that there is no multicollinearity based on the values of the variance inflation factor (VIF between 1.051 and 4.106), because multicollinearity is only assumed above the critical threshold of VIF = 10 (cf. Hair 2009, p. 230; Backhaus et al. 2015, p. 108).

The **accuracy** of the regression models used is evaluated using the model $\chi^2$ test and pseudo R-squareds according to Cox and Snell and to Nagelkerke. The model to explain the **generation of general product innovation ($Y_1$)** has a model $\chi^2$ value of 279.551 (df = 23) when including all the parameters and is therefore statistically significant at a significance level of 0.05. This means that the model's explanatory power is decisively improved by the selected explanatory variables (cf. Hair 2009, p. 262f.).

When including all the explanatory variables, the model to explain the **generation of substantial environmental product innovation ($Y_2$)** achieves a model $\chi^2$ value of 159.874 (df = 23), which is equivalent to statistical significance ($p < 0.05$) of the model parameters. The values of the $R^2$ statistics following Cox and Snell (0.147) and Nagelkerke (0.233) and a forecast quality of 80.9 %, checked in the classification matrix, all indicate the model's goodness of fit.

## 7.3 Results of the logistic regression model

### 7.3.1 Influence of the digital transformation of the production environment

The **digital transformation of the production environment ($X_1$)** operationalised using the I4.0 readiness index is only suitable as an explanatory factor for **generating general product innovation ($Y_1$)** to a limited extent. Only the jump from non-users of ICT to the next basic group proves statistically significant (Wald test, $p < 0.05$). We were not able to identify a significant influence of even more extensive ICT use in the context of achieving general product innovation.

However, the digital transformation of the production environment ($X_1$) does have a statistically significant (Wald test, $p < 0.05$) positive influence on the **tendency of a company to generate substantial environmental product innovation ($Y_2$)** with regard to the discrete step between non-users of ICT and the basic group and between non-users of ICT and the leading group. The overall construct also proves statistically significant ($\chi^2 = 5.537$, $p < 0.1$) when comparing the models with and without the variables. The odds ratio for generating environmental product innovation is higher by a factor of 1.76 for companies with average digitalisation in the production environment than for non-users of the analysed ICTs. The odds ratio is even higher at 2.07 for companies belonging to the leading group, i.e. is more than doubled compared to the group of non-users of ICTs. However, the explanatory power of the digitalisation indicator used as a general explanatory factor for environmental product innovation activity is somewhat limited as this is only confirmed at the 10% level of significance in the $\chi^2$ test.

The results do show, however, that the digital transformation of the production environment is more relevant as an influencing factor for environmental product innovation than for general product innovation. We can interpret this as a first indication that mainly product innovations with aspects that improve the environment benefit from the new possibilities offered in the digitalised factory, such as improved company-internal (cf. Hilty and Aebischer 2015, p. 31; Ameri and Dutta 2005, p. 582ff.) and company-external (cf. Koch et al. 2014, p. 7; Stock and Seliger 2016, p. 539f.; Lacy 2015, p. 11) integration of the innovation process, as well as the opportunities provided by new sustainable business models (cf. Stock and Seliger 2016, p. 540; Kagermann 2015, p. 23ff.; Prause 2015, p. 164). Further increases in environmental innovation activities may be expected at even higher levels of the digital transformation towards Industry 4.0 in the future.

### 7.3.2 Influence of environmental management

The use of **environmental management certificates and systems ($X_2$)** proves to be a statistically significant (Wald test, $p < 0.1$) explanatory factor for the **generation of substantial environmental product innovation ($Y_2$)**. Companies applying environmental management are roughly twice as likely to act as environmental product innovators (odds ratio = 1.85) as those not using such schemes. This finding is in line with earlier studies that observed the high importance of general management attention to environmental issues (cf. Qi et al. 2010, p. 1364) and the use of environmental management systems, such as ISO 4001, for environmental innovation activities (cf. Horbach 2008, p. 172; Horbach et al. 2012, p. 117; Jakobsen and Clausen 2016, p. 138; Rehfeld et al. 2007, p. 97).

### 7.3.3 Influence of research and development

The process of **product development ($X_3$)** proves a statistically significant construct ($\chi^2$ test, $p < 0.05$) with regard to **realising** both **general product innovation ($Y_1$)** and **substantial environmental product innovation ($Y_2$)**. It is noticeable that developing products in line with customer specifications has a negative influence on the probability of generating both kinds of innovation when compared to the reference group “Developing a standard program or a basic program with variants”.

Company spending on R&D in 2014 as a measure of **R&D activity ($X_4$)** also proves an important explanatory factor for generating both **general product innovation ($Y_1$)** and **substantial environmental product innovation ($Y_2$)**. Conspicuously, the positive impact of these R&D activities is less pronounced for environmental product innovation (odds ratio = 2.06) than for general product innovation (odds ratio = 2.37).

**R&D cooperation with companies ($X_{5a}$)** inside and outside the value chain only shows a statistically significant influence ($p < 0.05$) in relation to **generating general product innovation ($Y_1$)**. When controlling the other explanatory variables, there is hardly any influence on the generation of **substantial environmental product innovation ($Y_2$)**.

**R&D cooperation with research institutions ($X_{5b}$)** is a statistically significant determinant for realising both kinds of innovation. Remarkably, its importance as an explanatory variable is roughly the same **for realising general product innovation ($Y_1$)** (odds ratio = 1.56, $p < 0.05$) and **substantial environmental product innovation ($Y_2$)** (odds ratio = 1.52, $p < 0.1$).

### 7.3.4 Influence of general company characteristics

Almost all the general company characteristics we examined do not seem to have a statistically significant explanatory function in a multivariate analysis. We cannot confirm the presumed correlations with **substantial environmental product innovation ($Y_2$)** in relation to **company size ($X_6$)**, **company age ($X_7$)**, **position in the value chain ($X_8$)** or **product complexity ($X_{10}$).**

We only identified statistically significant correlations in the analysed regression models with regard to **employee qualification ($X_9$)** and **industry affiliation ($X_{11}$)**. The qualification level only has a decisive influence on the probability of **realising general product innovations ($Y_1$)** (odds ratio = 1.18, $p < 0.05$). Employee qualification does not seem to influence the **generation of environmental product innovation ($Y_2$)** to a statistically significant extent. The absorptive capacity, which increases with higher employee qualification (cf. Cohen and Levinthal 1990, p. 129), therefore also only seems to foster general innovation activities, regardless of whether these contain aspects that improve the environment or not.

# 8 Summary: the digital transformation as a factor influencing environmental product innovation

## 8.1 Discussion of the empirical results

The bivariate analysis of the I4.0 readiness index and substantial environmental product innovation, i. e. the environmental product innovation achieves at least two impacts, showed a statistically significant positive group difference. 29 % of the digitalised companies in the leading group generate substantial environmental product innovations, while only 10 % of the non-users of ICT in the production environment realise this innovation output. 21 % of the digitalised companies in the basic group generate these kinds of innovation (cf. Figure 9). In relative terms, therefore, highly digitalised companies are better environmental innovators.

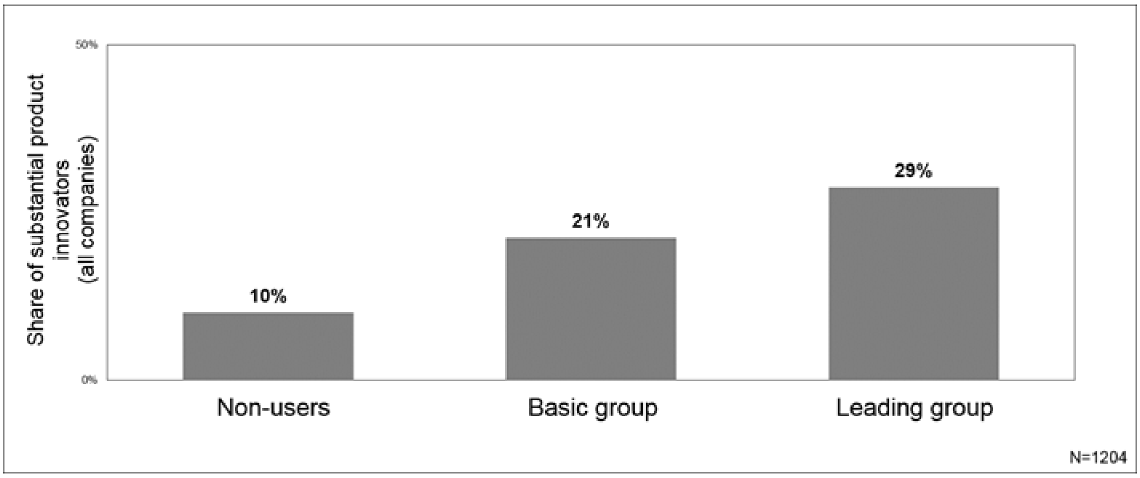


Figure 9: Share of substantial environmental product innovators in the different digitalisation groups of the I4.0 readiness index in the manufacturing sector in Germany (own diagram)

There are also positive, statistically significant group differences or potential correlations with generating environmental product innovation with regard to using individual ICTs. Users of real-time production control systems are the only ones that do not seem to have a noticeable lead with regard to environmental product innovation activity. These group differences are still statistically significant even when we consider classical company characteristics such as the product development process, company size, product complexity and industry affiliation as control variables. We therefore find empirical proof for the presumed causal relationship between digital transformation and the generation of environmental innovations.

In our study of the digital transformation of the production environment in the manufacturing sector, we find additional confirmation of the observed group differences in the bivariate analyses when controlling all the relevant determinants for generating environmental product innovation in a logistic regression model. Whether a company is part of the basic group with a lower level of digitalisation or the leading group using CPS-related systems proves to be a statistically significant explanatory variable of substantial environmental product innovation output.

Companies in the leading group with regard to the digitalisation of the production environment, i.e. with high readiness for networked production in Industry 4.0, are more than twice as likely to generate environmental product innovations with at least two impacts as non-users of production-related ICTs (odds ratio = 2.07). However, this strong correlation is only confirmed at a significance level of 10% by a $\chi^2$ test of the overall construct. Its explanatory power in the overall model is limited and mainly due to its indirect influence on other model parameters.

Nevertheless, our results indicate that the highest possible digital transformation of the production environment does have a certain significance for environmental product innovation activity in the manufacturing sector. Overall, it seems certain that the digitalisation of the production environment determines the special case of product innovations that improve ecological sustainability to a much greater extent than is the case for general product innovation.

## 8.2 Summary and outlook

In this study, we identified indicators of the enabling influence of the digital transformation of the production environment on environmental product innovation activity in the manufacturing sector on a conceptual and an empirical level. At the conceptual level, we formulated three main levers of influence based on a literature review of the main determinants of environmental product innovation in innovation research and the systematisation of the environmental impacts of digitalisation processes. This is the first time that the potential enabling role that digital transformation can play in environmental product innovation activity by improving the company-internal and external integration of the innovation process and enabling new business models was formulated and justified in innovation theory.

We then tested this conceptual influencing relationship in bivariate and multivariate analyses. In these analyses, the digital transformation of the production environment proved to be a statistically significant determinant of generating environmental product innovations in manufacturing, even when considering numerous relevant control variables. However, the construct has limited significance as an explanatory factor in the model and its relevance for environmental innovation is probably due to its indirect influence on other model parameters.

In particular, we found indications that, not only a moderate increase in using ICTs in the production environment, but especially strong digitalisation aimed at improving the readiness for Industry 4.0, can significantly increase environmental production activity in industrial companies. It can therefore be assumed that these effects of promoting environmental innovation will become even more pronounced as digital transformation continues to progress in the manufacturing sector.

In our empirical analyses, we were able to narrow down the specific environmental innovation impacts of digitalisation. We identified reduced energy consumption during use and simpler maintenance and retrofitting of the new products as the main effects that are influenced the most effectively by increased ICT use in the production environment. If further studies confirm this correlation, this result allows the ecological impacts of the digital transformation to be determined and evaluated more precisely.

Overall, our results indicate that digitalisation is accompanied by ecological sustainability effects especially in the manufacturing sector, but potentially in other industrial segments as well, which have not yet been completely defined and assessed. It therefore makes sense to consider the digital transformation in sustainability and environmental policy and in ecological sustainability research to a greater extent.

Our study raises many possible questions for research. On the one hand, further empirical studies should test whether the digital transformation’s potential effects of driving environmental innovation can be observed to an increasing extent as digitalisation progresses. In particular, the attempt should be made to map the policy framework conditions of the macro-level more precisely when designing surveys.

Furthermore, it seems useful to verify and specify the potential influence of digitalisation on environmental innovation activity identified in our study using suitable qualitative and quantitative evaluations. This could be done using qualitative expert interviews and focus group studies with relevant stakeholders from corporate innovation processes, while, quantitatively, factor analysis seems suitable to verify the influence model.

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Karlsruhe 2019