VDI Zentrum Ressourceneffizienz

Im Auftrag des:

Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit

NATIONALE KLIMASCHUTZ INITIATIVE

Resource Efficiency through Industry 4.0

Potential for SMEs in the Manufacturing Sector

Baden-Württemberg
MINISTERIUM FÜR UMWELT, KLIMA UND ENERGIEWIRTSCHAFT

Bayerisches Staatsministerium für Umwelt und Verbraucherschutz

HESSEN Hessisches Ministerium für Wirtschaft, Energie, Verkehr und Landesentwicklung

RheinlandPfalz MINISTERIUM FÜR UMWELT, ENERGIE, ERNÄHRUNG UND FORSTEN

June 2017

Study: Resource Efficiency through Industry 4.0 - Potential for SMEs in the Manufacturing Sector

Authors:

TU Darmstadt - Institut IWAR, field SuR: Prof. Dr. rer. nat. Liselotte Schebek; Dr.-Ing. Jan Kannengießer; Alessio Campitelli, M.Sc.; Julia Fischer, M.Sc.
TU Darmstadt - Institut PTW: Prof. Dr.-Ing. Eberhard Abele; Christoph Bauerdick, M.Sc.
TU Darmstadt - field DiK: Prof. Dr.-Ing. Reiner Anderl; Sebastian Haag, M.Sc.
Fraunhofer IPA: Prof. Dr.-Ing. Dipl.-Kfm. Alexander Sauer; Dr.-Ing. Jörg Mandel; Dr.-Ing. Dominik Lucke; Dipl.-Ing. Ivan Bogdanov, M.Sc.; Anne-Kathrin Nuffer, M.Sc.; Prof. Dr.-Ing. Rolf Steinhilper; Dr.-Ing. Johannes Böhner; Dipl.-Wirtsch.-Ing. (FH) Gerald Lothes; Christoph Schock, M.Sc.
DFKI: Prof. Dr.-Ing. Dr. h.c. Detlef Zühlke; Dr.-Ing. Christiane Plociennik; Dipl.-Inf. (FH) Simon Bergweiler

We would like to thank Dr.-Ing. Andreas Schlegel, Head fo Department Resource Efficient Factory, Fraunhofer Institute for Machine Tools and Forming Technology for his professional support.

Technical contact persons:
Stefan Kirmes, M.Eng., VDI Zentrum Ressourceneffizienz GmbH
Dr.-Ing. Christof Oberender, VDI Zentrum Ressourceneffizienz GmbH
Dr. Martin Vogt, VDI Zentrum Ressourceneffizienz GmbH

The study was commissioned by the VDI Zentrum Ressourceneffizienz, which works on behalf of the Federal Ministry for the Environment, Nature Conservation, Construction and Reactor Safety, in cooperation with the Ministry for the Environment, Climate and Energy of Baden-Württemberg, the Bavarian State Ministry for the Environment and Consumer Protection, the Hessian Ministry for Economics, Energy, Transport and Regional Development and the Ministry for the Environment, Energy, Food and Forestry of Rhineland-Palatinate.

The study was funded by the National Climate Protection Initiative of the Federal Ministry for the Environment, Nature Conservation, Construction and Nuclear Safety and the participating state ministries.

Edited by:

VDI Zentrum Ressourceneffizienz GmbH (VDI ZRE)
Bertolt-Brecht-Platz 3
10117 Berlin
Tel. +49 30-2759506-0
Fax +49 30-2759506-30
zre-info@vdi.de
www.ressource-deutschland.de

Cover picture: VDI ZRE

Printed on environmentally friendly recycled paper.

VDI ZRE Publications:
Studies

Resource Efficiency through Industry 4.0

Potential for SMEs in the Manufacturing Sector

CONTENTS

LIST OF ABBREVIATIONS

BDE	Data acquisition
BMBF	Federal Ministry of Education and Research
BMUB	Federal Ministry for the Environment, Nature Conservation, Construction and Nuclear Safety
BMWi	Federal Ministry for Economic Affairs and Energy
BWS	Business warehouse system
CAD	Computer-aided design
CAE	Computer-aided engineering
CAM	Computer-aided manufacturing
CEE	Circular economy engineering
CO_2	Carbon dioxide
CO_2-eq.	CO_2 equivalents
CPPS	Cyber-physical production system
CPS	Cyber-physical system
DFKI	German Research Centre for Artificial Intelligence GmbH
DiK	Data processing in construction
DPWS	Devices profile for web services
ERP	Enterprise resource planning
ErP	Energy-consumption-relevant products
FEM	Finite element method
FGS	Frech gating system
FU	Functional unit
GPRS	General packet radio service
HK	Recommendations for action for SMEs

HMI	Human machine interface
HP	Recommendations for action for policy
HW	Recommendations for action for science
ICT	Information and communication technology
IoT	Internet of things
IP	Internet protocol
IPA	Institute for Production Engineering and Automation
ISO	International Organisation for Standardisation
IT	Information technology
KDD	Knowledge discovery in databases
SMEs	Small and medium enterprises
LTE	Long term evolution
MDE	Machine data collection
MES	Manufacturing execution system
NFC	Near field communication
OEE	Overall equipment effectiveness
OPC	Object linking and embedding for process control
OPC-UA	Object linking and embedding for process control – unified architecture
PA	Practical application
PDM	Product data management
PIUS	Production-integrated environmental protection
PLM	Product Life Cycle management
PPS	Production planning and control
ProgRess	German resource efficiency programme
PTW	Production management, technology and machine tools

QR	Quick response
REP	Resource efficiency potential
ReSET	Resource self-assessment tool
RFID	Radio-frequency identification
SAG	Strategy group
SOA	Service-oriented architecture
PLC	Programmable logic controller
SQL	Structured query language
SuR	Material flow management and resource management
UMTS	Universal mobile telecommunications system
USB	Universal serial bus
VDI	Association of German Engineers
VDI ZRE	VDI Zentrum Ressourceneffizienz GmbH
VPN	Virtual private network
WLAN	Wireless local area network
WMS	Warehouse management system
WSDL	Web services description language
XML	Extensible markup language

1 INTRODUCTION

1.1 Motivation

The digital transformation in the development and manufacture of products, also known as Industry 4.0, is increasingly becoming a key challenge for companies in the manufacturing sector in Germany. The successful design of this fourth industrial revolution is one of the most important prerequisites for maintaining the competitiveness of Germany as a location for industry. The second major challenge is the necessary decoupling of economic growth from resource consumption, which can only be achieved through increasingly efficient use of natural resources in companies. The optimal design of the interaction between digital transformation and resource efficiency, as well as the consistent use of the resulting potentials for a reduction of the consumption of material and energy, are therefore of crucial importance.

In 2014, material costs accounted for, by far, the largest cost block in the manufacturing industry,[1] at around 43%. By contrast, the costs for personnel were just under 19%, and for energy at 1.9%.[2] Although energy costs account for a significantly lower proportion of gross value added compared to material costs, these are not negligible. In Germany, in 2014, 29% (2,514 petajoules) of total final energy was attributable to the manufacturing industry.[3]

Against this background, resource efficiency[4] in production is an important factor in the competitiveness of companies. Because savings in the area of materials and energy make themselves clearly noticeable economically. At the same time, resource efficiency is a central topic in politics. One motivation for this is the supply of raw materials: Germany is dependent on imports as a resource-poor country. The demand for raw materials today is twice as

1 Manufacturing industry: "Refers to the mechanical, physical or chemical transformation of substances or parts into goods. These are raw materials or primary materials from agriculture, forestry, fisheries and fish farming, mining, quarrying, as well as products of this sector itself. The substantial change or re-processing of goods is generally regarded as the manufacture of goods and assigned to the manufacturing sector." (Federal Statistical Office (2008), p. 186).

2 Cf. Federal Statistical Office (2016a).

3 Cf. Federal Statistical Office (2016b).

4 The term resource efficiency is used in this study in the sense of a more efficient use of natural resources, cf. Chapter 2.2 and the Glossary.

high as in 1970,[5] and increasingly so-called “critical” raw materials [6] (such as magnesium or silicon) are used for high-tech products.[7] Another important motivational factor, however, is the fact that the consumption of raw materials and energy is responsible for many global environmental and sustainability problems, such as climate change, the emission of pollutants in the environment, but also for local and regional environmental impacts of mining of raw materials.[8] This problem becomes more serious on a global scale due to the economic growth of densely populated newly industrialised countries. This raises the question of equitable access to raw materials for all nations worldwide and, above all, to the planet’s boundaries in terms of the sustainability of the environment.

The concept of resources is therefore interpreted in politics today as “natural resources”: These essentially include, on the one hand, the raw materials taken from nature, on the other hand, the impact on the “natural sink” environment and the ecosystem, among other things, caused by emissions into air and water or landfilling of waste.[9, 10]

The goal of sustainable resource management is to decouple economic growth and prosperity from the use of natural resources.[11] Policies in Germany has set corresponding objectives: Within the framework of the sustainability strategy, the trends in total raw material productivity[12] of the years 2000 - 2010 are to be continued until 2030.[13] In addition, final energy productivity is to be increased by 2.1% per year in the period from 2008 to 2050, and primary energy consumption is to be reduced by 20% by 2020 and 50% by 2050 (figures compared to 2008 in each case).[14] In order to support

---

5 Cf. BMUB (2016b).

6 Critical raw materials: Economically significant raw materials whose supply is considered critical. For the list and definition of the EU cf. EU (2014).

7 Cf. Marscheider-Weidemann, F. et al. (2016), p. 233 et seq.

8 Cf. UBA (2015).

9 Cf. UBA (2012).

10 Cf. also VDI 4800 Part 1: 201602 (For more information see Chapter 2.2).

11 Cf. BMUB (2016b).

12 Total raw material productivity: Gross domestic product and imports, based on the abiotic primary material used (Raw Material Input – RMI) (Cf. Bundesregierung (2016), p. 37).

13 Cf. Bundesregierung (2016), p. 37.

14 Cf. Bundesregierung (2016), p. 37.

the achievement of these and the previous objectives, the German government decided in 2012 to adopt the "German Resource Efficiency Programme" (Prog-Ress) and to update it in 2016 (ProgRess II)[15]. An important field of action of the programme is resource efficiency in production. Corresponding objectives are also pursued by many federal states in independent resource efficiency programmes and activities.

New opportunities to increase resource efficiency in the economy are expected today from the digital transformation.[16] The integrated networking of all sectors of the economy will fundamentally change both industrial production itself and the products and services offered by companies. In addition, this networking will lead to new business models and value creation processes.[17]

The keyword "Industry 4.0", which was first coined at the Hannover Messe 2011[18], interpreted this transformation as a "fourth industrial revolution"[19]. This can result in significant economic consequences: According to estimates, successful digitalisation of the industry can lead to additional economic growth between 200 and 425 billion euros in Germany by 2025. There is also a strong expectation that this growth can go hand in hand with efficiency gains and "dematerialisation", and counteract the scarcity of natural resources.[20] If this digitalisation does not ssucceed, however, economic losses of up to 600 billion euros can be expected.[21]

Opportunities to reduce the consumption of materials and energy can be found at all levels of the value chain in principle:

- At the **process level**, energy consumption and material losses can be reduced by better control or utilisation of machines.

---

[15] Cf. BMUB (2016a).
[16] Cf. Neligan, A. and Schmitz, E. (2017), p. 18.
[17] Cf. Roland Berger Strategy Consultants (2015).
[18] Cf. Bischoff, J. (2015).
[19] Cf. Roth, A. (2016).
[20] Cf. BMBF (2013).
[21] Cf. BMWi (2015c), p. 4.

- At the **product level**, better maintenance and predictive replacement of components can increase service life, and labelling of components can facilitate future recycling.

- The digitalisation of products and user applications may lead to completely new **system solutions or innovations**, among other things, through the convergence of products and services.[22]

The study "Understanding Industry 4.0 as an Opportunity" expects resource savings through digital transformation of up to 50%[23].

However, the digital transformation itself requires resources:

- The production of digital transformation components requires materials, including critical raw materials (e.g. silicon or germanium for sensors).

- The operation of hardware and software requires electrical energy and thus contributes to the consumption of (fossil) primary energy sources and the emission of greenhouse gases.

In Germany, for example, the electricity consumption due to information and communication technologies (ICT) in 2014 amounted to approximately 57.2 TWh[24, 25] (corresponding to around 10% of total electricity consumption[26]), of which around 9.6 TWh is from industry.[27] Estimations by the German Federal Government for the year 2011 suggest that the electricity demand of data centres and telecommunications networks, in particular, will double by 2020.[28] A holistic view of the opportunities of digital transformation to increase resource efficiency must therefore also take into account the efficiency of the provision and use of ICT – including the critical raw materials involved.

[22] Cf. Fraunhofer IPA and Dr. Wieselhuber & Partner GmbH (2015).
[23] Cf. Plass, C. (2015), p. 5.
[24] Cf. UBA (2017), p. 132.
[25] In the UBA study (2017), ICT technologies included desktop PC, notebook, monitor, printer, server, telephone and router.
[26] Cf. BDEW (2015), p. 17.
[27] Cf. UBA (2017), p. 216.
[28] Cf. German Bundestag (2011).

1.2 Objectives

The present study was commissioned by the VDI Zentrum Ressourceneffizienz GmbH, which operates on behalf of the Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety, in cooperation with the Ministry of Environment, Climate and Energy Baden-Württemberg; the Bavarian State Ministry for the Environment and Consumer Protection, the Hessian Ministry of Economic Affairs, Energy, Transport and Regional Development; and the Ministry of the Environment, Energy, Food and Forestry Rhineland-Palatinate.

The aim of the study is to systematically study the impact of digital transformation on resource efficiency, with a focus on identifying the impact on natural resources. The study focuses on small and medium-sized enterprises (SMEs) in the manufacturing sector, for which digital transformation is a special challenge, but also an opportunity. Main questions of the study are:

Research questions of the study

- What are the "resource-efficient measures" of digital transformation, and to what extent do they open up the potential for resources savings?
- To what extent have "resource-efficient measures" of digital transformation already arrived in practice, and what experiences have companies gained from them?
- What best practice examples are there for SMEs, and what challenges can SMEs face in implementing a digital transformation to increase resource efficiency?
- How can the opportunities of digital transformation for increasing resource efficiency be specifically promoted?
- Which approaches are there for companies as well as stakeholders in politics and science?

SMEs often lack the time and staff to get an overview of the possibilities of digitalisation in the industry. The necessary know-how for the introduction of digitalisation measures in one's own enterprise is also unavailable. Nevertheless, SMEs are considered to be particularly suitable for implementing their Industry 4.0 ideas in the form of new products, markets and business models due to their greater flexibility compared to large companies. The fact is, however, that the pioneering role in terms of digital transformation lies with large companies and not with SMEs.[29, 30]

Against this background, the present study focuses on the potentials that enable digital transformation within the industry – and especially in SMEs – to increase resource efficiency. The goal is to illustrate in which areas and in what way such potentials exist. In addition, recommendations for action are to be derived in order to exploit such potential as much as possible in the future. With a focus on SMEs, concrete measures will also be described, and examples of best practice will be presented on how opportunities and synergies for increasing resource efficiency in the context of digital transformation can be specifically exploited.

1.3 Methodological approach

The core elements of the study are the structured analysis of the literature and expert knowledge of the participating partners (Chapter 2, Chapter 3 and Chapter 4), the development of a systematic methodology for the evaluation of resource efficiency potentials (Chapter 5) and the investigation of practical examples in companies (Chapter 6 and Chapter 7). This information basis was supplemented by a workshop with participants from industry, science, associations and the administration. In addition, a “Resource Efficiency through digitalisation" conference was held, during which industry participants exchanged views. Furthermore, the study identified eleven measures of digital transformation that can be used directly within the company, which contain considerable potential for resource efficiency (Chapter 8). In summary, approaches have been developed for SMEs as well as for stakeholders in politics and science (Chapter 9).

---

29 Cf. Bischoff J. (2015).
30 Cf. Neligan, A. and Schmitz, E. (2017).

2 BASICS AND CONCEPTS

2.1 Digital transformation and Industry 4.0

The terms “digital transformation” and “Industry 4.0” refer to the connection between the physical and the digital world. Specifically, this means for the industry and therefore also the manufacturing sector, the connection of systems, machines, workpieces and products with digital technologies[31], which is made possible by new information technologies, in particular by the Internet and cyber-physical systems (CPS). Based on the digitalisation of processes and the decentralised collection of data, networks are created with (continuous) exchange of information that enable innovative and novel production and value chains, and can lead to system innovations with far-reaching changes in the economy and society.[32]

Digital transformation

The term **digital transformation** implies a process-related view of the described facts: “Transformation” was coined as a political-scientific term, which describes the fundamental change of political regimes, social orders and economic systems[33]. Today, it is also used for technology-driven change processes, if they have far-reaching socio-economic consequences, such as in the case of the transition of the energy system from fossil to renewable energy[34]. Such significant changes are also to be expected or even already partially observed through information technology.

Industry 4.0

In contrast, the term **Industry 4.0** refers in a narrower sense to (producing) companies. Secondly, it refers less to a process than to a specific state to which the digital transformation of production leads. In a study by the Federal Ministry for Economic Affairs and Energy (BMWi) within the scope of

31 Cf. BMBF (2013).
32 Cf. RNE (2016), p. 7.
33 Cf. Merkel, W. (2010).
34 Cf. Büscher, C. and Schippl, J. (2013), pp. 11 - 19.

the accompanying research on the technology programme AUTONOMIK for Industry 4.0[35], the following definition can be found:

Definition: Industry 4.0

"In the industrial context, the term Industry 4.0 refers to the connection of the digital world of the Internet with the conventional processes and services of the manufacturing industry. It involves horizontal and vertical networking along the value chain with the transfer of control from top to bottom."[36]

The Association of German Engineers (VDI) has graphically represented Industry 4.0 as a house:[37] (Figure 1): Industry 4.0 in the sense of future production is based on the **Internet of Things and Services**.[38] It covers all levels of the company and its value chains and can be described as horizontal and vertical integration.

---

35 Cf. BMWi (2015a).

36 BMWi (2015a), p. 7.

37 Cf. Malanowski, N. and Brandt, J.C. (2014), p. 7.

38 The Internet of Services is part of the Internet, which maps services and functionalities as granular, web-based software components, while the Internet of Things represents the linking of physical objects (things) to a virtual representation on the Internet or an Internet-like structure. The full definition can be found in the Glossary. (Promotorengruppe Kommunikation (2013), pp. 84 - 87).

Figure 1: The Industry 4.0 house (source: VDI e.V.)[39]

Vertical and horizontal integration

- **Vertical integration** stands for the complete networking between all company levels.[40] It therefore consists of networking production resources, e.g., automation devices or services with each other.
- **Horizontal integration** of a value chain comprises the networking of all machines, devices and employees at a company level and links them within the value chain, i.e., between companies. Horizontal integration via value networks, which goes beyond the individual factory location, also enables the creation of dynamic value networks.[41]

  Similar definitions can be found in the study "Uncovering the Potentials of the Application of 'Industry 4.0' in SMEs"[42].

[39] Excerpt from Malanowski, N. and Brandt, J. C. (2014), p. 7.
[40] Cf. Malanowski, N. and Brandt, J. C. (2014), p. 6.
[41] Cf. VDI/VDE-Gesellschaft und ZVEI (2015), pp. 5 - 7.
[42] Cf. Bischoff, J. (2015).

The shift to Industry 4.0 can take different steps, timescales and sections. Against this backdrop, this study focuses on the concept of digital transformation, which identifies all the different stages, measures or levels at which companies can move towards Industry 4.0.

2.2 Resources and resource efficiency

Natural and business resources

Resource efficiency is a term widely used today both in business and politics. It combines the entrepreneurial principle of efficient economic activity with the basic principle of sustainable development to preserve "natural capital" – the natural resources of society. However, the interpretations of the respective resources differ significantly:

Resources from a business and political point of view

- From a business point of view, **resources** include all economically necessary factors for production, in particular, operating and auxiliary materials, materials and substances, energy, capital, personnel, know-how and time.[43]
- In German and European politics, the term resource is defined in the sense of **natural resources** as follows:

  "Resource that is part of nature. These include renewable and non-renewable primary raw materials, physical space (area), environmental media (water, soil, air), flowing resources (e.g. geothermal, wind, tidal and solar energy) and biodiversity. It is irrelevant whether the resources serve as sources for the production of products or as natural sinks to absorb emissions (water, soil, air)."[44]

This definition of natural resources is also followed by a guideline, which described for the first time in 2016 a methodological framework for the determination of resource efficiency: VDI 4800 Part 1 "Resource Efficiency –

[43] Cf. Schebek et al. (2016), p. 5.
[44] UBA (2012).

Methodological Principles and Strategies"[45], which is supplemented by other papers on specific aspects (e.g. supply risks of raw materials)[46].

Connection of operational and natural resources

The guideline VDI 4800 Part 1 forms the basis of the methodical procedure within this study. However, both the perspective of operational and natural resources should generally be taken into account in order to link the societal goal of reducing the consumption of natural resources with operational options for action. In addition, it should be noted that in most cases, the impact on natural resources cannot be determined directly in a company.[47] Rather, it results from the upstream or downstream chains (production or subsequent further processing, utilisation and disposal) of the respective operational resources. For example, electrical energy itself is not a natural resource; it exerts its influence through the consumption of primary energy sources, e.g., coal, and the resulting environmental impact, such as the rising CO_2 content of the atmosphere and the large-scale land use by open-pit mining.

The existing connection between operational and natural resources is shown by the assignment of common operational resources to the natural resources influenced by them[48] in Table 1. It turns out that natural resources are influenced by certain operational resources, namely the consumption of final energy (electrical or thermal energy), materials (e.g. auxiliaries) and surface/soil. This subset of operational resources is referred to as the so-called **tangible operational resources**. In addition, at the operational level, emissions into the air and water, and the accumulation of waste result in the consumption of natural resources in the form of impact on the sustainability of the environment.[49]

---

[45] Cf. VDI 4800-1: 2016-02.

[46] At present, the guideline VDI 4600: 2012-01 "Cumulative Energy Demand (CED) – Terms, Calculation Methods" and the draft guideline for VDI 4800 Part 2: 2016-03 "Resource Efficiency – Assessment of Raw Material Consumption" are available. The planned directive VDI 4800 Part 3 "Resource Efficiency; Indicators for Assessing Environmental Impacts" is still in preparation.

[47] Cf. Schebek et al. (2016), p. 3.

[48] Cf. UBA (2012) and the slightly modified description according to VDI 4800 Part 1: 2016-02.

[49] This also applies to operations outside of establishments: For example, transport operations require the tangible operational resource fuel, which consumes the natural resource petroleum.

Resources in the context of this study

The concept of resources is concretised in the study by the following terms:

- **Natural** resources
- **Operational** resources
- **Tangible operational** resources
- **Intangible operational** resources

The definitions can be found in the Glossary (p. 184).

Table 1: Allocation of natural resources to operational resources

Natural resources			Operational resources		
According to UBA (2012)[50]		According to VDI 4800-1 (2016)	Designation	Unit	Examples
Primary raw materials	Primary raw materials (renewable, fossil)	Raw materials	Supplies (raw materials, primary products, tools, machinery, consumables and auxiliaries)	mg, kg, t	Plastics, metals, chemicals, lubricants, etc.
	Primary energy sources (renewable, fossil)	Energy resources	Demand for electrical and thermal energy	kWh, MJ	Consumption of electrical energy and heat for e.g. heating and cleaning operations
Environmental media	Water	Water	Water consumption	l, m^3	Drinking water and service water for e.g. cleaning and cooling operations
		Ecosystem services	Emissions into water	kg/m^3, g/l	Pollution of the water by pollutants
	Air	Ecosystem services	Emissions into air	kg/m^3, g/l	Contamination of air by pollutants
Environmental media / physical space	Land/soil	Land/soil	Land use	m^2, ha	Developed areas for buildings and roads, agricultural and forest land
		Ecosystem services	Emissions into the soil, eliminated waste	kg/m^3, g/l	Pollution of the area by pollutants in the soil or the dumping of waste
Flowing resources (e.g. solar and wind energy)	Illustrated using primary energy sources (renewable)	Energy resources	Demand for electrical and thermal energy	kWh, MJ	Consumption of electrical energy and heat for e.g. heating and cleaning operations from renewable energy sources
Biodiversity	Illustrated using land/soil	Not considered			

[50] Based on EU (2005).

Methodology for determining the consumption of natural resources

The determination of the consumption of natural resources from the consumption of operational resources taking into account upstream and downstream chains can be based on the methodological basis of Life Cycle Assessment (LCA) according to DIN EN ISO 14040. The Life Cycle Assessment identifies material flows from nature and into nature, as well as the associated environmental impacts, over the complete process chain of products, materials or other consumptions (e.g. electrical energy). This principle of consideration of the complete process chain – the "life cycle" – is part of the guideline VDI 4800, which also refers to the LCA standard DIN EN ISO 14040.

Resource efficiency

Guideline VDI 4800-1: 2016-02 defines the concept of **resource efficiency** as follows: "ratio between a certain benefit or result and the resource use required for it."[51] To determine resource efficiency, therefore, a **benefit** or **outcome** must be defined. One such benefit could be the production of a particular product (e.g. an engine block), but also the performance of a particular technical process (e.g. a bore hole of a certain depth). A service, such as the transport of goods over a certain distance or the provision of information via electronic media, can also be defined as a benefit. With reference to the standard DIN EN ISO 14040, the term benefit or outcome can be equated with the term used in the life cycle assessment of the **functional unit** (FU), which is defined as "quantified performance of a product system for use as a reference unit".[52].

Based on these benefits in the form of an object or fact, the next step is to define so-called **"system boundaries"** (system frameworks), within which the resource consumption is to be determined. This definition of the system limits must follow the already-mentioned requirement to consider the complete life cycle in terms of a life cycle assessment according to DIN EN ISO

[51] VDI 4800-1: 2016-02, pp. 6 - 10.
[52] DIN EN ISO 14040: 2009-11, p. 10.

14040 so that possible problem shifts to upstream and downstream processes can be identified.[53] VDI 4800 Part 1 states how the system boundaries are to be determined depending on a specific benefit. These indications are based on the consideration that the potential increase in efficiency ("efficiency potential") is influenced by different types of innovation. These types are described for four different levels of innovation: Type 1: Product improvement, Type 2: Redesign innovation, Type 3: Concept innovation and Type 4: System innovation. The higher the innovation type, the greater the system boundary and the change in the process or product will be. For type 1, there may be small changes (e.g. material substitution); and for type 2, major changes (e.g. modification of the manufacturing process). In contrast, type 3 refers to changes in the product concept; and in type 4, significant changes in the product concept, which also cause a change in the required infrastructure.[54]

[53] Cf. VDI 4800-1: 2016-02, p. 7.
[54] Cf. VDI 4800-1: 2016-02, p. 35.

3 INDUSTRY 4.0: STATUS AND PERSPECTIVES

3.1 Technological basis

Industrial companies today face increasing national and international competition. All in all, it requires a constant adaptation of the products, production and logistics to the current market situation, productivity improvements and innovation in order to remain competitive. Measures to increase resource efficiency are an important building block here for optimisation.

An important foundation is the availability of up-to-date information at all locations and at any point in the life cycle of a product. The life cycle of a product covers its development, production, operation and maintenance up to recycling. On this basis, all parties involved in value creation (people, machines and products) can be adapted to target specifications and the current situation, and can carry out their tasks in an optimised manner. Having an extensive networking of the participants here provides the key to success.

The use of sensors and actuators, which are equipped with information and communication technologies and are networked, forms a starting point for the implementation on a technical level. This also involves the intensive digitalisation of technical and business processes as well as the intertwining of the physical and digital worlds. In this context, so-called cyber-physical systems (CPS) and the "Internet of Things and Services" are used as further key concepts to structure these guiding ideas.[55]

The goal is to build intelligent value networks. These consist of intelligent, digitally networked systems that enable a vision of self-organised production, a "smart factory": Machines, systems, logistics and products communicate and cooperate directly with each other and with humans. Cross-company production and logistics processes are intelligently linked to make production more efficient and flexible.

Overall, these developments radically change the way products are developed, manufactured, sold and operated, which is why this transformation

[55] Cf. Bischoff, J. (2015).

process is also referred to as the fourth industrial revolution in the context of industrial production.[56]

The term “Industry 4.0” provides a framework to unify previously separated development trends in microsystems technology, automation and production information technology (including product life cycle management, digital factory and factory operation). In contrast to the preceding subject-specific development trends, the following aspects are characteristic of Industry 4.0:[57]

- A holistic approach based on the production life cycle,
- Real-time synchronisation of the physical world with models in the digital world, and
- A flexible and secure networking of information in different tools and systems.

In addition to cyber-physical systems, further concepts and technologies related to “Industry 4.0” will be presented below.

Cyber-physical systems (CPS)

In general, cyber-physical systems (CPS) are defined as:

> “Embedded systems; production, logistics, engineering, coordination and management processes; as well as Internet services; which use sensors to directly record physical data and act on physical processes via actuators, are interconnected via digital networks, use data and services available worldwide, and have multimodal man-machine interfaces. CPS are open socio-technical systems that enable a range of novel functions, services and features.”[58]

CPS build on mechatronic systems or “smart objects”. A CPS consists of sensors, actuators, a user interface and functions that perform all the tasks of

[56] Cf. Promotorengruppe Kommunikation (2013).
[57] Cf. Lucke, D. et al. (2014), p. 8.
[58] Promotorengruppe Kommunikation (2013).

data acquisition, processing and output. In contrast to mechatronic systems, the sensors and actuators can be smart CPS-embedded systems that already contain “higher-quality” signal processing or control functions as well as “Internet Protocol” (IP)-enabled, i.e., internet-capable communication interfaces.

The key difference from previous approaches is the constant networking of components and the use of Internet technologies, software services, service-oriented architectures (SOA) and the use of open standards.[59] CPS specialising in production applications are referred to as cyber-physical production systems (CPPS).

Depending on the application, CPS can be implemented as highly distributed systems. In addition to intelligent networking, an advantage is that the computing power can be distributed and thus any functions can only be implemented economically. An example of this is offered by teleservice platforms, which are connected to machines via the Internet. The machines store the acquired machine status data in a decentralised manner and already carry out a sensor data processing, which requires only a low level of computing power, e.g. averaging over a measurement period. Only the processed metrics are transferred to the cloud-based data storage to minimise the burden on the communication network. From the cloud-based data storage, in turn, a wear simulation of a machine component, which requires high computing power, can be executed on a central server. The result is then made available to another server with average computing power running the web-based user interface. Depending on the application, the system boundary of a CPS can range from machine components to machines, entire factories and value networks, which can be distributed around the world. From a technological point of view, CPS is assigned to the various levels that represent them. Sub-CPS or CPS components are usually part of the infrastructure of a machine or system. Overall, new products can be implemented with CPS, and more varied data can be generated and in higher quantities. Due to these properties of the components, so-called “smart products” are created, which usually consist of three elements:[60]

---

[59] Cf. Lucke, D. et al. (2014), p. 13.
[60] Cf. Fraunhofer IPA and Dr. Wieselhuber & Partner GmbH (2015), p. 15.

- The physical element that defines the basic functionality of the product,
- The intelligent element that enhances the performance of the physical element in the future, and
- The networking element that enables the shifting of parts of the intelligence from the product.

Smart sensors and actuators

Sensors are technical components that gain information about the environment through the qualitative or quantitative detection of certain physical or chemical parameters. Smart sensors are also capable of converting and transmitting the acquired signals in the form of digital data. They also have an IP-capable communication interface. Thus, these are embedded systems which can also process the measured values directly and therefore only transmit measured values outside the tolerance to the higher-level system.

Smart sensors are currently being driven by the trend of miniaturisation and the integration of functions, e.g., for signal processing and communication directly in the sensor as a microsystem. Typical of this are accelerometers, gyroscopes or microphones. Another trend is the software-based implementation of previously “wired” functions with processors that can be programmed flexibly. The aim here is to enable an improvement or retrofit of functions in the operating phase at the same time. Another trend is the use of IP-enabled communication interfaces such as Ethernet in conjunction with Transmission Control Protocol (TCP/IP) and web services. Besides the classic sensors, technologies for automatic identification and data capture (Auto-ID) of objects, for example via Radio Frequency Identification (RFID), can be added.

Actuators are components that influence the physical environment. These are systems of electronics, mechanics and software programmes that convert electrical signals into movements, forces and torques. Actuators allow a controller to influence a system. Smart actuators also have built-in functions, such as an analogue-to-digital converter, and can be controlled by third-party CPS through their IP capability. In the field of microsystems and microelectronics (smart actuators), the integration of functions, e.g., for control, condition diagnostics and residual life prediction or "plug and produce" are trends for easier and faster commissioning. Through the use of cyber-physical add-on modules, such as smart measuring equipment or tools, it is desirable to easily integrate additional process steps to flexibly adapt the range of applications of machine tools.

Similarly, user interfaces represent building blocks of CPS, which are usually part of a higher-level CPS, e.g., a machine. A distinction is made between the physical part, the hardware, and the user interfaces of a software. One of the most important trends here is the proliferation of multimodal interfaces. Multiple communication channels are used side by side to make interactivity with the CPS more intuitive. In the consumer goods industry, this approach has already been implemented many times by controlling smartphones and tablets via a touchscreen, but also via voice input. Similarly, voice processing systems are used, e.g., for pick-by-voice systems in modern logistics centres. These are systems with voice recognition processes for paperless order picking in the warehouse.[61]

The intelligent factory (Smart Factory)

A networking of smart objects can be implemented company-wide or even between companies by CPS. These form the basis for the implementation of a smart factory. In this process, different objects in a production system interact bidirectionally between man and machine.

Typical architectures for machine-to-machine applications consist of data endpoints for sensor and actuator networks, communication networks, database servers, middleware that connects the different participants at a higher level of communication or software level, and the software that contains the application logic. The communication network can be designed as a local area network (LAN), as a wide area network, as the Internet or the Internet of Things (IoT), as the Wireless Internet of Things (WIoT), as a wireless local area network (WLAN) or as a mobile network.

---

[61] **Cf. Lucke, D. et al. (2014), pp. 16 - 32.**

Information distributed and deployed in the Smart Factory can be order-specific, product-related, or process-related. They may also include knowledge about the factory structure as well as the operational resources used in the factory. Product-related information can accompany a product until the end of its product life and can therefore be returned to the manufacturer by means of product return, e.g., for reprocessing or recycling. Job-related information is generated as part of the order creation, which is expanded and used in the course of order processing. Information technology (IT) systems support the integration of various sources of information.[62]

Factory 4.0 represents a company as a networked, global system at a microeconomic level. Outside the factory, there is a 4.0 supplier network (Logistics 4.0: fully integrated supply chain), future resources (renewable energy, alternative raw materials) and new customer requirements. Inside the factory, new production technologies, new materials and new ways of storing, processing and using data are considered. Key technologies include cloud computing, big data, security against attack and manipulation of IT systems, advanced manufacturing systems via CPS, driverless transport systems, robotics and 3D printing / additive manufacturing that make up Factory 4.0.[63]

A Smart Factory can take into account individual customer requirements and even manufacture individual pieces economically. The production is completely transparent, can be changed at short notice and react flexibly to faults and failures. In addition, Industry 4.0 offers the opportunity to meet current challenges in terms of material and energy efficiency as well as urban production. Resource productivity and efficiency can be improved in a Smart Factory on an ongoing basis across the entire value network.[64]

An important effect of intelligent networking is the outsourcing of product functionalities to the “cloud”. Cloud computing generally describes the provision of computing and storage capabilities over the Internet as a service.

---

[62] **Cf. Fraunhofer IPA and Dr. Wieselhuber & Partner GmbH (2015), pp. 15 - 16.**

[63] **Cf. Roland Berger Strategy Consultants (2014), pp. 9 - 11.**

[64] **Cf. Plattform Industrie 4.0 (ed.) (2013), p. 5.**

In this respect, there are different characteristics of the range of services offered.

Cloud computing carries out data exchange between product and operating environment, manufacturers, users and other systems. Likewise, a platform for storing data as well as executing software services may also be created.[65] Local services and processes are moved to the cloud in order to evaluate information on demand and deliver it over the Internet.[66]

Big Data

The move to Industry 4.0 is associated with tremendous data growth. In order to be able to manage and use this ever-increasing amount of data in a meaningful way, an approach to dealing with mass data has been developed: “Big data”. This term refers to the economically meaningful collection and application of decision-relevant findings from qualitatively diverse and differently structured information. This approach brings together different disciplines around managing and usage of large amounts of data.[67]

The collection and evaluation of generated data play an increasingly important role. These are data on processes, quality characteristics, products and employees as well as their environment, with the aim of process and quality improvement. In the production sector, where increasing quality requirements, increased complexity and high cost-pressure compete, the collection and analysis of process data are of great value.[68] The use of “Big Data” and “Advanced Analytics” can result in a 20 - 25% increase in production volume and a 45% reduction in downtime[69], which in turn minimises standby losses and thus saves energy for the operation of the systems.

---

[65] Cf. Fraunhofer IPA and Dr. Wieselhuber & Partner GmbH (2015), p. 15.
[66] Cf. Fraunhofer IPA and Dr. Wieselhuber & Partner GmbH (2015), p. 14.
[67] Cf. Fraunhofer IPA and Dr. Wieselhuber & Partner GmbH (2015), p. 14.
[68] Cf. WGP (2016), pp. 24 - 25.
[69] Cf. McKinsey Digital (2015), p. 11.

Data mining

The basis of the material- and energy-efficient design of production processes is the use of systems for production data acquisition and processing.

The underlying technological approach involves gaining new information from existing data and is called “data mining”. Quantitative data from different perspectives are computationally analysed in order to identify patterns, categorisations and the summary of potential relationships and influences.[70]

An important foundation for this is provided by measurements in real-time, which are characterised by the fact that they are carried out at very short intervals. They are also heavily integrated into the manufacturing process, with a distinction between in-process, post-process and in-line measurements, depending on the application requirements. Real-time data providers are external sensors, but often also machine or system controllers. Online measurements are continuous and repetitive measurements with a measurement high-rate during the process. They do not take into account real-time capability requirements.[71]

In practice, the term “data mining” is often used synonymously with “Knowledge Discovery in Databases” (KDD). In addition to the actual data mining, KDD also includes the preparation, i.e., the analysis and evaluation of existing data as well as the evaluation of the results. Certain data points are checked for consistency (e.g. contradictory start and end times of processes), correctness (e.g. increasing quantities in manufacturing processes) and completeness. In addition, a test for stochastic dependence takes place so that the data can be corrected independently of the error itself or other influences. After analysis and evaluation, generic algorithms (such as decision tree learning) are applied to the datasets with the aim of identifying (cross) connections and trends. This is followed by a correction of the faulty data points.[72]

---

[70] Cf. Schmitt, R., Brecher, C., Nau-Hermes, M. and Berners, T. (2015), p. 33.

[71] Cf. Schmitt, R., Brecher, C., Nau-Hermes, M. and Berners, T. (2015), pp. 15 - 16.

[72] Cf. WGP (2016), p. 29.

3D printing

A distinct target of Industry 4.0 is custom-made production at the expense of mass production. Key factors here are complex software solutions, Internet-based communication techniques, and disruptive technologies that network value creation stages in a novel way.[73]

Industry 4.0 thus brings more freedom and flexibility to production processes by enabling batch size 1 production at a relatively low cost. Also, distribution processes of spare parts or products of low complexity can be simplified by only transferring data. Only the physical production should take place locally. This becomes apparent in the case of 3D printing technology: The market for 3D printers and related services is estimated to nearly triple by 2017 compared to 2012.[74]

The 3D printing technology, once only applicable to polymers and metals, is now suitable for a range of materials such as glass, bio-cells, sugar and cement. The maximum size of 3D printed parts has increased more than tenfold in the last 25 years.[75]

A renowned British manufacturer of aircraft engines has set itself the goal of using 3D printing technology for the production of engine components. Some of these parts have long lead times and delivery times of up to 18 months. 3D printing would significantly shorten this process and enable the production of lightweight components with even lower weight.[76]

Digital shadow

The combination of the aforementioned technologies leads directly to a sufficiently accurate digital image of the processes "[...] in production, development and adjacent areas with the purpose of creating a real-time evaluation base [...]" [77] of all relevant data. This is defined as a digital shadow. Similar to the black box in aviation, the digital shadow refers to a production writer, which can provide information about past and current states on the one hand

---

73 Cf. DIHK (2015), pp. 5 - 6.
74 Cf. Roland Berger Strategy Consultants (2014), p. 12.
75 Cf. McKinsey Digital (2015), p. 13.
76 Cf. Roland Berger Strategy Consultants (2014), p. 18.
77 Knüpffer, G. (2016).

and, on the other hand, also allows a prognosis of future states. The digital shadow first illustrates the real production process in the virtual world. Based on this, the digital twin, a widely used term, represents a refined and mostly specialised model of a machine or system through a process model and simulation.

In order to create a digital shadow, error-free basic data must first be available before the data is compressed and further processed. At the same time, clear traceability of the data must be ensured when storing the data records so that a valid evaluation basis can be created. This requires a comprehensive recording of production data from different sources. For example, order data from a machine data collection (MDE) system can be stored and processed in a cloud-based decentralised manner.[78] Siemens thus postulates that the digital twin can exploit the prevailing potential for improving the efficiency and quality of mechanical engineering. The associated advantages can thus be, e.g., straightforward commissioning, error-free operation or short changeover times.[79]

3.2 Standardisation and committees

The development of standards and norms is of particular importance for the efficient interaction of different systems of different users. The implementation of new technologies and concepts by the increasing digital transformation of the industry can be secured by means of defined standards and norms.

[78] Cf. WGP (2016), p. 23.
[79] Cf. Siemens Aktiengesellschaft (2015).

Standardisation bodies and their tasks

- The main task of the DIN / DKE Steering Committee Industry 4.0 is to develop the topic of Industry 4.0 strategically, conceptually and organisationally from the point of view of standardisation. The "Standardisation Roadmap" task force was established under this steering group.[80]
- This working group also updated the second version of the German Standardisation Roadmap on Industry 4.0. It is a signpost for stakeholders from different technological sectors and supports the market acceptance of new technologies during research and development.[81]
- The "Standardisation Council Industry 4.0" was founded at the Hanover Fair 2016. The aim is to ensure the initiation and coordination of standards of digital transformation. The initiative aims to accelerate standardisation processes and strengthen the competitiveness of the German industrial location. New Industry 4.0 solutions and the standards used in them can be tested by working closely with the newly founded association "Labs Network Industry 4.0".[82]
- The technical management board of the International Organisation for Standardisation (ISO) has agreed to set up a strategy group (SAG) on Industry 4.0 / Smart Manufacturing. The aim is to work closely with the International Electrotechnical Commission and the International Telecommunication Union. The tasks of the SAG include the development of a definition of Industry 4.0. In addition, the portfolio of currently existing standards and the current standardisation activities are to be determined.[83]

3.3 Architectural models

The Industry 4.0 factory will be shaped by an unprecedented level of automation with massive use of the Internet. Different systems need to communicate and interact with each other. For this to succeed, interfaces must be

---

[80] Cf. DIN (2015b), p. 21.
[81] Cf. DIN (2015b), p. 7.
[82] Cf. Plattform Industrie 4.0 (2016).
[83] Cf. DIN (2015a).

harmonised. This, in turn, requires that the design of these interfaces is geared to internationally harmonised norms and standards.

A reference architecture, i.e. a uniform concept and method structure, forms the basis for this. It creates a common structure and language for the uniform description and specification of concrete system architectures for the application. There is a proposal from the Industry 4.0 platform for a solution-neutral reference architectural model Industry 4.0 (RAMI 4.0), which forms the basis for the further work of the platform (Figure 2).[84]

Such architectures should enable the interconnectedness of the corporate management level with the operating, process and control level up to the field level. In order to be able to set up a customer-specific company and production processes, “plug-and-produce”-capable production modules, optimised production planning and control on a customer-by-customer basis with the possibility of ad-hoc networking of products and resources must be implemented. To do this, the IT systems of the company management level (office floor) must be networked with the systems of production (shop floor) and be able to communicate with one another without barriers and media disruptions. These are the basis for a customer-specific, varied and tailor-made production.[85]

The three-dimensional model represents the Industry 4.0 space. Its basic features are based on the Smart Grid architectural model (SGAM) defined by the European Smart Grid Coordination Group (SG-CG). It has been adapted and expanded on the basis of Industry 4.0 requirements.

The vertical axis depicts the layers of different views, such as data image, functional description, communication behaviour, hardware/assets or even business processes. This corresponds to the approach in IT to group complex projects into manageable subunits.

[84] Cf. Plattform Industrie 4.0 (2017).
[85] Cf. Plass, C. (2015), p. 8.

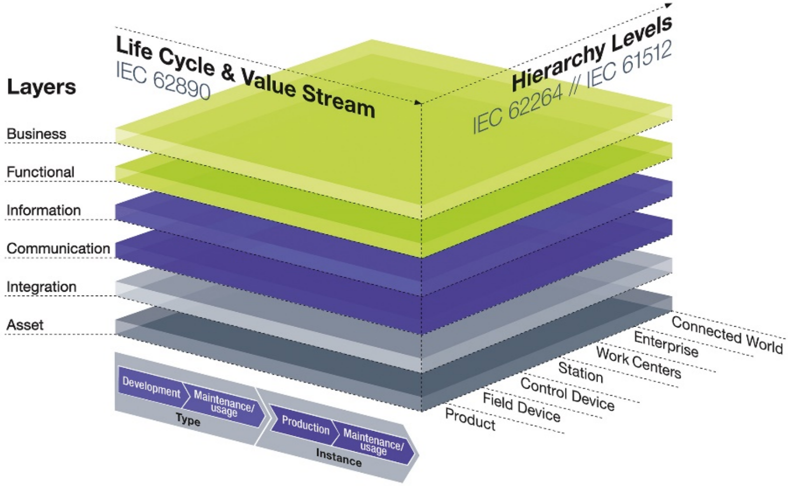

Figure 2: Reference architectural model/reference architectural model Industry 4.0 (RAMI 4.0)

Another important aspect is the presentation of the product life cycle with its included value chains. This is illustrated in the horizontal axis on the left. Dependencies can also be represented in the reference architectural model in this way, e.g., continuous data acquisition over the entire life cycle.

The third axis shows the location of functionalities and responsibilities within factories or plants. These are not device classes or hierarchy levels of the classic automation pyramid, but a functional hierarchy. Thus, the reference architectural model creates the prerequisites for describing highly flexible concepts as well as the step-by-step migration from the present to the Industry 4.0 world.[86]

The current organisational structures of companies consist of hierarchically separated levels, e.g., the enterprise network (office floor) or the real-time network (shop floor). The enterprise network encompasses the entire networking of systems and applications of business processes in product development, order processing and logistics as well as in finance. The real-time

[86] Cf. VDI/VDE-Gesellschaft und ZVEI (2015), pp. 5 - 7.

network contains all systems in production: Machines, control systems and sensors.

The two levels and the system landscape are networked through the Manufacturing Execution System (MES) as a central component. MES enables the integration of IT. ZVEI published a model in 2014 (Figure 3), which still has the enterprise network (office floor) and real-time network (shop floor) levels. Although the two levels are already well networked in themselves, this networking takes place only with considerable expense, since the necessary standards and standards are still lacking.

The central communication and management platform of all components involved in the system is thus in the foreground in this architectural model. The interface between the office floor and the shop floor is implemented on the basis of SOA (Service Oriented Architecture) concepts as a common integration mechanism. However, additional standards are needed as a basis for connecting to the enterprise network.[87]

[87] Cf. Plass, C. (2015), pp. 15 – 16.

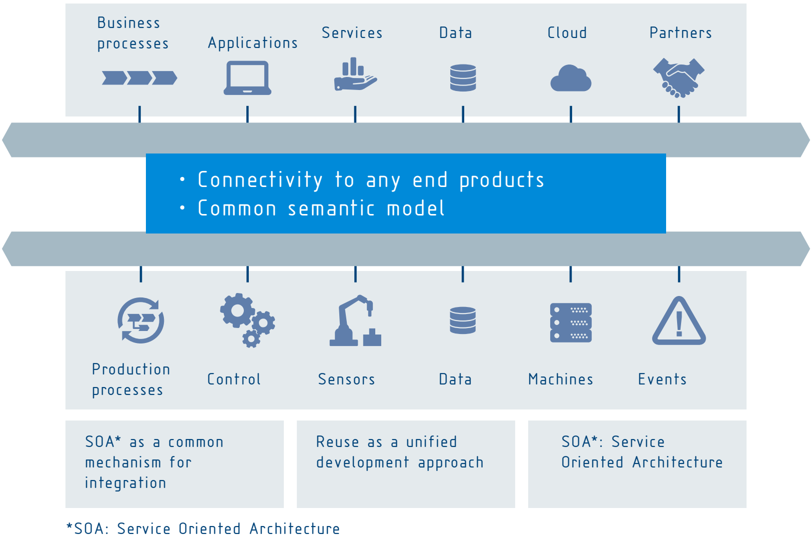

Figure 3: Establishment of connectivity through the principle of service oriented architecture (central connection between the office floor and the shop floor ZVEI 2014)

In 2015, SAP released a basic concept of the IoT platform, which opens another perspective in the architecture discussion. The upper hierarchical level describes business systems that are integrated into the rest of the system via an interface. This IoT platform (Figure 4) contains the layers “Analysis and Forecasting”, “Basic Applications” and the “App Store” for applications and represents a technology in the cloud. The data generated from this form the basis for further services of partners, customers and other users. This model focuses on newly generated services, business models and end-to-end processes. One challenge in implementing these new business models is clarifying who owns the data and who is authorised to use or process it. This decides who has sovereignty over the new business model – the system provider, the plant builder or the emerging service companies.[88]

[88] Cf. Plass, C. (2015), pp. 16 - 18.

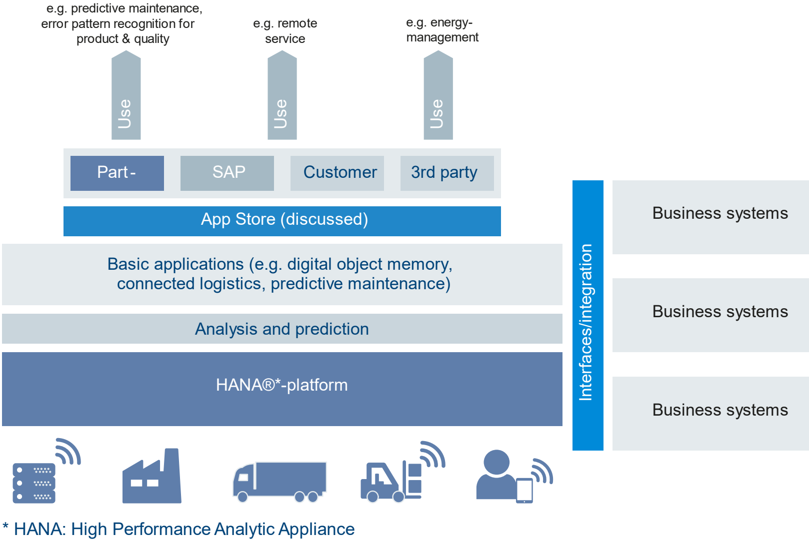

Figure 4: Platforms with different services for implementing IoT business models (based on the open basic concept of the IoT platform - SAP, 2015)

4 DIGITAL TRANSFORMATION AND RESOURCE EFFICIENCY

A range of ways to save operational material resources, such as energy and materials, but also “intangible” resources, such as capital, were already shown in the preceding chapter on the technological foundations.

The following chapter presents solutions and application examples from the field, research endeavours as well as which influences the digital transformation can have on the reduction of resource consumption. Such influences are therefore already recognisable, with the examples shown here being at different stages of development of the digital transformation towards Industry 4.0. In this respect, the transitions of the stages are running smoothly.

According to a recent study[89], which examines a variety of reports on funded research projects, manufacturing companies are using a variety of digital transformation technologies and system solutions as pilot measures at various levels, thus allowing them to optimise their material and energy use, among other things. The variety of measures is just as big as that of the corporate landscape. In the following, this is illustrated by examples from the literature, which are arranged according to different levels – process, company, supply chain. These levels correspond exactly to the places where the respective technologies and system solutions are used in practice.

4.1 Individual solutions at the process level

Digitisation in industrial forging

For an industrial forging process, demand-based compressed air generation has shown energy savings of up to 10%, while the use of electronic ballasts has resulted in an average of 5% less energy consumption. The use of a material simulation based on the finite element method (FEM) resulted in energy and material savings in the single-digit percentage range. Within this industrial process, software-aided design of the process chain and the resulting optimisation of the process parameters also led to energy savings by reducing the heating temperature for blanks. During heat treatment, online

---

[89] Cf. Dückert, E., Schäfer, L., Schneider, R. and Wahren, S. (2015).

process control, in conjunction with temperature measurement on the belts, allowed the use of residual heat from the annealing process for the annealing furnaces. A process control computer processed the measured values in the annealing model into a real-time heat balance, which allows demand-driven heating of the annealing furnaces. This ultimately led to energy savings of more than 50%, in addition to the reduction of consumables and auxiliary materials.[90]

Optimisation potential through data mining

Within the project EIDOdata of the University of Duisburg-Essen and the University of Applied Sciences Kempten, a software was developed that shows achievable optimisation potentials by the evaluation of different process data in production processes of companies. This example of data mining helps companies to use energy and raw materials more efficiently, which enables both environmentally friendly and cheaper production.[91]

Increasing the recycling rate of metal using sensors

A widespread measure of digitalisation is the use of sensor technology. In the case of the metal industry, this measure leads to higher efficiency of the recycling process. A sensor-based sorting system for metal removal in the shredder light fraction increases the recovery of recyclable metals from the shredder scrap (6% by weight of metals) and leads to a nearly metal-free shredder light fraction (residual metal content in the waste fraction <1% by weight). At the same time, a computer calculates the exact position of the individual materials, which are deliberately ejected from the mass flow at the end of the belt by means of compressed air. As a result, energy consumption for compressed air treatment is up to two-thirds lower than in the case of automatic sorting systems previously available on the market.[92] Within the recycling process of Hydro aluminium Recycling Deutschland GmbH, a new shredder system precisely separates the individual alloys after an analysis. A special X-ray system and different screening methods are used for accurate sorting. A computer analyses the X-ray measurements and controls the compressed air nozzles on the basis of the calculated real-time data. This

90 Cf. Emec, S. et al. (2013), Appendix 3.
91 Cf. EIDOdata GmbH, in preparation (no date).
92 Cf. Dückert, E., Schäfer, L., Schneider, R. and Wahren, S. (2015), p. 155.

enables a sorted separation. Consequently, the recycled aluminium can be re-introduced into the material cycle. 30,000 tonnes of aluminium can be recovered every year in this way. At the same time, CO_2 emissions are reduced by 200,000 tonnes per year.[93]

Intelligent control concepts

The energy consumption of electric drives for operating pumps, compressors and fans can also be reduced by about a quarter using electronic speed control. However, due to the self-consumption of the electronic components, the technology is limited to use in systems that are mainly operated at partial load. In addition, depending on the usage profile, standby losses can account for up to half the annual electricity consumption of a machine. Intelligent control concepts for switching off machines during off-peak periods can minimise these losses and thus contribute to further energy savings. Such control concepts are already being used by companies to optimise energy consumption. The approach is particularly common in the food industry, vehicle construction, metal production and the plastics industry.[94]

Optimisation of auxiliary materials and consumables through dynamic process control

In addition, the development of dynamic process control in process manufacturing can reduce the use of certain auxiliary materials and optimise the supply of consumables. In the secondary metallurgical treatment of steel, the oxygen supply is optimised within the process to minimise the burnup of chromium and other metals in the decarburisation of high-chromium steels.[95]

Sensorless control

The development of a process for sensorless control of linear motors in a film stretching line enables the motors to consume energy as required. This reduces energy consumption. In the case of the process peripherals, the use of

---

[93] Cf. VDI ZRE (2014a).

[94] Cf. Schröter, M., Weißfloch, U. and Buschak, D. (2009), pp. 5 - 6.

[95] Cf. Dückert, E., Schäfer, L., Schneider, R. and Wahren, S. (2015), p. 40.

speed-controlled screw compressors in compressed air generation also offers the same benefits.[96]

Demand-oriented control in the production of stators

In the production of stators in forming processes, resources are saved by controlling the process according to requirements. The equipment of pre-heating and cooling tanks with a temperature control and a secondary circuit with heat exchanger leads both to the improvement of the bath service life as well as to energy savings. This reduces the consumption of water and energy in the form of heat. In general, needs-based control of industrial processes, e.g., by switching off or demand-driven control of electronic motors under certain conditions, can reduce the consumption of electrical energy.[97]

Demand-oriented control of the process peripherals

Targeted control of other energy consumers of the process peripherals, such as lighting or heating, air-conditioning and ventilation systems, can contribute to significant energy savings. One measure is the needs-based control of the lighting or its adaptation to the requirements of a work process. A corresponding control of hot water pumps also leads to the avoidance of energy losses. In painting processes (application, drying, hardening), an energy-saving circuit for the air output in conjunction with frequency-controlled fans for supply and exhaust air or the integration of demand-oriented management of air output optimises the energy use.[98]

Control of industrial processes through data monitoring

Another measure for the intelligent control of industrial processes is the acquisition of process-relevant data by digital control systems in real-time. Extensive data monitoring can help with the efficient use of resources. With the help of time recording of all production processes and their regular evaluation, the SME MSR Technologies GmbH was able to save large amounts of

[96] Cf. Dückert, E., Schäfer, L., Schneider, R. and Wahren, S. (2015), p. 54.
[97] Cf. Dückert, E., Schäfer, L., Schneider, R. and Wahren, S. (2015), p. 65.
[98] Cf. Dückert, E., Schäfer, L., Schneider, R. and Wahren, S. (2015), p. 90.

material and energy and thus reduce costs. Immediate notification of production errors means that you can intervene directly in the production process. The reject rates and the associated use of materials are thereby significantly minimised.[99] A short film by the VDI Resource Efficiency Centre entitled “Fast, accurate and efficient with data monitoring” is dedicated to precisely this topic.[100] In process manufacturing, too, the collection of relevant data makes it possible to monitor the concentration of process chemicals, among other things. A timely adjustment of parameters to comply with process-related values leads to a reduction of emissions and material and energy savings.[101]

Online monitoring in process manufacturing

Galvanising also involves real-time measurement in the bath or analytical online monitoring of metal concentrations in the electrolyte to optimise the flow and density. An inhomogeneous material application is avoided, thus optimising the use of materials. Control and regulation electronics as well as a suitable measuring system are required for this.[102] For heat treatment in process manufacturing, the use of automatic temperature control has a positive effect on the consumption of energy resources. Equipping a raising hearth furnace with a demand-oriented control leads not only to an improved control of the steel quality as a function of the reference temperature, but also to savings in the amount of gas required.[103]

Forecasting and simulation in plastics processing

Another digitalisation measure is the use of auxiliary tools, such as forecasting and simulation software. In the processing of plastics and rubber, the software-based design of extruder and plasticising units leads to an energetic optimisation of the injection-moulding process by reducing the heat required. In addition, the engine power of the extruder and plasticising unit can be reduced, which additionally saves energy.[104]

---

[99] Cf. VDI ZRE (2014b), p. 24.
[100] Cf. VDI ZRE (2014c).
[101] Cf. Dückert, E., Schäfer, L., Schneider, R. and Wahren, S. (2015), p. 101.
[102] Cf. Dückert, E., Schäfer, L., Schneider, R. and Wahren, S. (2015), p. 112.
[103] Cf. Dückert, E., Schäfer, L., Schneider, R. and Wahren, S. (2015), p. 118.
[104] Cf. Dückert, E., Schäfer, L., Schneider, R. and Wahren, S. (2015), p. 52.

Cut minimisation through online cutting plans

Digital tools are also used when cutting material. In metalworking, for example, a software for waste minimisation, an algorithm as well as an analysis tool are used for generating online cutting plans. An optimal quality-based allocation can thus lead to the reduction of the waste material or an increase in the output quantity.[105]

Individual vehicle solutions using the modular system

For a vehicle manufacturer, custom vehicle solutions could be implemented using manufacturing processes with a "sophisticated modular system". The construction time of the vehicles, the use of resources and the associated CO_2 emissions could thus be sustainably reduced.[106]

4.2 System solutions at the operation level

Business information systems in combination with measuring sensors

An example from the chemical industry showed how the use of a suitable operating information system stored all available data on the energy and material consumption of a production plant in a central database and enabled their evaluation over a longer period of time. In this way, savings potentials could be identified and exploited by further measures. In the course of the central data collection and evaluation, all heterogeneous data in the company were made available to all employees in real-time with a high temporal resolution and a high compression. This can save on average 5 to 10% of the energy used without major investment. The software, in combination with measuring sensors for analysis of the cleaning in place (CIP), made it possible to halve the rinsing times in the tank. This saved several thousand cubic meters of water per year with the same cleaning result.[107]

[105] Cf. Dückert, E., Schäfer, L., Schneider, R. and Wahren, S. (2015), p. 74.

[106] Cf. IHK NRW (2015), p. 21.

[107] Cf. Zettl, E., Hawthorne, C., Joas, R., Lahl, U., Litz, B., Zeschmar-Lahl, B. and Joas A. (2014), pp. 62 - 66.

Smart production services

An application example in the field of smart production services is a trading platform for process parameters of complex production systems, such as laser cutting data for defined sheet metal materials. Plant operators and manufacturers, as well as raw material suppliers, are involved. Instead of purchasing a production machine with a set of standard parameters, the necessary process data can now be obtained from the market as needed. As a result, the plant operator can react even more flexibly to the increasing trend towards batch size 1 and thereby save necessary test material, among other things.[108]

Metering & Accounting

Another system solution at the level of the entire company is Metering & Accounting. It is the basis for process control and should also provide metrics for active efficiency management. Metering & Accounting represents all the processes and technical equipment needed to collect reproducible data in the production, transport, storage and consumption of resources. Metering includes the methods and technical facilities for measuring and recording resource consumption such as gas, water, electricity, etc. Accounting includes the system and the corresponding infrastructure for recording, summarising and analysing the collected data.

Smart service

In the smart-service world, generic methods and services are required in order to be able to map cross-application scenarios with many stakeholders and high process complexity (e.g. CO_2-footprint of goods). Engineering solutions must be reconciled with these methods and services as well as innovative business models (e.g. energy marketplaces for small producers).[109]

---

[108] Cf. acatech – Deutsche Akademie der Technikwissenschaften und Arbeitskreis Smart Service Welt (2015), pp. 60 - 61.

[109] Cf. acatech – Deutsche Akademie der Technikwissenschaften und Arbeitskreis Smart Service Welt (2015), p. 183.

"Social" machines

A completely new system solution is provided by a well-known machine tool manufacturer from Baden-Württemberg, using the first so-called "social" machines. Each component has its own intelligence and knows which process steps have to be carried out. Since "social" manufacturing can process information about the workload and also communicate with other sites, production is automatically optimised. This way, customers can receive images of their products, and in this case of machinery, in real-time during production and have the opportunity to respond early to their needs.[110]

Monitoring, control and optimisation via MES

The Industry 4.0 platform has provided an Industry 4.0 map online, which is illustrated by practical examples of where the same approach is already used in practice in Germany. For example, the project "Increasing transparency and efficiency" is presented, in which a company uses an MES to monitor, control and optimise its own moulding production. In the manufacturing environment, it serves as a central information and data hub. The correlation of real-time data from different sources enables an efficient use of resources, in addition to condition-based maintenance of the production facilities.[111]

Automatic floor conveyor systems

Another example shows how a packaging manufacturer can handle small batches and material efficiency economically. The transport by forklift led to damage to the cardboard boxes, which could no longer be sold. Production was automated in the context of Industry 4.0 by the replacement of forklift trucks with new automatic floor conveyor systems. A trolley picks up the cardboard boxes and automatically distributes them to the belt conveyor systems where the material is processed. Thanks to the digitalisation of materials management, material handling is much gentler, clearer and more efficient. Barcodes improve the representation of material and processing status. In addition, the customer can receive the delivery status in real-time.[112]

---

[110] Cf. Roland Berger Strategy Consultants (2014), p. 18.

[111] Cf. Plattform Industrie 4.0 (2016).

[112] Cf. IHK NRW (2015), p. 32.

Information, communication and automation solutions

Through the use of information, communication and automation technology, several optimisation levers and corresponding application examples can be identified to improve the use of resources in production.[113] Basic technologies and system solutions used for this are, for example, simulation and forecasting models, and smart software agents that interconnect components of the manufacturing management system (such as MES). Other technologies include (self-learning) assistance systems and wireless diagnostic tools for maintenance and repair, lab-on-chip systems for real-time analysis of the tiniest amounts of substance, and a value-chain-spanning network of material flows through interface optimisation in value chains for an improved use of resources. Information, communication and automation solutions thus support material efficiency, production recycling and the recovery of energy loss. Process chains and process stages must be considered in an integrated way so that the resource cycles can be networked.[114]

Chemical leasing

Savings of approximately 10 - 70% solvent or approximately 30 - 50% energy can be achieved through the application of innovative business models such as the resource-oriented concept of “Chemical Leasing”. The concept of “use instead of own” can only function undisturbed if the flow of information between the business partners functions smoothly. With automated measurement and sensor technology, e.g. the fabric provider can observe in real-time what quantities of a particular substance are currently available to the user and what the expected consumption will be. This can then guarantee foresighted planning without bottlenecks. Even simple measuring instruments such as water meters or control elements can help save 5 to 10% of the resources used in the chemical industry.[115] As a resource- and energy-intensive industry, the chemical industry will focus even more intensely on innovations in process and product development in the future in order to increase

---

[113] Cf. Behrendt, S. and Erdmann, L. (2010), p. 28.
[114] Cf. Behrendt, S. and Erdmann, L. (2010), pp. 29 - 36.
[115] Cf. Zettl, E. et al. (2014), p. 62.

resource efficiency. The limited availability of raw materials and the increasing demand for consumer goods, among other things, in newly industrialised countries, accelerate this process.[116] The "digitalisation of production" as a process innovation can also contribute to creating promising and resource-saving framework conditions in this industry.[117]

4.3 System solutions at the supply chain level

RFID technology

By using RFID systems, which can be integrated into MES systems, goods can be seamlessly identified within their warehouse or across the supply chain. This leads directly to integrated product tracking solutions of material movements in the manufacturing chain. This system solution creates consistent transparency of production and quality data and leads to an optimisation of the production processes.[118] In the end, these digitalisation tools can be used systematically to save resources.

Metallurgical Internet of Things

The digital integration of specific technologies and systems through global networking in the metal industry leads to the description of circular economy systems as dynamic feedback control loops, i.e., the metallurgical Internet of Things (IoT). This is the global interconnection of the system infrastructure in the metalworking sector, which reflects all the technology elements in the associated infrastructure. Other terms include the digitised Web of Metals (WoM) or System Integrated Material Production (SIMP). The approach is illustrated by the following:[119]

- System optimisation models for multimetal processing that map large m-IoT systems, which provide the link to the computer-aided design (CAD) tools of the original equipment manufactures and establish a recycling index by quantifying the resource efficiency;

---

[116] Cf. Malanowski, N. and Brandt, J. C. (2014), p. 16.
[117] Cf. Malanowski, N. and Brandt, J. C. (2014), p. 18.
[118] Cf. Behrendt, S. and Erdmann, L. (2010), pp. 42 - 44.
[119] Cf. Reuter, M. A. (2016), pp. 1 – 4.

- Optimisation of industrial system solutions to create a circular economy within a corporation (CEC) as well as in society;
- Real-time measurement of the properties of ores and waste in smart factory structures, coupled with the modelling, simulation and optimisation of reactors for industrial mining processes and factories for the processing of primary and secondary raw materials;
- Big data analysis and process control of industrial systems in the metal industry through the use of artificial intelligence and computer-aided engineering (CAE) technologies;
- Technologies, simulations and analysis tools for the processing of minerals and metallurgical process technology, all of which are key factors in circular economy;
- Visualisation of the results of all tools used to estimate the resource efficiency of the circular economy system in a way that is understandable to consumers and the public,
- Intelligent integration of tools and methods that estimate resource efficiency and provide sustainable solutions called “circular economy engineering (CEE)”.

4.4 System solutions at the product life cycle level

In light of the fourth industrial revolution and the consideration of the entire product life cycle, the types of added value are also changing. This creates opportunities for the development and implementation of new innovative business models and thus also emerging challenges. Previous products and business models can be significantly changed or even replaced by Industry 4.0. In this context, services and products are increasingly converging. In the past, these were mostly separated and sometimes offered by different sides. In the future, products and services will be more closely integrated, according to a life-cycle approach. It will no longer be the pure product that is offered, but also the benefits. This approach leads to the development of three strategic directions or corresponding business models.

- The increase in the availability contribution is aimed at increasing the time available of a machine for processing. This means that companies are increasingly orienting themselves to taking on responsibility for operational availability in the form of a pay-per-hour model.

- Another way is to increase the productivity contribution. This encourages companies to no longer limit themselves to the provision of means of production, but to take responsibility for production. In the corresponding pay-per-piece business model, sales are no longer assigned to the machine itself, but to every part it produces.

- The aim of the approach of increasing the application contribution is to increase the benefit for the end customer. The pay-per-value business model is evolving from this approach, with one's own product having a significant impact on the end product.

Digital transformation favours the implementation of these strategic approaches. Increasingly intensive networking with the customer and his processes or the life-cycle-wide consideration are leading to an increasingly stronger integration between manufacturers and operators.[120]

4.5 Current research and development activities and perspectives

Working group "Research and Innovation" of the Industrie 4.0 platform

An important cornerstone for achieving the goals of Industry 4.0 is research and development. The working group "Research and Innovation" of the Industry 4.0 platform aims to bundle research activities in the area of Industry 4.0 and to work on them according to a structured and prioritised research agenda. The basis for this is provided by a series of research roadmaps on various Industry-4.0-relevant research and innovation topics, which are described in detail in a current profitability[121] report.[122]

[120] Cf. Lucke, D. et al. (2014), pp. 23 - 25.
[121] Cf. Plattform Industrie 4.0 (2015).
[122] Cf. Plattform Industrie 4.0 (2015), p. 18.

Effizienfabrik

"Effizienzfabrik" is a joint initiative of the German Engineering Federation (VDMA) and the Federal Ministry of Education and Research (BMBF). It provides information on the results of current research projects and offers experts an exchange platform in the area of resource efficiency and electromobility.[123]

E-energy: ICT-based Energy System of the Future

Against the backdrop of dwindling energy resources and rising energy demand, the Federal Ministry for Economic Affairs and Energy (BMWi) has launched the flagship project "E-Energy: ICT-based Energy System of the Future". Core aspects of the project include comprehensive digital networking, computer-based control and computer-based monitoring of the entire energy system. The BMWi has initiated the E-Energy technology competition to develop integral ideas and system concepts for an "Internet of Energy" with the aim of accelerating innovation developments.[124]

Alliance for more resource efficiency

In Baden-Württemberg, companies in the manufacturing sector have the opportunity to publicise their successfully implemented or planned resource efficiency measures as part of the "Allianz für mehr Ressourceneffizienz" launched by the Ministry of the Environment, Nature Conversation and Nuclear Safety as well as the Energy Sector Baden-Württemberg.[125]

E^3 production

The Fraunhofer Society has initiated the lead project "E^3-Production" with the aim of exploring, at a comprehensive level, how substances, energy and information flows in emission-neutral "E^3 factories" can be better planned, implemented and controlled in the future with energy- and resource-efficient production taking humans into consideration. With this lead project, twelve Fraunhofer institutes are making an important contribution to the national

[123] Cf. Forschungskuratorium Maschinenbau (2016).
[124] Cf. BMWi (2010), pp. 66 - 68.
[125] Cf. UTBW (2016).

sustainability strategy of the Federal Government. The lead project demonstrates an E³ research factory integrating all the pillars of E³ production.[126]

UltraEfficient Factory in an Urban Environment

The project "UltraEfficient Factory in an Urban Environment" (Figure 5) aims to design production in a sustainable and efficient manner. In order to integrate approaches of the "green economy" in machine and plant construction, three Fraunhofer institutes are investigating and evaluating currently used technologies in the project funded by the Ministry of the Environment, Nature Conversation and Nuclear Safety as well as the Energy Sector Baden-Württemberg and linking them with sustainable technology innovations. The aim is to create ultra-efficient factories that make the best possible use of resources – for greater sustainability and lower environmental impact.[127]

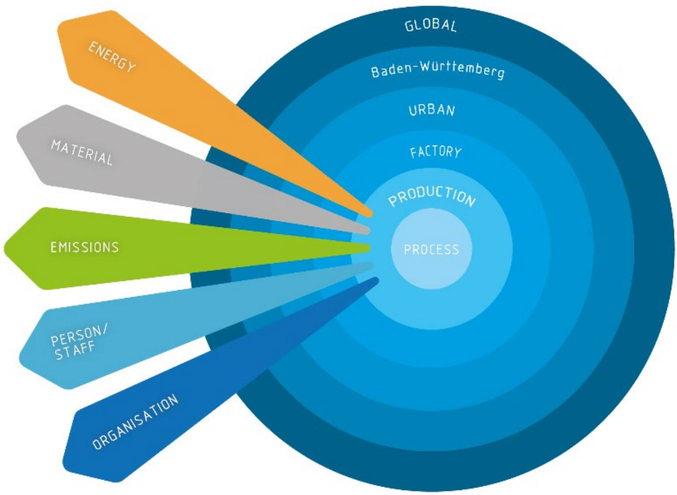

Figure 5: An Overview of the UltraEfficient Factory (Source Fraunhofer Society)

[126] Cf. Fraunhofer-Gesellschaft (2014).
[127] Cf. Fraunhofer IPA (2016).

RES-COM – Resource conservation by context-activated machine-to-machine communication (M2M)

Concepts and scenarios for context-enabled resource conservation through highly networked and integrated sensor-actuator systems from embedded to cyber-physical systems in production have been developed and implemented at the prototype stage in the project "RES-COM – Resource Conservation by context-activated machine-to-machine communication (M2M)", funded by the Federal Ministry of Education and Research. The demonstration system (Figure 6) is based on functional modules, which are networked by cyber-physical systems and are controlled dynamically by service-oriented architecture.[128, 129] Services that are semantic and are dynamically orchestrated are used to directly control the modular manufacturing units. The manufacturing process is planned and implemented according to the manufacturing order that each product dictates based on its active digital product memory. Production parameters and planning process are dynamically adjusted depending on the context: "High order state and reliable production" or "Resource-saving production".

[128] Cf. Abele, L., Ollinger, L., Heck, I. and Kleinsteuber, M. (2012).
[129] Cf. Loskyll, M., Heck, I., Schlick, J. and Schwarz, M. (2012).

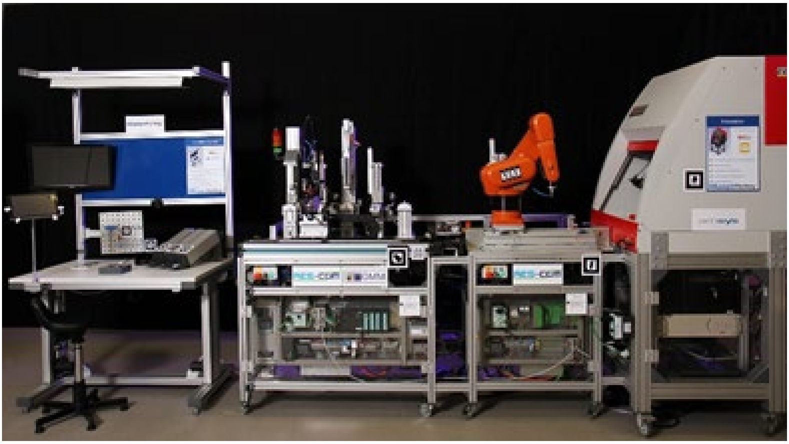

Figure 6: The demonstration system of the projects RES COM - Conservation of resources by context activated M2M communication (Source: DFKI)

Summary

The measures and practical examples described in this chapter, as well as the research projects presented, show that positive effects on the efficient use of resources are already recognisable through the digital transformation.

The fluid development stages of this transformation make it difficult at the present time to point out direct connections between the use of Industry-4.0-promoting technological components or solutions and a direct increase in resource efficiency.

Any interactions could therefore only be partially identified. However, the described information, automation and control measures in practice, which serve as the basis for holistic Industry 4.0 solutions, can enable a more transparent and efficient use of resources.

5 PROCEDURE OF THE SCIENTIFIC INVESTIGATION

5.1 Methodology

As described in Chapter 2.2 (p. 19), the guideline VDI 4800 Part 1 forms the basis of the methodology for resource efficiency in this study. The concept of resource efficiency potential is not explicitly defined in VDI 4800. However, it can be said that it corresponds to a possible improvement of resource efficiency through a specific change. Such a change may be a product or process improvement or an innovation of the types mentioned in VDI 4800 (Chapter 2.2, p. 19). Therefore, the following definition is used for the present study:

Resource efficiency potential

Resource Efficiency Potential (REP) refers to the potential increase in resource efficiency through digital transformation for a particular benefit or outcome compared to a reference state defined for that benefit or outcome.

To determine the REP, as mentioned in the definition, a reference state in the form of a conventional process must be described, which is changed by the digital transformation. Data on the conventional process consumptions and data on the consumptions of the state after the digital transformation has to be collected and compared for a quantitative description. As an alternative calculation, information about savings in the digital transformation can be directly deducted using the details of the expenses, e.g., hardware necessary. Thus, the REP is described in the form of the change of the operational material resources.

If the natural resources themselves are to be identified, records for the complete life cycle are required that are available in life cycle assessment databases, or they can be derived from other sources. By multiplying by the factors of such datasets, the REP of the natural resources can be described analogous to the relationships shown in Table 1 (p. 22).

These natural resources can in turn be set in relation to societal indicators, such as the sustainability indicators available in Germany. This provides a consistent indicator system that links operational parameters with societal goals (Figure 7).

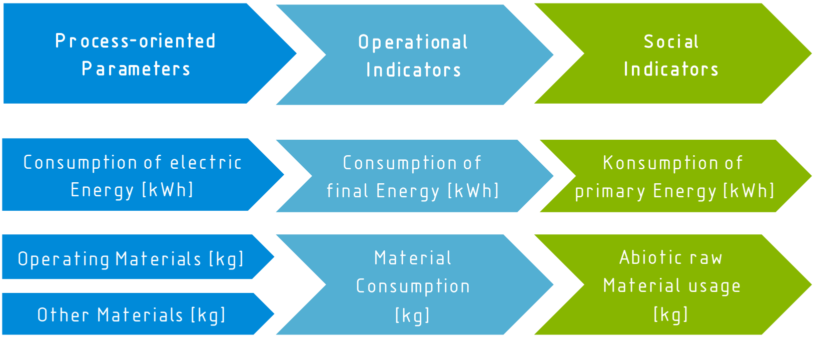

Figure 7: Assignment of process related parameters to company and social dicators

Such a system has already been used in a study on the resource efficiency of machining [130]processes. It has been shown that there is still a need for research on a methodologically consistent application. For example, the process-related life cycle approach is conceptually different from the definition of currently used economic indicators. An appropriate scientific discourse on the further development of important indicators is currently being conducted.[131] Therefore, in principle, the procedure described here provides a consistent indicator for measuring the success of sustainability goals in the area of natural resources.

5.2 Basic data to evaluate resource efficiency

5.2.1 Data sources

Information on consumption of production or savings through digital transformation can usually be collected at the company level. In the present study, this is done on the basis of the evaluation of the case studies (Chapter 6, p. 77). The data sources for the area of production processes therefore represent the information provided by companies on consumption or savings, insofar as they can be found in the case studies or are known to the companies themselves.

[130] Cf. Schebek L. et al. (2016).

[131] Cf. Hirschnitz-Garbers, M. et al. (2014).

In addition, the costs for the digital transformation must be described when determining the REP. These expenses may include organisational, logistical or other case-related changes, which are determined as much as possible from the case studies, similarly to the information on production itself. However, the “core area” of the expenditures of the digital transformation includes the technologies of the digital transformation and its components, i.e. hardware and software. These influence the natural resources through mainly two effects: The hardware needs raw materials for their production; hardware and software together consume energy during operation. The companies themselves had no information on these consumptions.

The study therefore carried out a detailed analysis of the literature on the costs of the digital transformation. The documents that were published in connection with the Energy-related Products Directive (ErP Directive) were also taken into account. The ErP Directive, also known as the Ecodesign Directive, lays down requirements for the design of energy-related products that are environmentally sound. The scope of the framework directive concerns product groups which, first, have a high market volume throughout Europe, second, are energy-relevant and, third, have a high potential for improving their environmental compatibility. The directive defines only the basic objectives and the procedure for the legislative process. Detailed requirements are only specified by so-called implementing measures and become final.[132, 133] The following product groups can be identified as relevant for the digital transformation: PCs and monitors, printing devices, stand-by and off-mode losses, external power supplies, smart grid devices and utility meters, as well as servers.[134] Implementing measures have already been published for the first four product groups mentioned. A preliminary draft of the implementing measure is currently in progress for the smart grid appliances and consumption meters product group. For the server product group, such a preliminary design already exists [135], to which reference is made accordingly in the evaluation of the expenses of digital transformation.

[132] Cf. EU (2009).
[133] Cf. EBAM (2015).
[134] Cf. UBA (2014).
[135] Cf. EU (2015b).

The findings can be summarised as follows:

- Life cycle assessment studies were carried out on a number of components of the digital transformation, preferably on consumer-related products such as laptops or smartphones, which analysed raw material and energy consumption. The comparatively small number of these studies, however, only partially depicts the current diversity of components.

- As expected, the production phase is decisive for the consumption of raw materials and the associated environmental impacts. But also the disposal phase has to be considered: High recycling rates have a positive impact on the environmental impact of the products. With regard to future recycling processes, especially for critical raw materials, there is currently a very high degree of uncertainty.

- In the case of servers, it could be shown that the energy consumption can be assigned to 5% of the production phase and to 95% of the utilisation phase[136]. However, this can be different for end devices such as laptops.[137]

- Interestingly [138]enough, hardware constitutes the direct "energy consumer" in the form of electricity, but estimates suggest that up to 90% of the required energy needs for ICT hardware are attributable to the software.[139] This shows that the software is a key driver of the energy efficiency of ICT applications.

- In addition to life cycle assessments of individual components, macroeconomic assessments are available for the energy consumption during the utilisation phase. These show that, on the one hand, the energy consumption of end devices such as smartphones or notebooks falls as they become

[136] Cf. EU (2015a).
[137] Cf. Andrae, A. S. G. and Andersen, O. (2010).
[138] Cf. Hilty et al. (2015), p. 37.
[139] Cf. GHGP (2013), p. 4.

more efficient. On the other hand, cloud computing is significantly increasing the power requirements of data centres and telecommunications networks.[140]

Factors that may be used for the quantification of expenses are presented in tables in the following Chapters 5.2.2 and 5.2.3.

5.2.2 Energy consumption during the utilisation phase

The energy consumption of hardware system elements as well as of specific data transfer actions from LCA studies are presented in Table 2. The information on the hardware does not reflect the influence of the software, since the inclusion of software-related indicators is a methodological challenge.[141]

[140] Cf. BMWi (2015b), p. 40 et seqq.
[141] Cf. Hilty et al. (2015), p. 37.

Table 2: Energy consumption of system elements during the utilisation phase

System element	Consumption electr. energy (use)	
	Consumption	Unit
	Computer	
Laptop PC[142]	47.5 - 116	kWh per year
Desktop PC (with LCD screen)[143]	215	kWh per year
Thin client[144]	35.7	kWh per year
Mobile devices		
3G smartphone[145]	2	kWh per year
Tablet[146]	6.44	kWh per year
Server		
Data server[147] – max. 96 GB	1661 - 13286	kWh per year
MicroServer – max. 40 TB [148]	1117	kWh per year
NAS server – max. 40 TB [149]	3723	kWh per year
Rack server – max. 120 TB [150]	5585	kWh per year
Enterprise Storage [151]	3279	kWh per year
	Use of devices	
3D printing of plastic[152]	0.072 - 0.135	kWh per hour pressure
	Data transfer	
Data transfer from virtual desktops [153]	0.30 - 0.34	kWh per GB
A Google query [154]	0.0003	kWh per query
A 500k Email [155]	0.00014 - 0.00013	kWh per Email

Influence of data centres and cloud computing

At a macroeconomic level, it is generally expected that especially as a result of the digital transformation of cloud computing, the associated energy requirements for Internet use and external data centres will rise sharply.[156, 157, 158] The Preliminary Study on the Implementing Regulation of

[142] Cf. Andrae, A. S. G. and Andersen, O. (2010).
[143] Cf. Andrae, A. S. G. and Andersen, O. (2010).
[144] Cf. Andrae, A. S. G. (2012).
[145] Cf. Andrae, A. S. G. and Andersen, O. (2010).
[146] Cf. Andrae, A. S. G. (2012).
[147] Cf. EU (2015a), p. 26.
[148] Cf. HPE (2017).
[149] Cf. Synology (2017).
[150] Cf. LaCie (2017).
[151] Cf. EU (2015a).
[152] Cf. Wittbrodt et al. (2013), p. 715.
[153] Cf. Andrae, A. S. G. (2012).
[154] Cf. eLife (2017).
[155] Cf. Andrae, A. S. G. (2012).
[156] Cf. eLife (2017).
[157] Cf. BMWi (2015b).
[158] Cf. German Bundestag (2011).

the ErP Directive for the Enterprise Server (ENTR 9) product group predicts that the total workload of data centres in Europe will increase by 14% annually. At the same time, cloud-related workloads are rising much more than conventional workloads (between 3 and 6%) at up to 30%.[159]

A study by Fraunhofer IZM and Borderstep estimates that the demand for electrical energy from data centres (including server, storage and network technology) in Germany will increase to 16.4 TWh per year by 2025 (see 2015: 12 TWh per year). The required computing power and storage capacity will increase as a result, which in turn will result in increased energy requirements from servers, storage and associated network technology.[160]

Influence of the networking of sensors and actuators

The increased energy demand can also be caused by the increased networking of sensors with controls that make the Internet of Things (IoT) possible.[161] Based on a Cisco forecast, a global financial growth of $19 trillion by 2020 is expected in the IoT area.[162] In contrast, General Electrics estimates that the value of the IoT will be more than $15.5 trillion by 2020, with 5% attributable solely to sensor networking.[163, 164]

Influence of data transfer

The 2007 study by Matsuno, Takahashi and Tsuda [165] looked at whole networks and the impact of ICTs on the environment for Japan. Here, the individual components were not considered, but only the data transfer in the network. The investigations have shown that the transmission of 1 MB of information involves CO_2 emissions of approx. 2.5 g (reference: Japan).[166]

[159] Cf. EU (2015b), p. 17 et seq.
[160] Cf. BMWi (2015b), p. 41.
[161] Cf. BMWI (2015b), p. 24 et seq.
[162] Cf. Cisco (2015).
[163] Cf. Bryzek, J. (2014), p. 7.
[164] Cf. GE (2014).
[165] Cf. Matsuno, Y., Takahashi, KI and Tsuda, M. (2007).
[166] Cf. Matsuno, Y., Takahashi, KI and Tsuda, M. (2007).

In light of this, a number of technological options have been developed to reduce the energy needs of data centres. Overall, there is still considerable potential for increasing efficiency here.[167]

5.2.3 Raw material consumption and other expenses in the production and disposal phase

The consumption of raw materials, as well as other expenditures over the life cycle (e.g. primary energy consumption or CO_2 emissions) of hardware components are summarised in **Table 3**.

Table 3: Material composition and other component expenses

Components	Material consumption acc. parts list	Primary energy consumption	CO2 equivalent (CO2-eq.)
	Materials	Production phase (materials and production)	Production phase (materials and production) & disposal phase
Server			
Data server[168]	s. Table 4	6,053 - 26,435 MJ [per server]	245 - 1,160 kg of CO_2-eq. [per server]
Enterprise Storage[169]	s. Table 4	17,184 MJ [per storage]	811 kg of CO_2-eq. [per storage]
Data transfer (related to the utilisation phase)			
Network data transfer[170]	-	-	0.002 kg of CO_2-eq. [per MB]
Data transfer from virtual desktops[171]	-	-	0.29 - 0.38 kg of CO_2-eq. [per GB]
Data transfer via UMTS with mobile phone[172]	-	-	429 kg of CO_2-eq. [per GB]
Sensors			
Sensor (level measurement)[173]	Casing: 0.61 g Polyurethane: 0.70 g Electronics: 0.1 g Battery: 0.059 g Other substances: 0.059 g	-	-

[167] Cf. Fichter, K. (2007), p. 24.
[168] Cf. EU (2015a).
[169] Cf. EU (2015a).
[170] Cf. Matsuno, Y., Takahashi, KI and Tsuda, M. (2007).
[171] Cf. Andrae, A. S. G. (2012).
[172] Cf. Andrae, A. S. G. (2012).
[173] Cf. Bonvoisin, J., Lelah, A., Mathieux, F. and Brissaud, D. (2012) and (2014).

Components	Material consumption acc. parts list	Primary energy consumption	CO2 equivalent (CO2-eq.)
	Materials	Production phase (materials and production)	Production phase (materials and production) & disposal phase
		Computer	
Laptop PC (EU)[174]	-	350 - 840 kWh[a)] [per laptop PC]	94 - 614 kg CO_2-eq.[b)] [per laptop PC]
Desktop PC (US)[175]	Alu & steel: 2.45 kg Display: 2.18 kg Plastic: 1.54 kg Glass: 0.62 kg Hard disk: 0.55 kg PCBs: 0.40 kg Power adapter: 0.28 kg Other substances: 0.23 kg	-	426 kg CO_2-eq.[b)] [per desktop PC]

[a)] Primary energy consumption of production
[b)] CO_2 equivalent of production including transport

		Computer	
Desktop PC incl. LCD screen (EU)[176]	Desktop computer LCD screen, keyboard mouse, computer usage	2200 kWh[a)] [per desktop PC]	3200 kg of CO_2-eq.[b)] [per desktop PC]
Thin Client (global)[177]	-	-	32 kg of CO_2-eq. [c)] [per Thin Client]
		Mobile devices	
3G smartphone (EU)[178]	-	64 kWh[a)] [per smartphone]	16 kg CO_2-eq.[b)] [per smartphone]
Tablet (global)[179]	-	-	22 kg of CO_2-eq. [c)] [per tablet]
Tablet (US)[180]	Battery: 0.13 kg Aluminium: 0.76 kg Display: 0.11 kg Glass: 0.06 kg Plastic: 0.02 kg PCBs: 0.042 kg Other metals: 0.012 kg (50% copper / 50% steel)	-	190 kg CO_2-eq.[d)] [per tablet]

[a)] Primary energy consumption of production
[b)] CO_2 equivalent of production including transport
[c)] CO_2 equivalent of the production phase including use
[d)] CO_2 equivalent of materials, production, transport, use and disposal

174 Cf. Andrae, A. S. G. and Andersen, O. (2010).
175 Cf. Apple (2009) and Cf. Andrae, A. S. G and Andersen, O. (2010).
176 Cf. Andrae, A. S. G. and Andersen, O. (2010).
177 Cf. Andrae, A. S. G. (2012).
178 Cf. Andrae, A. S. G. and Andersen, O. (2010).
179 Cf. Andrae, A. S. G. (2012).
180 Cf. Apple (2014) and cf. Hischier, R., Achachlouei, A. M. and Hilty, L. M. (2014).

Findings from life cycle assessment studies as well as further literature on "sensors" and "data servers" are presented below regarding their relevance to digital transformation in companies.

Sensors

The material composition of sensors can vary greatly depending on the measurement principle and type. In general, sensors often consist of a sensing element (microcontroller, electronics, board), a power source (e.g. battery, capacitor) and a casing. The casing may be made of metals (e.g. steel, aluminium), metal alloys (e.g. nickel-iron), semiconductors (e.g. silicon, III-V semiconductors), plastics (e.g. polyamide), or resins and ceramics (e.g. ceramic fibre optics).[181, 182] Depending on what a sensor measures, the weight of a sensor can also vary (from grams to tonnes). For example, when measuring wind speeds of wind turbines, a sensor can weigh over a tonne. However, in such cases, the measuring element nevertheless weighs little, and only the housing is adapted to the application. A study on wireless sensor networks[183] described the material composition of a sensor quantitatively (Table 3).

Data server

A preliminary-study on the ErP Directive commissioned by the European Commission investigated the environmental impact of the life cycle approach of two scenarios for servers (Rack Server and Blade System Server) and one scenario for an enterprise storage system.[184] The results of this study show that only 5% of the energy consumption are attributable to the production phase, while the remaining 95% are attributable to the utilisation phase. The high reuse (25 - 50%) and recycling rates (depending on the material: from 5% for plastics to 70% for metals) of the products have a positive effect on the environmental impact. This means a reduction of CO_2 emissions by 5% for the examined servers. The production phase is particularly important in terms of abiotic raw material consumption and the consumption of critical

---

[181] Cf. Hering, E. and Schönfelder, G. (2012).
[182] Cf. Tränkler, H.-R. and Reindl, L. M. (2014).
[183] Cf. Bonvoisin, J., Lelah, A., Mathieux, F. and Brissaud, D. (2012) and (2014).
[184] Cf. EU (2015a).

raw materials installed in the servers. The supplies and the critical raw materials used in the three products studied can be found in Table 4.

Table 4: Material used for data servers and Enterprise Storage[185]

Materials used	Rack server	Blade system (with 8 servers)	Enterprise storage
Memory	96 GB	768 GB	40 TB
Frame	12.27 kg	–	5.44 kg
Steel	2 kg	128.36 kg	26.38 kg
Aluminium	2.1 kg	7.73 kg	9.49 kg
Plastics (various)	1.6 kg	2.41 kg	2.25 kg
Copper	0.83 kg	2.17 kg	0.92 kg
PCBs	0.98 kg	3.24 kg	1.58 kg
Electronics	1.24 kg	5.43 kg	3.4 kg
Control board / motherboard	1.67 kg	6.54 kg	5.04 kg
Other materials (e.g. zinc, cables, paper)	0.33 kg	0.91 kg	0.39 kg
Critical raw materials in circuit boards and hard disk drives			
Neodymium	4.18 g	16.70 g	34.83 g
Silicon	11.01 g	24.40 g	28.53 g
Dysprosium	<1 g	<1 g	2 g
Praseodymium	<1 g	2.32 g	4.84 g
Palladium	<1 g	2.06 g	2.41 g
Platinum	<1 g	<1 g	<1 g
Antimony	<1 g	<1 g	<1 g
Gallium			
Germanium			
Cobalt			
Total weight	**23.02 kg**	**156.79 kg**	**54.89 kg**

Another aspect that needs to be considered in the context of resource efficiency and resource use of ICT technologies is the service livfe of individual ICT technologies. The relevance of service life is explained in more detail below.

[185] Cf. EU (2015a), p. 11 et seq., 14 et seq. and 20.

Influence of the service life of ICT technologies

The service life of different ICT technologies can vary widely. Various life cycle assessment studies assume the following service-life periods for specific ICT technologies: Laptop – approx. 3 - 4.5 years [186], smartphone – approx. 3 years[187], server – approx. 4 years[188] and sensor – 4 to 7 years[189](sensor-specific). The short service lives of ICT technologies can be explained in part by the fact that the devices themselves evolve rapidly, within a few months in some cases (e.g. due to greater storage capacity, increased performance), and consumers are therefore motivated to replace older models with more up-to-date models. On the other hand, new software comes onto the market very quickly, which is no longer compatible with the hardware due to new requirements. Because of this required compatibility with the software, the hardware must therefore be replaced.[190] This replacement has a direct effect on the consumption of other raw materials for the production of the hardware.

5.3 Characterisation of the digital transformation

5.3.1 Structuring approaches

For various reasons, the methodological approach of the study requires structuring in order to conceptualise the digital transformation. On the one hand, case studies in the form of interviews and questionnaires require the use of compact terminology in order to communicate with the interview partners. On the other hand, the evaluations (e.g. REP determination, analysis of challenges and opportunities) require "reference quantities" for statements and/or quantitative facts.

In particular, two areas must be defined by structuring approaches: First, the previous remarks in Chapter 3 show that it is not possible to derive a clear definition of individual technologies or measures of the digital transformation from the literature, but that many different views exist side by side.

[186] Cf. Andrae, A. S. G. and Andersen, O. (2010), p. 829.
[187] Cf. Andrae, A. S. G. and Andersen, O. (2010), p. 831.
[188] Cf. EU (2015a). p. 26.
[189] Cf. Bonvoisin, J., Lelah, A., Mathieux, F. and Brissaud, D. (2012), p. 151.
[190] Cf. Hilty et al. (2015), p. 10.

This makes it difficult to clearly identify such “technologies” or "measures" within case studies that can be applied to resource efficiency. On the other hand, Chapter 2.1 (p. 16) alluded to the fact that the concept of digital transformation is a process-related view and that companies may be at different stages of this process. These stages should also be specified since not all measures or options for action can be expected to apply to any company, regardless of its “digital state of development”. The following presents the structuring used in the study for these two areas.

5.3.2 Measures of digital transformation

For the structuring of the digital transformation, the term “**measure**” was chosen for the study. The measures to be identified should be based on common terminologies of digital transformation, which are a combination of digital technologies, components and processes. These terminologies should be widely known to practitioners and should be described in the clearest possible terms to enable a clear understanding of the measure both in the context of case studies and in the subsequent evaluation. On the other hand, the description of measures should not be so specific as to coincide with individual applications of practice found only in a single investigated establishment.

Since there is no clear definition of such measures in the literature, a list of eleven digital transformation measures was defined and validated in the case study analysis.

This list of generic measures (Table 5) provides the common basis for analysing the practical applications in the companies studied in relation to the REP, the challenges and opportunities, as well as the development of recommendations for action. It is to be expected that these generic measures will occur in practice in different individual combinations and forms. For this reason, the term “**practical application**” is used in the context of the case studies. This designates the combination or expression of different measures found in the real company.

Measures or their implementation in a practical application can be characterised in terms of their resource consumption by system elements of the digital transformation. Such system elements are components that are differentiated according to software and hardware, which are necessary for the implementation of a measure or a practical application and have an influence on resource consumption. Such components can be described either as generic components of measures or as concrete components of a practical application in a real company. The generic components are assigned to the eleven measures described in Table 6.

Table 5: Identification of eleven digital transformation measures

ID	Measure	Description
M1	Networking of sensors and actuators	A central prerequisite for the digital value added is the digital connection of sensors and actuators. It defines the basis for monitoring and recording data from different sensors and actuators over a longer period of time, and also for combining them in an integrated process.
M2	Use of digital object memories	Physical objects (products, machines) are equipped with a digital memory. Relevant data are stored in the memory and are directly accessible on the machine or on the product.
M3	Decentralised control	The smart workpiece becomes an important building block in the decentrally controlled manufacturing and value network. It possesses knowledge of its properties and provides information on how it can be manufactured and what the goal of manufacturing is. This way, it can control its own production process.
M4	Measures for staff support and assistance	Assistance systems can assist staff (with the help of mobile devices) in a variety of tasks in production and assembly. Software systems provide recommendations for the design of the production process on the basis of the networked infrastructure and the evaluation of the available sensors.
M5	Dynamically cooperating systems and modularisation	Modularly encapsulated functionality allows manufacturing facilities to be easily supplemented by new or modified plant components, and to create, modify, or resolve interoperability between two or more parties with minimal effort.
M6	Introduction and use of positioning and localisation systems	Positioning and localisation systems make it easier to find machinery and equipment in a production facility. Even the manufactured products can be located more easily and integrated into the production order.
M7	Condition monitoring	Various operating states of plants and processes are continuously analysed on the basis of recorded data and with the help of suitable software solutions, and deviations are marked and reported. Unexpected system failures should be avoided by constant monitoring and analysis.
M8	Predictive maintenance	Predictive maintenance systems are designed to detect machine failures (such as machine breakdowns or malfunctions) before they occur. Faults should be prevented by maintenance or early repairs.
M9	Comprehensive data integration	The comprehensive data integration and the uniform access to data structures enable an integrated view of production and order planning. For the implementation of agile production processes, a vertical integration of Enterprise Resource Planning systems (ERP system) is mandatory.
M10	Virtual product development	In virtual product development, a digital, three-dimensional model of a new product is designed in the computer. The virtual model can be modified, tested and optimised by simulations. Cost-effective physical prototypes can be created based on the model using new manufacturing techniques such as 3D printing.
M11	Cloud computing	Individual workspaces (e.g. programmes, software packages, storage space, computing capacity) are no longer provided on the hard disk, but via the Internet or local networks (the cloud).

Table 6: Use of generic components for the eleven measures identified

ID	Generic components								
	Hardware							Software	
	Sensors	Actuators	Server	Mobile End devices	Computer	Microcontroller	Communication technology	Interface & function	Communication technology
M1	X	X	-	-	-	X	-	X	-
M2	-	-	X	-	-	X	X	X	X
M3	-	-	-	-	-	X	-	-	X
M4	X	X	X	X	-	X	-	X	-
M5	-	-	-	-	-	X	-	-	X
M6	X	-	-	X	-	-	X	X	-
M7	X	X	X	X	X	X	X	-	X
M8	X	X	X	X	X	X	X	-	X
M9	X	-	X	-	-	-	-	X	-
M10	X	X	X	X	X	X	X	X	X
M11	X	X	X	X	-	X	-	X	-

5.3.3 Digital maturity

The so-called maturity of digitalisation describes how far a company has already developed in the process of digital transformation. Building on existing literature approaches, the Competence Centre for SME 4.0 Kaiserslautern has defined a maturity model[191] for determining the digitalisation status of companies, especially SMEs. This was used in the study and is described below. A study by Acatech[192] has also developed a model for a maturity-based approach. The study makes the classification according to the technologies used.

The model considers the five dimensions of enterprise strategy, people, technology, products and services, and organisation and processes for each of the five levels of Explorers, Beginner, Advanced, Expert and Pioneer in the context of Industry 4.0 (Figure 8).

[191] Cf. Hellge, V. (2017).
[192] Cf. Schuh, G., Anderl, R., Gausemeier, J., ten Hompel, M. and Wahlster, W. (2017).

Figure 8: Levels of digital maturity

The requirements increase in all dimensions beyond the maturity levels to the highest maturity level "5" of the model. It is possible for every interested company to carry out this individual maturity determination for free online on the website of the Competence Centre for SME 4.0 Kaiserslautern[193].

Level 1: Industry 4.0 Explorer

The company is at the beginning of the digital transformation process, and digitalisation projects are still in the very beginning of the process of discovering and planning.

Level 2: Industry 4.0 Beginner

The company has identified potentials and planned the corresponding first digitalisation solutions. Managers are now faced with the task of assessing initial insights and experiences and setting further priorities for further development in order to initiate concrete implementations.

Level 3: Industry 4.0 Advanced

The company is already using its first digitalisation solutions in some areas. According to this, executives have identified potentials, set priorities, and first effects can be specified and evaluated on the basis of business key figures.

Level 4: Industry 4.0 Expert

The company uses different digitalisation solutions in several areas. Employees and managers have captured digital trends and transferred them to the

[193] Cf. Competence Centre for SME Kaiserslautern (Mittelstand 4.0-Kompetenzzentrum Kaiserslautern, no date).

company. Digitisatoin is part of corporate governance and a focus in the further development of the company. Sometimes first effects can be specified using business key figures.

Level 5: Industry 4.0 Pioneer

The company uses digitalisation solutions in a targeted manner and uses them for future-oriented further development. Employees and managers have integrated digital trends and opportunities and can transfer them to the company. Potentials arising from digital solutions are proactively pursued in the company. Digitisatoin and Industry 4.0 are central elements of the company's strategy and development.

5.4 Methodology of case studies

Case studies were conducted in enterprises to illuminate industrial transformations of digital transformation and their impact on resource efficiency in enterprises. The goal of the case studies is to identify and, if possible, quantify positive and negative interactions between digital transformation measures and operational resource efficiency.

In this study, the design and methodology of the **Case Study Research by Yin**[194] serve as a basis for the case study analysis. This is well suited to create uniform case studies due to its flexible design. Case studies were conducted in companies to capture measures and potentials of digital transformation to increase resource efficiency according to the Yin[195] methodology. The procedure and the main contents of the respective steps are shown in Figure 9. For this, the first steps “Plan” and “Design” have been summarised.

---

[194] Cf. Yin, R. (2014).
[195] Cf. Yin, R. (2014).

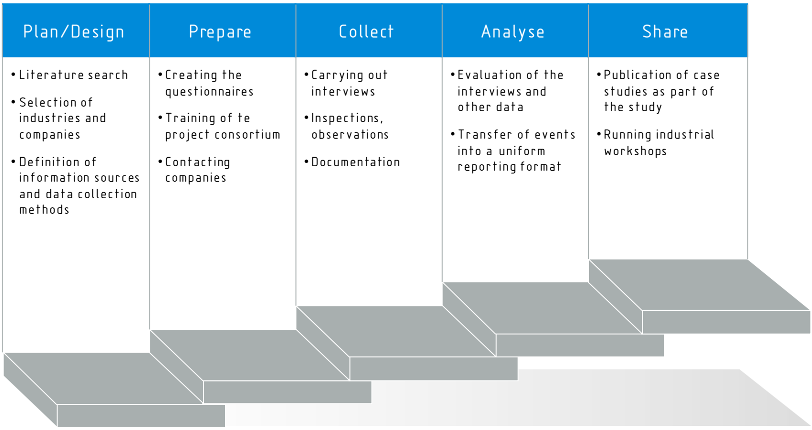

Figure 9: Case study procedure based on Yin (2014)

The basic planning of the case study is carried out and designed in **"Plan and Design"**. The measures in digital transformation to increase the resource efficiency of SMEs are the subject of the study. The study examines not only SMEs themselves, but also companies that are pioneers and offer solutions, as well as companies that, due to their structure, correspond to an SME.

"Prepare" involves the preparation of data collection at the companies. Due to the large number of measures and their potential impact on resource efficiency, an "embedded case design", in which several objects are analysed both qualitatively and quantitatively, was used to prepare and conduct the case studies. In order to guarantee the validity of the methodology, the following data sources were used[196]:

- Interviews
- Direct observations
- Company-in-house documentation (e.g. key figure reports)

[196] Cf. Yin, R. (2014), p. 106.

To conduct the interviews, a semi-structured questionnaire was developed and used in consultation with the project consortium, allowing a guided discussion instead of a query. Direct observations were made during company inspections. Documentations are all documents that are relevant to the measures under investigation, such as process manuals, value stream documents, or key figure reports. The internal and external validity of the case studies is ensured since the generated content has been checked, and all interview partners have been asked the same questions. The reliability of the information is ensured by the documentation of planning, implementation and evaluation.

Five areas were queried in the interview questionnaire:

(1) Company Information

(2) Digital transformation

(3) Resource efficiency

(4) Interactions

(5) Measures

The collection of data at the companies took place in the **“Collect”** step, taking into account the data source interviews, the direct observations and documentation.

The “**Analyse”** step analysed the data collected in the case studies, which were used to document the interview and other sources of information. A model for the formulation of the case studies was prepared to ensure a uniform reporting format.

In the **“Share”** step, the results (see case study portraits in Appendix 1 p. 213 et seqq.) were shared by the publication of case studies within the present study.

6 ANALYSIS OF CASE STUDIES

6.1 Identification of relevant industries

In principle, case studies are intended to cover companies in sectors that are highly relevant in terms of the economic and environmental criteria. The identification of such sectors was made for the manufacturing sector on the basis of the definition of economic [197]statistics. The detailed branch structure of the manufacturing industry (NACE Rev.2[198], sections C10 - C33) was summarised in Table 7 to a total of eleven sectors, which served as the basis for further considerations.

Table 7: Summary of economy sectors

Economy sector (WZ)	Industry
WZ08-10 Production of food and feed	Food industry
WZ08-11 Beverage production	
WZ08-13 Production of textiles	Textile industry
WZ08-14 Manufacture of clothing	
WZ08-15 Manufacture of leather, leather goods and shoes	
WZ08-17 Manufacture of paper, cardboard and articles thereof	Paper industry
WZ08-20 Production of chemical products	Chemical industry / process manufacturing
WZ08-21 Manufacture of pharmaceutical products	Pharmaceutical industry
WZ08-22 Manufacture of rubber and plastic products	Plastics industry
WZ08-23 Manufacture of glass, glassware, ceramics; processing of stone and earthworks	Glass industry
WZ08-26 Manufacture of computer equipment, electronic and optical products	Electrical industry
WZ08-27 Manufacture of electrical equipment	
WZ08-24 Metal production and processing	Machine manufacture
WZ08-25 Manufacture of metal products	
WZ08-28 Manufacture of machinery and equipment	
WZ08-29 Manufacture of motor vehicles and motor vehicle parts	
WZ08-30 Other vehicle construction	
WZ08-33 Repair and installation of machinery and equipment	
WZ08-31 Manufacture of furniture	Furniture industry
WZ08-32 Manufacture of other articles	Production of other goods

To classify the economic relevance (Table 8), the industry turnover, the number of employees and the number of enterprises were analysed in detail. Statistics from the Federal Statistical Office formed the basis for the economic-relevance analysis[199]. In terms of the criteria considered, the food, chemical,

[197] Cf. Federal Statistical Office (2008).
[198] Cf. EU (2008).
[199] Cf. Federal Statistical Office (2016c).

electrical and plastics industries, as well as machine manufacture, have proven to be the most relevant industries within the manufacturing sector.

In addition to the economic relevance of the sectors, an analysis was also carried out with regard to the ecological relevance (Table 8) and the significance for resource efficiency. In addition to the input material flows, such as the raw materials used, the energy input and the water input, the corresponding output material flows in the form of CO_2 equivalents, wastewater volumes and hazardous waste were also considered. Statistics from the Federal Statistical Office formed the basis for the ecological-relevance analysis[200, 201, 202, 203]. The chemical and machine manufacture industries were highly relevant here.

Table 8: Economic- and ecological-relevance of the industries

Industry	Economic-relevance	Ecological-relevance
Food industry	High	Medium
Textile industry	Medium	Low
Paper industry	Medium	Medium
Chemical industry	High	High
Pharmaceutical industry	Low	Medium
Plastics industry	High	Medium
Glass industry	Medium	Medium
Electrical industry	High	Medium
Machine manufacture	High	High
Furniture industry	Low	Low
Production of other goods	Low	Low

In the following, the industries (food, chemical, plastics, electrical and machine manufacture) classified in at least one of the two categories of high relevance are considered for their process characteristics and specifics for further investigation in the case studies.

- A low vertical integration, high cycle times and a wide range of parts are characteristic for the production in the **plastics industry**. For the case studies, the plastics industry is relevant, as it is characterised by high economic relevance, especially for SMEs.

[200] Cf. Federal Statistical Office (2016d).
[201] Cf. Federal Statistical Office (2015a).
[202] Cf. Federal Statistical Office (2015b).
[203] Cf. Federal Statistical Office (2015c).

- In the **electrical industry**, products are usually manufactured with a high degree of automation, short cycle times and a multi-stage manufacturing process. In addition, the electrical industry is characterised by a large number of raw materials required and the potential supply risks that may result, which is why it has been selected for in-depth investigations.

- The **machine manufacture** industry is characterised by a variety of manufacturing processes, complex production processes and a high degree of vertical integration with mostly small to medium quantities. This industry is included for the case studies because of these specific features and the high economic and environmental relevance.

- The food industry and the chemical industry are both largely process-oriented. The products are produced by batch production or continuous manufacturing. Due to the higher ecological relevance, the **chemical** industry was selected representatively for further investigation. However, during the study period, no suitable companies could be found to participate in the case studies.

6.2 Selection of companies

Ten case studies were carried out in central and southern Germany (Figure 10). The selection of the companies was the responsibility of the research partners, taking into account the identified relevant sectors and the proposals of involved ministries. The companies are based in the four federal states of Baden-Württemberg, Bavaria, Hesse and Rhineland Palatinate. The case studies cover the machine manufacture, plastics and electrical industries. The ten case studies from the three sectors cannot cover all areas of digitalisation in the industry. However, a high degree of transferability of results to other companies and other manufacturing processes is given (Table 5, p. 71) in many cases by the generalised description of the digital transformation measures.

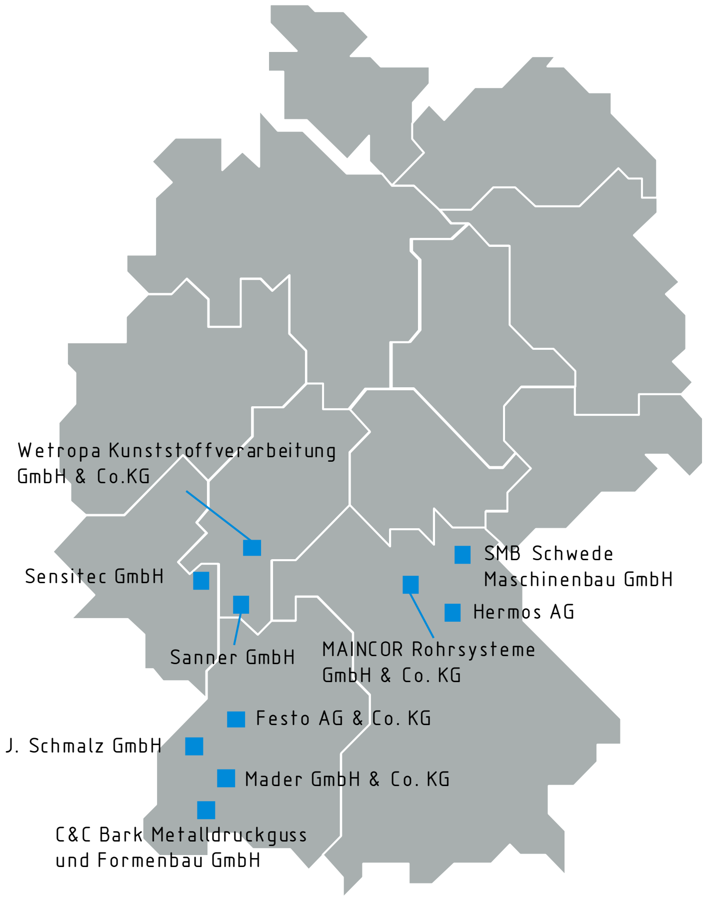

Figure 10: Overview of the geographical distribution of the case study partners

Table 9 gives an overview of the companies studied, their industry and a summary of the case study content. The detailed presentation of the case studies can be found in the form of case study portraits in Appendix 1 (p. 213 et seqq.).

Table 9: Case study overview

Company	Industry	Case study content
C&C Bark Metall-druckguss und For-menbau GmbH	Machine manufac-ture	The SME manufacturer of magnesium die-cast parts has introduced an Enterprise Resource Planning system (ERP system) across all production processes. This has reduced the material cycle, but also rejects and rework-ing. As a result, the use of magnesium could be made more efficient. (Appendix 1 A1, p. 213 et seqq.)
Mader GmbH & Co. KG	Machine manufac-ture	The SME expert in compressed air extended its product portfolio with the new compressed air leakage app for mobile devices. This provides a real-time overview of losses caused by energy and costs, thus providing cus-tomers with transparency about compressed air leaks. (Appendix 1 A2, p. 218 et seqq.)
J. Schmalz GmbH	Machine manufac-ture	The family-owned world market leader in the field of vacuum clamping technology has switched production to single-part production in some assembly areas. This has led, among other things, to a sustainable increase in material efficiency in the production of highly custom-ised products in small batch sizes. (Appendix 1 A3, S. 221 et seqq.)
MAINCOR Rohrsys-teme GmbH & Co. KG	Plastics industry	The manufacturer of pipe systems has optimised the in-house storage processes through an information man-agement system. (Appendix 1 A4, S. 229 et seqq.)
Sensitec GmbH	Electrical industry	The manufacturer of magnetoresistive sensors has im-plemented paperless production by expanding its work-piece carriers with digital data storage. (Appendix 1 A5, p. 232 et seqq.)
Hermos AG	Electrical industry	The SME automation technology manufacturer has digi-talised and optimised the planning and implementation of the added-value process by means of a business warehouse system that enables integrated data integra-tion. (Appendix 1 A6, p. 236 et seqq.)
Sanner GmbH	Plastics industry	The plastics SME Sanner has seen the potential of digi-talisation and has already implemented measures of vir-tual product development for the rapid development of prototypes. The company also relies on the use of cloud services to increase resilience and better communica-tion with overseas sites. (Appendix 1 A7, p. 239 et seqq.)
Festo AG & Co. KG	Machine manufac-ture	The family-owned company Festo has implemented or tested various digitalisation measures (e.g. Condition Monitoring). (Appendix 1 A8, p. 244 et seqq.)
SMB Schwede Mas-chinenbau GmbH	Machine manufac-ture	The strapping machine manufacturer has optimised product development, production and service with a dig-ital product twin. (Appendix 1 A9, p. 251 et seqq.)
Wetropa Kunst-stoffverarbeitung GmbH & Co. KG	Plastics industry	The plastics SME Wetropa has moved product develop-ment to the customer, creating customised products at low cost while conserving resources (e.g. material for prototypes). The prerequisite for this was the virtualisa-tion of product development in the company all the way to production. (Appendix 1 A10, p. 254 et seqq.)

6.3 Summary of the case studies

Overall, the case studies represented a crossing of mainly SMEs or locations of the sectors under consideration. All companies are concerned with the issue of sustainability, and the energy and environmental goals are partly anchored in the respective corporate policies. Specific analytical tools related to natural resources such as the CO_2 footprint are generally known, but are not implemented in the companies considered.

In the case studies, different levels were identified from Industry 4.0 Beginners to Industry 4.0 Experts in digital transformation. All companies use measures of digital transformation, but not primarily with the aim of increasing resource efficiency. In principle, measures are often implemented in connection with process automation. This extends from warehousing processes to documentation in the service area. Table 10 provides an overview of the use of digital transformation technologies. All case studies are not taken into account in all questions if the respective application is not relevant in the companies considered.

Table 10: Use of digital technologies in the case studies

Question	Number
Recording of machine and process data in production	9 out of 9
Benefits of digital systems in the value chain	10 out of 10
Use of digital technologies for process improvement	9 out of 9
Use of digital technologies at the level of machine and plant management	8 out of 8
Use of digital technologies at the level of employee support	8 out of 9
Use of digital technologies at the level of production management	5 out of 7

All surveyed companies record machine and process data in production and also use digital systems in the value chain. Likewise, all technologies of digital transformation are used for process improvement and at the level of machine and plant management.

The surveyed companies see great to very great potential for increasing the competitiveness of their own companies and their industry in the future in the course of digitalisation. The potentials range from the optimisation of processes and plants to the better integration of customers and suppliers.

The fact that the relationship between resource efficiency and digital transformation has often only been established by the case studies confirms the prevalent separation of the two within the enterprise organisation in some case studies. Nevertheless, the interactions between the two areas of action were perceived positively. The impact of digital transformation measures on the use of resources is often unknown or unmeasured in companies. This is due to the fact that consumptions of operational resources are usually not recorded specifically for processes, machines or plants.

7 RESOURCE EFFICIENCY POTENTIAL ANALYSIS

7.1 Procedure for the analysis of resource efficiency potentials

The methodology described in Chapter 5.1 forms the basis of the resource efficiency potential (REP) analysis. First, the digital transformation measures found in the case studies were identified on the basis of Table 5 (p. 71). It was shown that these measures are often used in combination with the goal of achieving a certain benefit in practice. For this reason, the measures were not examined separately but rather the combinations of digital transformation measures found in practice. This combination of measures, each of which serves a specific purpose – the “benefit” mentioned in Chapter 2.2 – is referred to as practical application in the following.

Steps of the REP determination

The determination of the REP through the digital transformation is described in the steps shown in Figure 11. For each practical application, a reference state, i.e. conventional production without the implementation of digital transformation measures, was presented with the same benefit. The reference state is abbreviated in the following to “before”, and the practical application to “after”. The existing dependencies between benefit and system framework are indicated by a double arrow.

The analysis explicitly identifies the effects of a practical application on tangible operational resources for a better understanding of the changes between “before” and “after” (e.g. reducing the error rate of a production line or avoiding transport costs).

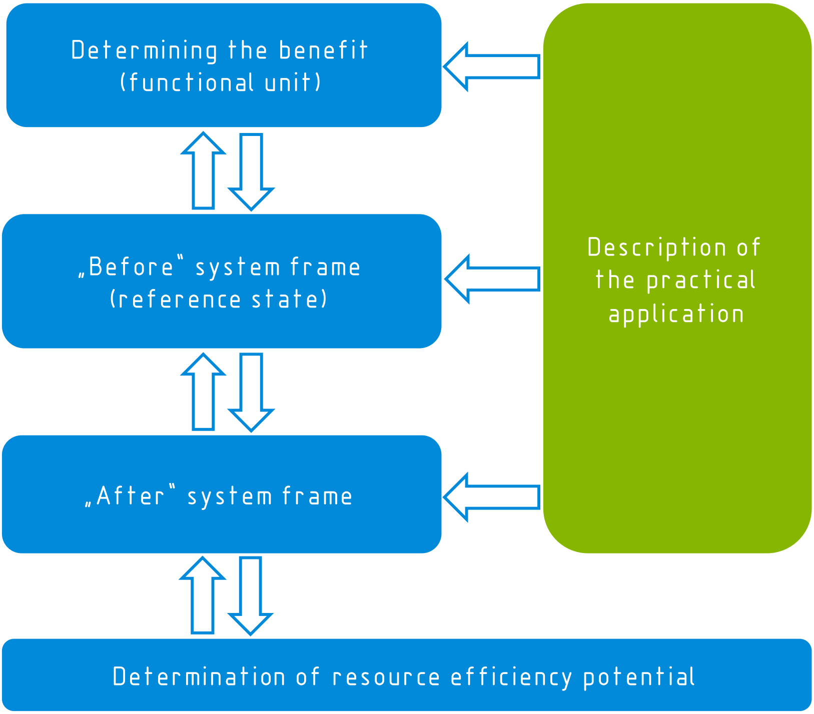

Figure 11: Methodology for REP determiniation of the digital transformation

For the REP determination, the relevant processes within the respective system framework ("before" or "after") must first be identified, then the tangible operational resource consumption of each individual process must be determined. The term "process" is used here in the sense of the process module of DIN EN ISO 14040, which represents the smallest component of a life cycle assessment for which input and output data must be quantified. These can be processes within the plant as well as processes of the upstream and downstream chains.

Consequently, conventional technological processes that require operational resources (e.g. electrical energy, operating and auxiliary materials, etc.) are relevant for the state "before", on the one hand, and their consumption can change as a result of digital transformation measures. On the other hand, other processes of conventional value chains, which influence the consumption of materials and energy (e.g. transport processes), have to be taken into account.

For the “after” state, the components and processes, which are newly added by the respective practical application, must be determined. These can be:

- **Hardware components**, whose material and energy must be used and whose operation requires energy or auxiliary materials and consumables,

- **software components**, whose application requires electrical energy and

- **other processes** (e.g. organisational processes, logistics) of new value chains inside and outside the company that consume material or require energy.

In addition, in the “after” state, the changed consumption, as well as the accumulated waste from processes of the previous state, must be determined for the digital transformation measure. If all the required data are available on the consumption of operational resources and the resulting waste or material and energy consumption of other processes, the consumption of natural resources can be determined by a life-cycle approach. The resource consumption, in terms of the benefit, reveals the resource efficiency of the “before” and “after” states. The difference is the REP of the examined practical application.

7.2 Individual presentation of the examined practical applications

In the following, the ten practical applications (PA) identified in the case studies are analysed for their savings and costs. An overview of the analysed practical applications can be found in Table 11.

Table 11: Overview of the practical applications studied

Overview of the practical applications studied		
ID	Name of the practical application	Company or case study
PA1	Optimised business processes	C & C Bark Metalldruckguss und Formenbau GmbH (related case study in Appendix 1 A1, p. 213 et seqq.)
PA2	Compressed air leakage app	Mader GmbH & Co. KG (related case study in Appendix 1 A2, p. 218 et seqq.)
PA3	One Piece Flow	J. Schmalz GmbH (related case study in Appendix 1 A3, p. 221 et seqq.)
PA4	Warehouse management system	MAINCOR Rohrsysteme GmbH und Co. KG (related case study in Appendix 1 A4, p. 229 et seqq.)
PA5	Data on a stick	Sensitec GmbH (related case study in Appendix 1 A5, p. 232 et seqq.)
PA6	Virtual product simulation	
PA7	Business warehouse system	Hermos AG (related case study in Appendix 1 A6, p. 236 et seqq.)
PA8	Virtual product manufacturing in prototype construction	Sanner GmbH (related case study in Appendix 1 A7, p. 239 et seqq.)
PA9	Cloud-based manufacturing	
PA10	FoamCreator	Wetropa Kunststoffverarbeitung GmbH & Co. KG (related case study in Appendix 1 A10, p. 254 et seqq.)

Each individual case is represented by a figure. The figures show the respective system framework after the introduction of practical applications as well as possible savings and costs due to additional components (green border) and discontinued processes (dashed border).

The information on savings and costs are estimates by the surveyed companies based on the interviews conducted. The following answer options were given: No savings, up to 25%, 25 to 50%, 50 to 75% and 75 to 100%. In addition, exact numerical values could be given if known.

7.2.1 PA1: Optimised business processes

In the case study of the company **C & C Bark Metalldruckguss und Formenbau GmbH** (Appendix 1 A1, p. 213), the ERP system implemented there is examined as a practical application (Table 12). The system enables better planning and execution of the company-specific production of magnesium die-cast parts.

Table 12: Characterisation of the practical application PA1

PA1: "Optimised business processes" (C&C Bark Metalldruckguss und Formenbau GmbH)	
Description of the practical application	From customer order entry in sales, production planning and control (PPS), and reservation of storage locations, to purchasing, data could be collected in all areas of the company and linked together by the incorporation of the Enterprise Resource Planning system (ERP system). The data can be called up at any time on workshop monitors, allowing conclusions to be drawn about the respective processes. In addition, information such as machine running times, machine downtime and reasons or rework rates could be evaluated. Prior to the integration of the ERP system, such networking did not exist. Internal processes were isolated from each other. Older machines were accordingly upgraded for the implementation of the practical application.
Introduced since	2015
Used measures	M6: Introduction and use of positioning and localisation systems M7: Condition monitoring M9: Comprehensive data integration
Vertical integration	- Data is collected from the field level to the ERP level in all areas of the company under consideration and linked together. - Positioning/traceability of individual products/batches provides security in the identification of faulty parts or recalls, among other things. - The actual production process for the production of magnesium die-cast parts is not changed by the ERP system.
Involved departments	Sales, Supply Chain Management, Procurement & Purchasing, Production, Logistics & Warehousing, Manufacturing & Assembly, Maintenance
Horizontal integration	- The exchange of digital data with customers and suppliers accelerates the production and communication process by avoiding media breaks and transmission errors, among other things. - The effects of the ERP system have a major impact on the corporate side.
Involved departments	Customers, suppliers

System framework before and after the introduction of the practical application

Before: The system frame of the "before" state covers the entire operational process for manufacturing the magnesium die-cast part. This begins with the goods receipt and includes the production processes "casting", "punching/casting off", "blasting/grinding", "manual deburring/polishing", "surface treatment", "CNC machining" and "pad printing/final inspection/shipping". This ends with the marketable product.[204]

After: The necessary hardware and software system elements from Table 13 are shown in Figure 12. As only intangible resources are affected for customers and suppliers, the effects outside the company are not taken into account.

[204] The aforementioned manufacturing process steps for the production of a magnesium die-cast part are summarised below under the collective term "process chain (internal)" for the sake of simplicity.

Functional unit (FU): A unit of the specific product is assumed as the FU for the “before-after” comparison [1 piece of magnesium die-cast part].

Table 13: Necessary system elements of PA1

Hardware		
Generic system elements	Concrete components	Relevant to the measure
Sensors	Pressure, temperature and optical sensors	M6, M7, M9
Server	Data server	M7, M9
Computer	Notebooks, workstations	M7
Software		
Generic system elements	Concrete components	Relevant to the measure
Software (function)	ERP [a] software	M6, M7, M9
Software (interfaces)	Impulse interfaces	M6, M7, M9

[a] ERP – Enterprise Resource Planning

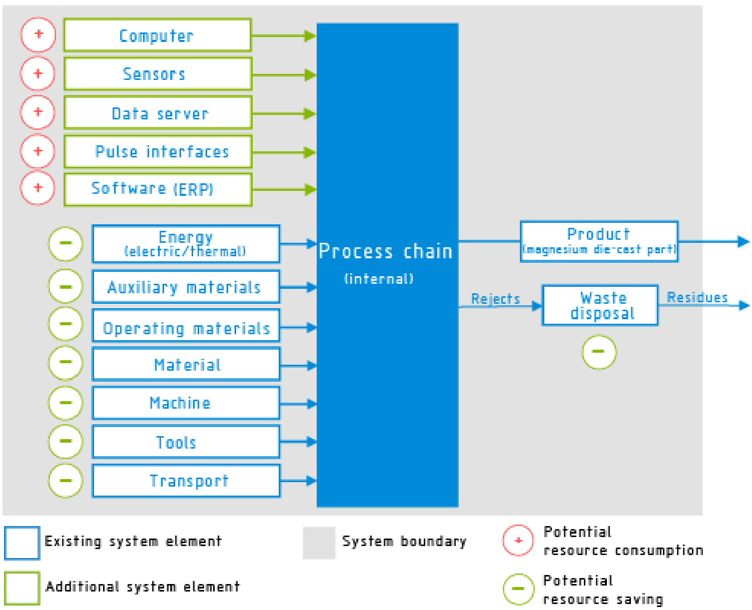

Figure 12: System frame of PA1 ("After") with savings and costs

Identification of savings and costs in tangible operational resources

Table 14 summarises the savings and costs as well as the available information bases.

Table 14: Savings and costs of PA1 [FU: 1 piece of magnesium die-cast part]

Savings in terms of FU				
Savings effects		Affected operational material resources	Savings per FU	Affected natural resources[c)]
Reduction of outstanding stock due to less overproduction	The product and process information (size of the batch, production status, location, etc.) can be accessed at any time to avoid overproduction. This leads to a reduction of the outstanding inventory.	Material (magnesium), machine/tools	up to 25%[a)]	Raw materials, energy resources, ecosystem services
Reduction of in-house transportation costs through localisation	The localisation of individual products or product batches makes it possible to reduce unnecessary transports between production steps.	Electricity, fuel	up to 25%[a)]	Energy resources, ecosystem services (emissions, especially CO_2)
Reduction of the error rate by locating defective parts	By tracking the products or product parts, defective (or not quality-compliant) parts can be located during production. They are removed directly from the production line and are no longer used for subsequent production steps.	Material (magnesium)	up to 25%[b) d)]	Raw materials, energy resources, ecosystem services
Costs related to the FU				
Hardware[d)]		Software[d)]		
Sensors, data servers, pulse interfaces		ERP[e)] software		

[a)] Questionnaire / case study interviews
[b)] Own estimation based on the case study analyses.
[c)] According to VDI 4800-1 (2016)
[d)] No information available on hardware quantities or power consumption of the software from the company.

[e)] ERP – Enterprise Resource Planning

7.2.2 PA2: Compressed air leakage app

From the case study of the company **Mader GmbH & Co. KG** (Appendix 1 A2, p. 218), the compressed air leakage app developed and used there is examined as a practical application (Table 15). In addition to other products and services for compressed air systems and pneumatic components, the company offers the application as an independent product for monitoring the entire compressed air process.

Table 15: Characterisation of the practical application PA2

PA2: "Compressed air leakage app" (Mader GmbH & Co. KG)	
Description of the practical application	The investigated company designs and implements complete compressed air systems. It also distributes products for a variety of applications. Within the service scope, leakages in the compressed air system were previously documented manually by an employee. An analysis of leakage points regarding losses as well as a comparison before and after repairs were not carried out. With the introduction of the compressed air leakage app, the compressed air losses at the customer's site can now be digitally recorded and analysed. For this, leakages, among other things, across the entire compressed air chain are detected using ultrasound measurement equipment and directly identified using QR codes at each site. Leakage-related data (size of the leakage, losses of energy and costs, repair recommendations, initial cost estimate) are transferred to a server at Mader and managed. The development and introduction of the compressed air leakage app was thus originally designed exclusively as an internal tool to support staff in making it easier to document compressed air leaks; upon customer request, it was further developed into an independent product. The customer has access to their own measurement data via a mobile device or computer. These are deposited on the company-owned server and can be accessed by the customer at any time.
Introduced since	2015 (in-house use of the compressed air leakage app) 2016 (compressed air leakage app for customers as a product)
Used measures	M1: Networking of sensors and actuators M2: Use of digital object memories M4: Measures for staff support and assistance M7: Condition monitoring M9: Comprehensive data integration
Vertical integration	- Data regarding compressed air leakages at the customer's site is recorded, stored and processed. Thus, the customised compressed air supply system can be monitored, maintained and optimised in real-time. - Data on customised measurements is made available through the compressed air leakage app.
Involved departments	Sales, Product Development, Process Planning & Development, Procurement & Purchasing, Logistics & Warehousing, Maintenance, IT & Cloud Services
Horizontal integration	- The compressed air leakage app is a customer-specific product solution. - Networking with the customer takes place via the company's internal IT system. Customer-specific data can be retrieved from the server in real-time via mobile devices / computers.
Involved departments	Customers, suppliers, service providers: Energy and Resource Enterprise Resource Planning (ERP) consulting

System framework before and after the introduction of the practical application

Before: The system frame of the "before" state includes the design and maintenance process of a compressed air system by Mader as well as the customer's compressed air supply process. The detection and recording of leaks in the compressed air system take place manually.

After: PA2 includes measures M1, M2, M4, M7 and M9. The hardware and software system elements required for the company itself and the customer from Table 16 are shown in Figure 13.

Functional unit (FU): The FU for the “before-after” comparison is assumed to be one unit of compressed air required to produce a custom product [1 standard cubic meter of compressed air produced].

Table 16: Necessary system elements of PA2

Hardware		
Generic System elements	Concrete components	Relevant to the measure
Sensors	Position, pressure/force, current/voltage, medium, temperature	M1, M4, M7, M9
Actuators	Pneumatic, non-continuous	M1, M4, M7
Server	Data server, application server	M2, M4, M7, M9
Mobile devices	Smartphone, tablet, data glasses with Bluetooth 4.0, WLAN[a],	M4, M7
Computer	Notebooks	M7
Software		
Generic system elements	Concrete components	Relevant to the measure
Communication technology	Bluetooth 4.0, (Industrial) WLAN[a], Internet protocol, GPRS[b], QR[c]	M2
Software (function)	Database, cloud storage, SQL[d] server, ERP[e] software	M2, M4, M7, M9
Software (interfaces)	XML[f] standard	M2, M4, M7, M9

[a] WLAN – Wireless Local Area Network
[b] GPRS – General Packet Radio Service
[c] QR – Quick Response
[d] SQL – Structured Query Language
[e] ERP – Enterprise Resource Planning
[f] XML – Extensible Markup Language

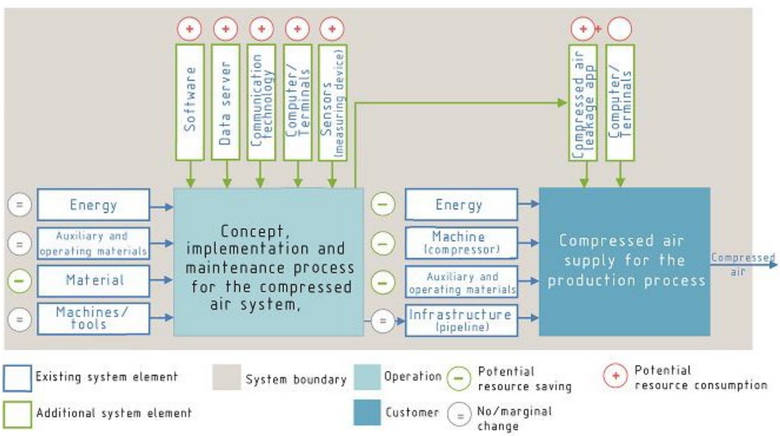

Figure 13: System frame of PA2 ("After") with savings and costs

Identification of savings and costs in tangible operational resources

Table 17 summarises the savings and costs as well as the available information bases.

Table 17: Savings and costs of PA2 [FU: 1 standard cubic meter of compressed air]

Savings in terms of FU				
Savings effects		Affected operational material resources	Savings per FU	Affected natural resources [b]
Reduction of energy requirements by optimisation of the compressed air system monitoring	Thanks to the optimised compressed air system monitoring, costs for the production of additional compressed air can be avoided. In this context, the required energy consumption decreases.	Electrical energy	up to 50 % [a]	Energy resources, ecosystem services
Reduction of material usage through paperless process management	The paperless documentation of compressed air leaks and the digital storage of customer-specific data in the in-house IT system minimise analogue documentation processes. In this context, the use of documentation material decreases.	Material (paper)	No information [a]	Raw materials
Costs related to the FU				
Hardware [c]		Software [c]		
Sensors, data servers, mobile devices, computers		Software, communication technology, compressed air leakage app		

[a] Questionnaire / case study interviews
[b] According to VDI 4800-1 (2016)
[c] No information available on hardware quantities or power consumption of the software from the company.

7.2.3 PA3: One Piece Flow

From the case study of the company **J. Schmalz GmbH** (Appendix 1 A3, S. 221), the one-piece production (one piece flow) implemented there for the production of individual surface grippers that are configurable by the customer are investigated as a practical application (Table 18). This PA includes the link to a smart replenishment logistics system (Kanban system).

Table 18: Characterisation of the practical application PA3

PA3: "One Piece Flow" (J. Schmalz GmbH)	
Description of the practical application	Surface grippers, among other things, are produced in the investigated company. One component of this surface gripper are foam parts, which are manufactured separately on cutting machines. In the past, the foam parts were conventionally standardised by means of a so-called milling pattern; they were produced in series according to customer requirements by an external service provider, and then stored until ordered by the customer. Due to excessively long storage times, the material properties of the foam parts deteriorated, so they could no longer be installed. After switching to "One Piece Flow", now mould images of foam parts are automatically transferred to the cutting machine after the customer places a custom order using CAD files; the cutting machine produces the required foam part overnight, which is then installed directly into the gripper. The grippers, manufactured in small batch sizes according to customer orders, are delivered immediately.
Introduced since	Successive implementation process from 2011 to 2014
Used measures	M1: Networking of sensors and actuators M7: Condition monitoring M9: Comprehensive data integration M10: Virtual product development
Vertical integration	- Reconstruction of the production line: From preferential series production to a flexible and custom production controlled by the order of the customer - Automated transmission of foam part mould images as CAD files to the cutting machine and subsequent production
Involved departments	Sales, Product Development, Process Planning / Development, Procurement & Purchasing, Production, IT & Cloud Services, Finance, Taxes, Legal, Subsidiaries Abroad
Horizontal integration	- Customer has direct access to custom production - Suppliers have access to the production-side Kanban system - Compatibility of ordering systems / product data between Schmalz, customers and suppliers
Involved departments	Customers (factory outfitter), suppliers

System framework before and after the introduction of the practical application

Before: The system frame of the status "before" includes the production in preferential series production of the gripping systems including the standardised (mass) production of the foam parts outsourced to an external service provider and storage until retrieval by the customer.

After: PA3 includes measures M1, M7, M9 and M10. The required hardware and software system elements from Table 19 are shown in Figure 14. The effects outside of operations (horizontal integration) are not taken into account, since only intangible resources are affected for the customers and suppliers.

Functional unit (FU): A unit of this specific product is assumed as the FU for the "before-after" comparison [1 unit of surface gripper].

Table 19: Necessary system elements of PA3

Hardware		
Generic system elements	Concrete components	Relevant to the measure
Sensors	Inertia, pressure/force, light, image cameras, temperature	M1, M7, M9 M10
Server	Application Server, OPC[a] server	M7, M9 M10
Computer	PLC[b] control, notebooks, embedded personal computer	M7, M10
Communication technology	Fieldbus systems, OPC-UA[c]	M7, M10
Software		
Generic system elements	Concrete components	Relevant to the measure
Software (function)	Simulation software, PDM/PLM[d]	M7, M9, M10
Software (interfaces)	XML[e] standard	M1, M7, M9, M10

[a] OPC – Object Linking and Embedding for Process Control
[b] PLC – Programmable logic controller
[c] OPC-UA – Object Linking and Embedding for Process Control – Unified Architecture
[d] PDM/PLM – Product Data Management/Product Life Cycle Management
[e] XML – Extensible Markup Language

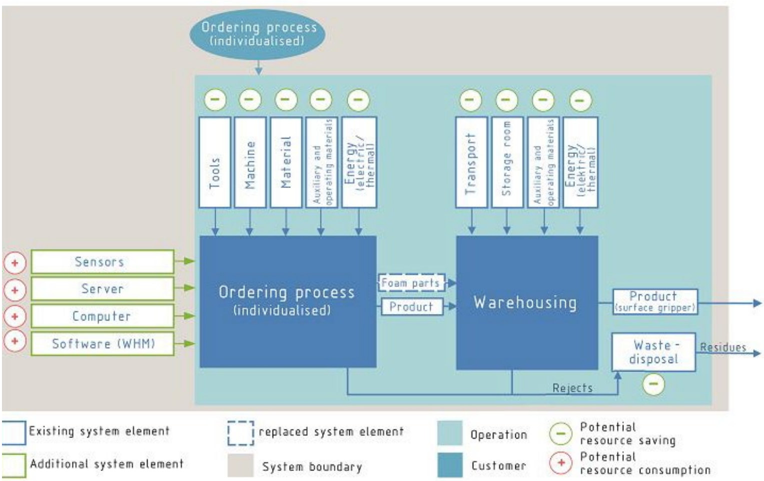

Figure 14: System frame of PA3 ("After") with savings and costs

Identification of savings and costs in tangible operational resources

Table 20 summarises the savings and costs as well as the available information bases.

Table 20: Savings and costs of PA3 [FU: 1 unit of surface gripper]

Savings in terms of FU				
Savings effects		Affected operational material resources	Savings per FU	Affected natural resources[c]
Avoidance of waste due to the prolonged storage of foam parts	Due to long storage times, the material properties of overproduced foam parts deteriorated, so they had to be disposed of as waste. The more flexible production line prevents overproduction and thus waste (foam).	Foam, wear machine / tools	up to 25%[a]	Raw materials, energy resources, ecosystem services
Reduction of transport costs	Previously, the foam parts were manufactured by an external service provider. Now production takes place directly at the assembly line. This reduces transport costs for the foam parts.	Electricity, fuel	up to 25%[a]	Energy resources, ecosystem services (emissions, especially CO_2)
Reduction of the error rate in production	The elimination of overproduction or the storage of foam parts reduces the likelihood that foam parts, which are stored too long or are no longer quality-compliant, are used in the production of the surface gripper. In this context, the error rate decreases.	Foam	50 to 75 %[a]	Raw materials, energy resources, ecosystem services
Savings of storage space through flexible production	By making production more flexible, inventories of foam parts were almost completely eliminated. The storage space can thus be used for other purposes or, if applicable, future expansion of the warehouse can be avoided.	-	Partial savings in construction costs for the warehouse[b), e)]	-
Costs related to the FU				
Hardware[d]		Software[d]		
Sensors, data servers, computers, communication technology		WHM software		

[a)] Questionnaire / case study interviews
[b)] Own estimation based on the case study analyses.
[c)] According to VDI 4800-1 (2016)
[d)] No information available on hardware quantities or power consumption of the software from the company.

[e)] Presumably low contribution; is therefore not included in the calculation.

7.2.4 PA4: Warehouse management system

From the case study of the company **MAINCOR Rohrsysteme GmbH & Co. KG** (Appendix 1 A4, p. 229), the Warehouse Management System (WMS) implemented there is analysed as a practical application (Table 21). This enables a controlled management and systematic control of the internal logistics processes.

Table 21: Characterisation of the practical application PA4

	PA4: "Warehouse management system" (MAINCOR Rohrsysteme GmbH & Co. KG)
Description of the practical application	MAINCOR manufactures pipe systems for a variety of applications. To optimise logistics processes, in particular storage and outsourcing processes, a Warehouse Management System (WMS) including optical object identification was implemented. The WMS represents a software-based management system for the organisation of warehouses. By marking the goods using product-specific barcodes, product information can be recorded in the WMS using manual operating devices, modified and retrieved from the system as needed. In addition to the functions of optimised warehouse management (quantity and storage location management, status of stored products, subsidy management and scheduling), it is also possible to check certain product statuses based on digital object memories.
Introduced since	2015
Used measures	M1: Networking of sensors and actuators M2: Use of digital object memories M4: Measures for staff support and assistance M6: Introduction and use of positioning and localisation systems
Vertical integration	- Optimisation of warehouse management is enabled. - The actual production process of the pipe systems is not changed by the WMS.
Involved departments	Sales, Production, Logistics & Warehousing, IT & Cloud Services
Horizontal integration	Customers have limited access to information about current storage capacities and stocks via the WMS.
Involved departments	IT service providers, customers

System framework before and after the introduction of the practical application

Before: In the system frame of the status "before", all operational processes for the storage of the pipe system parts ("chaotic" storage system) are recorded. The documentation of the warehouse logistics or specific product information is carried out in the same way.

After: PA4 includes measures M1, M2, M4 and M6. The required hardware and software system elements from Table 22 are shown in Figure 15. Although customers have access to areas of the in-house WMS, the material effects are exclusively on the corporate side[205].

Functional unit (FU): A unit of the produced product is assumed as the FU for the "before-after" comparison [1 piece of pipe system component].

[205] Effects outside the company are therefore not taken into account.

Table 22: Necessary system elements of PA4

Hardware		
Generic system elements	Concrete components	Relevant to the measure
Sensors	Inertia, current/voltage, medium, temperature	M1, M4, M6
Actuators	Electric, pneumatic, hydraulic	M1, M4
Server	Data server, application server	M2, M4
Mobile devices	Smartphones with Wi-Fi	M4, M6
Computer	PLC[a] control, workstations, notebooks	M2, M4, M6
Microcontroller	Pi	M1, M2, M4
Software		
Generic system elements	Concrete components	Relevant to the measure
Communication technology	(Industrial) WLAN[b], Internet protocol	M2
Software (function)	WMS[c] and simulation software, databases, SQL[d] server, CAE[e], PDM/PLM[f]	M2, M4, M6
Software (interfaces)	XML[g] standard, Data Dictionary, DPWS[h], WSDL[i]	M1, M2, M4, M6

[a] PLC – Programmable logic controller
[b] WLAN – Wireless Local Area Network
[c] WMS – Warehouse Management System
[d] SQL – Structured Query Language
[e] CAE – Computer-Aided Engineering
[f] PDM/PLM – Product Data Management/Product Life Cycle Management
[g] XML – Extensible Markup Language
[h] DPWS – Devices Profile for Web Services
[i] WSDL – Web Services Description Language

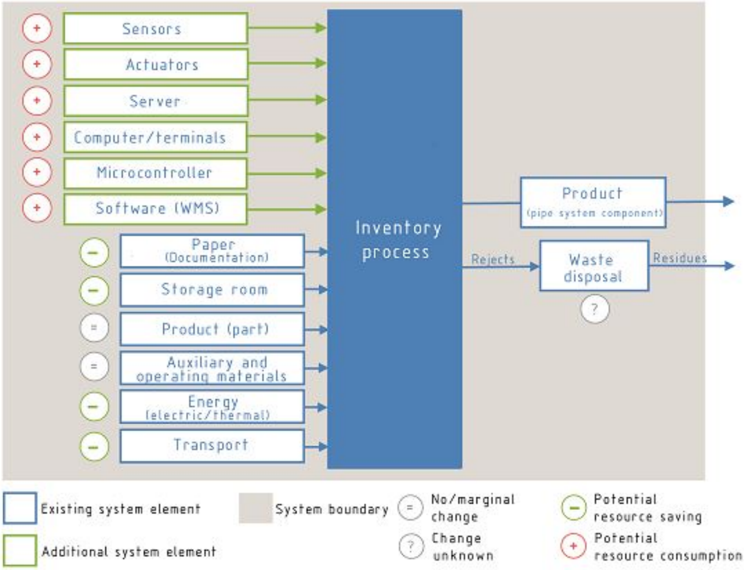

Figure 15: System frame of PA4 ("After") with savings and costs

Identification of savings and costs in tangible operational resources

Table 23 summarises the savings and costs as well as the available information bases.

Table 23: Savings and costs of PA4 [FU: 1 piece of pipe system component]

Savings in terms of FU				
Savings effects		Affected operational material resources	Savings per FU	Affected natural resources[c)]
Reduction of transport costs through digital object memory	After abolishing the chaotic storage system, products or product parts can now be located by tracking. In this context, unnecessary transport costs between the production line and the warehouse as well as the energy needed to find products or product parts are reduced.	Electricity, fuel	No information[a)]	Energy resources, ecosystem services (emissions, especially CO_2)
Savings of storage space through optimised warehouse management	Accelerated warehousing and retrieval processes as a result of the reduction of written documents, which increased the throughput of products in the warehouse. The required storage space can be reduced or optionally used for other purposes.	-	Partial savings in construction costs for the warehouse[b), e)]	-
Reduction of material usage by the digital storage system	The digital storage of product or (partially) process information in the WMS and the resulting paperless order processing minimise analogue documentation processes. In this process, the use of documentation (paper) decreases.	Paper, materials	No information[a)]	Raw materials
Costs related to the FU				
Hardware[d)]		Software[d)]		
Sensors, actuators, servers, end-devices/computers, microcontrollers		WMS[f)] software		

[a)] Questionnaire / case study interviews
[b)] Own estimation based on the case study analyses.
[c)] According to VDI 4800-1 (2016)
[d)] No information available on hardware quantities or power consumption of the software from the company.

[e)] Presumably low contribution; is therefore not included in the calculation.
[f)] WMS – Wireless Local Area Network

7.2.5 PA5: Data on a stick

From the case study of the company **Sensitec GmbH** (Appendix 1 A5, p. 232), the paperless production (data on a stick) for the production of wafers implemented there is investigated as a practical application (Table 24).

Table 24: Characterisation of the practical application PA5

PA5: "Data on a stick" (Sensitec GmbH)	
Description of the practical application	In the examined company, wafer, among other things, are produced via coating and structuring in a sterile production area. For the conversion to a paperless production, data carriers were integrated into the production process, which were used to document all production steps. These are included with each individual product; they receive all product-specific information and store it centrally in the company's own data management system (MES system). Prior to the integration of the practical application, data on the production or on the product were recorded in an analogue fashion on cleanroom paper. The background for the implementation was an increasing frequency of network failures through factory-related construction measures. This resulted in production stop every time. After the implementation of the practical application, production could be continued even in the event of network failure.
Introduced since	2011
Used measures	M1: Networking of sensors and actuators M2: Use of digital object memories M3: Decentralised control M6: Introduction and use of positioning and localisation systems M7: Condition monitoring M8: Predictive maintenance M9: Comprehensive data integration
Vertical integration	- Data is collected, stored and linked together from the field level in all areas of the company under consideration. - Real-time control of production processes is made possible. - The actual production process of the wafer is not changed.
Involved departments	Product Development, Process Planning & Development, Factory Planning, Supply Chain Management, Procurement & Purchasing, Production, Logistics & Warehousing, Manufacturing & Assembly, Maintenance, IT & Cloud Services
Horizontal integration	- The exchange of digital data with customers and suppliers accelerates the development and manufacturing process by avoiding media breaks and transmission errors. - The practical application effects mainly affect the company.
Involved departments	Customers, suppliers

System framework before and after the introduction of the practical application

Before: The system frame of the state "before" includes the production of wafers. These are routed through the production line on workpiece carriers, to which all product and process information are attached in paper form (including product data, work plan and production data).

After: PA5 includes measures M1, M2, M3, M6, M7, M8 and M9. The required hardware and software system elements from Table 25 are shown in

Figure 16. The previously required cleanroom paper is no longer required for the documentation. The effects outside of the company are not taken into account, since customers and suppliers do not have any operational material resources.

Functional unit (FU): A unit of the finished product is assumed as the FU for the “before-after” comparison [1 piece of wafer].

Table 25: Necessary system elements of PA5

Hardware		
Generic system elements	Concrete components	Relevant to the measure
Server	Data server, application server	M2, M7, M8, M9
Computer	Workstations	M7, M8
Communication technology	USB[a] sticks	M3, M6, M7, M8
Software		
Generic system elements	Concrete components	Relevant to the measure
Software (function)	Database, SQL[b] server	M2, M3, M6, M7, M8, M9
Software (interfaces)	Interfaces	M1, M2, M6, M7, M8, M9

[a] USB – Universal Serial Bus
[b] SQL – Structured Query Language

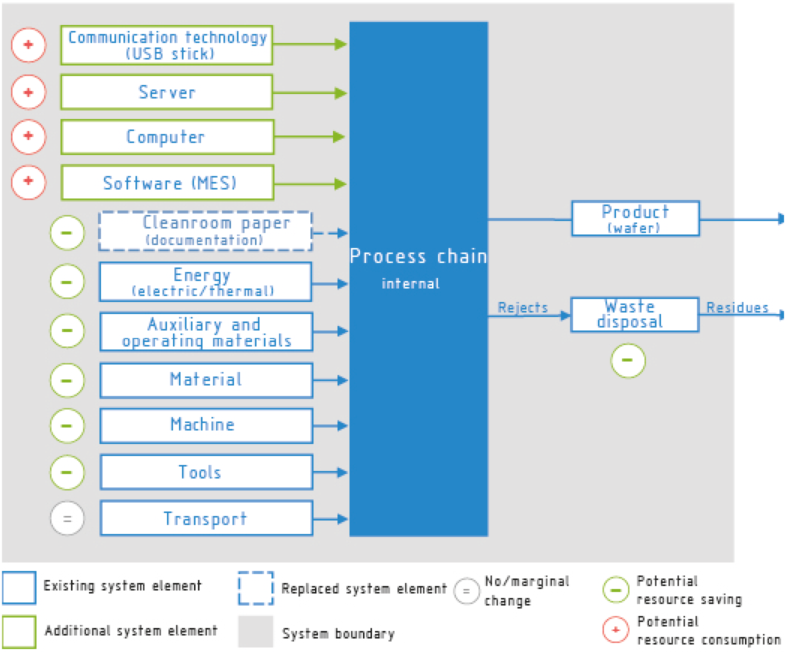

Figure 16: System frame of PA5 ("After") with savings and costs

Identification of savings and costs in tangible operational resources

Table 26 summarises the savings and costs as well as the available information bases.

Table 26: Savings and costs of PA5 [FU: 1 piece of wafer]

Savings in terms of FU				
Savings effects		Affected operational material resources	Savings per FU	Affected natural resources [b]
Avoidance of waste due to lower risk of contamination	The replacement of the cleanroom paper with data carriers reduces the risk of the entry of external substances into the sterile production area. In this context, the amount of scrap or waste decreases.	Material, wear machine / tools	up to 25%[a]	Raw materials, energy resources, ecosystem services
Reduction of the error rate by locating defective parts	By locating and sorting out defective wafer parts, these are not fed to any further processing steps. In this context, the error rate decreases.	Materials, wear machine / tools, operating and auxiliary materials	up to 25%[a] (photoresists: 5%; water: 10%)[a]	Raw materials, energy resources, ecosystem services
Saving of material by using the data carrier	Before the practical application was incorporated, all product- and process-relevant information on cleanroom paper with the workpiece was passed through the production line. The integration of data carriers saves 6,000 - 10,000 sheets of cleanroom paper per year.	Material (cleanroom paper)	up to 25%[a]	Raw materials, energy resources, ecosystem services
Reduction of energy requirements by means of real-time control	Previously, the production process had a relatively static character, and supply utilities were always operational. The real-time control of the production process and of supply facilities (targeted switching on and off) by using the MES system leads to a lower energy requirement.	Electrical energy	> 20%[a]	Energy resources, ecosystem services (emissions, especially CO_2)
Costs related to the FU				
Hardware[c]		Software[c]		
USB[d] sticks, servers, computers		MES[e] software		

[a] Questionnaire / case study interviews
[b] According to VDI 4800-1 (2016)
[c] No information available on hardware quantities or power consumption of the software from the company.

[d] USB – Universal Serial Bus
[e] MES – Manufacturing Execution System

7.2.6 PA6: Virtual product simulation

From the case study of the company **Sensitec GmbH** (Appendix 1 A5, p. 232), the virtual product simulation developed there for the development of product samples for magnetoresistive sensors is investigated as a practical application (Table 27). This practical application allows software tools to virtually simulate product samples before they are produced as a physical prototype.

Table 27: Characterisation of the practical application PA6

PA6: "Virtual product simulation" (Sensitec GmbH)	
Description of the practical application	Magnetoresistive sensors for path, angle, field and current measurement are produced, among other things, in the examined company. In the product development phase, the product samples required by the introduced practical application are first developed and simulated virtually before being manufactured for the first time. The virtual simulation of the sample is discussed with the customer in order to integrate possible changes in the digital model before the production of the first sample. For this, the production of a product sample is often sufficient. Before the implementation of the application, the production of the samples was necessary to present the product sample to the customer. When changes are required, the sample was adapted to the changes, manufactured and presented to the customer again. As a result, many prototypes often had to be manufactured.
Introduced since	2006
Used measures	M10: Virtual product development
Vertical integration	Product development requires a smaller number of manufactured product samples.
Involved departments	Sales, Product Development, Process Planning & Development, Factory Planning, Supply Chain Management, Production, Manufacturing & Assembly, IT & Cloud Services
Horizontal integration	The exchange of digital data with customers and suppliers is increased.
Involved departments	Customers, suppliers

System framework before and after the introduction of the practical application

Before: The system frame of the state "before" includes the production of magnetoresistive sensors. This includes the product development of the product samples as well as their production.

After: PA6 includes the measure M10. The required hardware and software system elements from Table 28 are shown in Figure 17. Virtual product development first involves a virtual simulation before producing a physical sample. The incorporation of PA6 does not affect the direct material cost (i.e., the materials contained in the product itself). The effects outside of the company are not taken into account, since customers and suppliers do not have any operational material resources.

Functional unit (FU): The magnetoresistive sensor as the product is assumed as the FU for the “before-after” comparison [1 unit of magnetoresistive sensor].

Table 28: Necessary system elements of PA6

Hardware		
Generic system elements	Concrete components	Relevant to the measure
–	–	–
Software		
Generic system elements	Concrete components	Relevant to the measure
Software (function)	Database, SQL[a] server, simulation software, CAE[b], PDM/PLM[c]	M10

[a] SQL – Structured Query Language
[b] CAE – Computer-Aided Engineering
[c] PDM/PLM – Product Data Management/Product Life Cycle Management

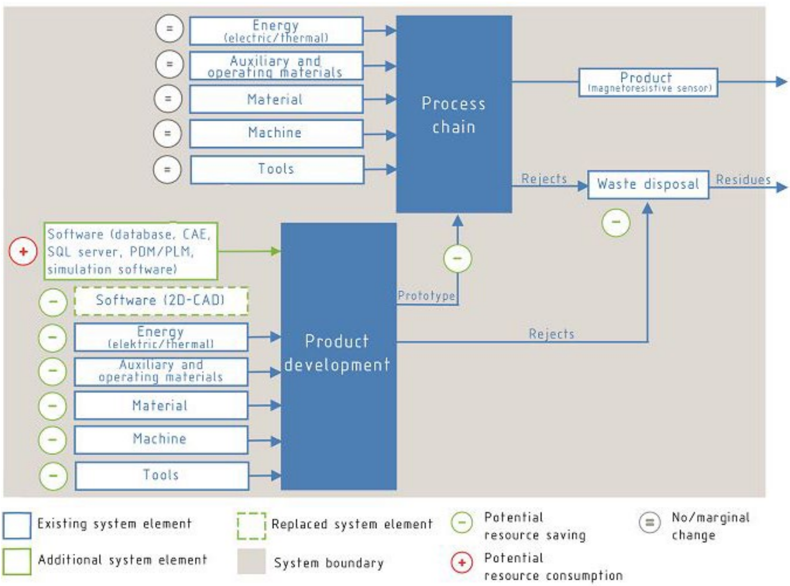

Figure 17: System frame of PA6 ("After") with savings and costs

Identification of savings and costs in tangible operational resources

Table 29 summarises the savings and costs as well as the available information bases.

Table 29: Savings and costs of PA6 [FU: 1 unit of magnetoresistive sensor]

Savings in terms of FU				
Savings effects		Affected operational material resources	Savings per FU	Affected natural resources [b]
Reduction of the error rate through digital data exchange	When exchanging data with customers and suppliers, transmission errors and media discontinuities can occur that could adversely affect product quality. The application reduces the error rate and thus also the potential rejects.	Materials, operating and auxiliary materials, machine wear	No information[a]	Raw materials, ecosystem services
Saving redundant prototypes	Previously, physical prototypes were needed to present the product to the customer. PA6 can reduce the number of samples based on the virtual simulation of prototypes. This saves supplies, auxiliary materials and consumables for the production of redundant samples. Since these redundant samples were disposed of, this practice immediately avoids waste.	Electrical energy, materials, operating and auxiliary materials, machine wear	up to 25%[a]	Energy resources, raw materials, ecosystem services
Costs related to the FU				
Hardware[c]		Software[c]		
–		Various software		

[a] Questionnaire / case study interviews
[b] According to VDI 4800-1 (2016)
[c] No information available on hardware quantities or power consumption of the software from the company.

7.2.7 PA7: Business warehouse system

From the case study of the company **Hermos AG** (Appendix 1 A6, p. 236), the business warehouse system (BWS) implemented there is investigated as a practical application (Table 30). This enables optimised planning and implementation of the company-specific production of building automation solutions through comprehensive data integration.

Table 30: Characterisation of the practical application PA7

PA7: "Business warehouse system" (Hermos AG)	
Description of the practical application	In the examined company, tailor-made building automation solutions are produced, among other things. After receiving a product order by the customer, the data is processed in the Business Warehouse System (BWS). The product- and process-spanning information stored in it (e.g. product parameters, product prices, suppliers and availabilities) enables both the circuit diagrams to be generated directly digitally and the product-specific software to be programmed directly in line with customer requirements. At the same time, the required components are ordered from the respective suppliers via the system. Based on the created circuit diagrams, the required cables, including insulation, cut and specific marking, regarding installation site, are manufactured automatically. The order processing with the subsidiary Hermos Schaltanlagen GmbH is documented completely electronically using the BWS until the product is delivered to the customer. Before the system was integrated, processes for the documentation and the order processing took place in an analogue fashion. Required components were ordered from the respective suppliers in larger quantities on stock. There was no automated production of specific product components.
Introduced since	the 90s (continuous development)
Used measures	M1: Networking of sensors and actuators M2: Use of digital object memories M3: Decentralised control M4: Measures for staff support and assistance M5: Dynamically cooperating systems and modularisation M6: Introduction and use of positioning and localisation systems M7: Condition monitoring M8: Predictive maintenance
Vertical integration	- Data is collected and linked in all areas of the company under consideration. - Digital networking enables paperless order and production processing.
Involved departments	Sales, Product Development, Purchasing & Procurement, Production, Service
Horizontal integration	- Direct networking with the subsidiary and with suppliers. - Automatic ordering of required components from suppliers via the BWS.
Involved departments	Customers, suppliers, subsidiaries (Hermos Schaltanalgen GmbH)

System framework before and after the introduction of the practical application

Before: The system frame of the state "before" includes the standardised production of a building automation solution as well as storage until retrieval by the customer.

After: PA7 includes the measures M1 to M8. The required hardware and software system elements from Table 31 are shown in Figure 18. The effects outside the Hermos AG entity and Hermos Schaltanlagen GmbH are not taken into account.

Functional unit (FU): A unit of the specific product is assumed as the FU for the "before-after" comparison [1 unit of building automation].

Table 31: Necessary system elements of PA7

Hardware		
Generic system elements	Concrete components	Relevant to the measure
Sensors	Position, movement, inertia, pressure/force, light, image cameras, magnet. Field, current/voltage, medium, temperature	M1, M4, M6 to M8
Actuators	Electric, pneumatic, hydraulic	M1, M4, M7, M8
Server	Data server, application and OPC[a] server	M2, M4, M7, M8
Mobile devices	Smartphone, tablet with Wi-Fi	M4, M6 to M8
Computer	PLC control, workstations, notebooks, embedded personal computers	M7, M8
Microcontroller	Tinkerforge, Pi, Aduino, ARIA, DigiConnect, .Net Gadgetete, MICA, Pic, Beagle board, in-house development	M1 to M8
Communication technology	Field bus systems, RFID[b]	M1 to M5, M7, M8
Software		
Generic system elements	Concrete components	Relevant to the measure
Communication technology	(Industrial) WLAN and Ethernet, Internet protocol, GPRS[c], UMTS[d], LTE[e], EnOcean	M2, M3, M5
Software (function)	Databases, cloud storage, simulation software, SQL[f] server, ERP[g], CAE[h], CAD[i], BDE[j], MDE[k], WMS[l], PPS[m]	M2 to M4, M6 to M8
Software (interfaces)	XML[n] standard, Data Dictionary, DPWS[o], WSDL[q]	M1, M2, M4, M6 to M8

[a] OPC – Object Linking and Embedding for Process Control
[b] RFID – Radio-Frequency Identification
[c] GPRS – General Packet Radio Service
[d] UMTS – Universal Mobile Telecommunications System
[e] LTE – Long Term Evolution
[f] SQL – Structured Query Language
[g] ERP – Enterprise Resource Planning
[h] CAE – Computer-Aided Engineering
[i] CAD – Computer-Aided Design
[j] BDE – Operational data acquisition
[k] MDE – Machine data acquisition
[l] WMS – Warehouse Management System
[m] PPS – Production planning and control
[n] XML – Extensible Markup Language
[o] DPWS – Devices Profile for Web Services
[q] WSDL – Web Services Description Language

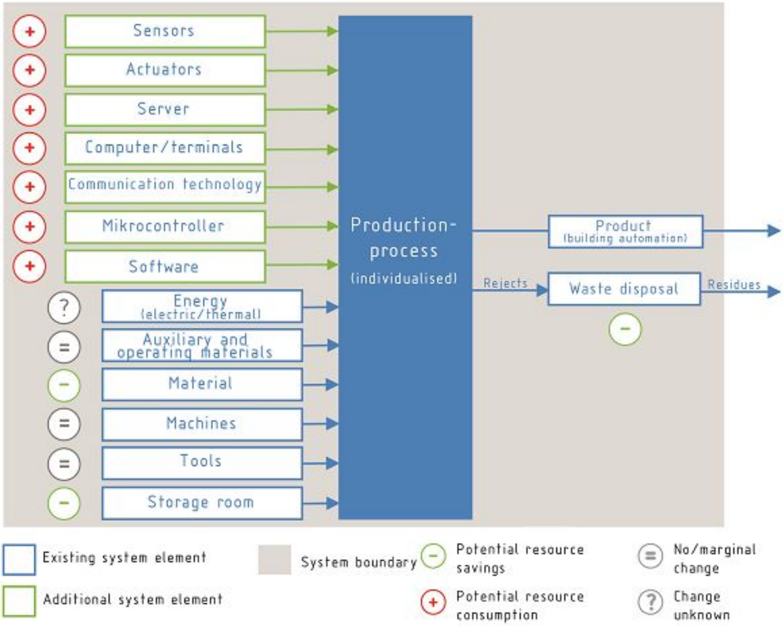

Figure 18: System frame of PA7 ("After") with savings and costs

Identification of savings and costs in tangible operational resources

Table 32 summarises the savings and costs as well as the available information bases.

Table 32: Savings and costs of PA7 [FU: 1 unit of building automation]

Savings in terms of FU				
Savings effects		Affected operational material resources	Savings per FU	Affected natural resources[c]
Savings of storage space due to needs-based component orders	By means of the continuous data integration and thus possible individual component orders per specific product, fewer materials have to be ordered in advance. This leads to a reduction of the storage space requirement for the components.	-	Partial savings in construction costs for the warehous[b), e)]	-
Reduction of material usage due to fewer wrong orders	In the past, suppliers ordered materials and components to be stocked in analogue fashion, resulting in frequent incorrect orders. Due to the customised production and the associated automatic ordering of components via the Business Warehouse System (BWS), fewer incorrect orders are made. In this context, the cost of materials decreases.	Materials	up to 25%[a)]	Raw materials, ecosystem services
Costs related to the FU				
Hardware[d)]		Software[d)]		
Sensors, actuators, servers, computers/end-devices, communication technology, microcontrollers		Communication technology, various software		

[a)] Questionnaire / case study interviews
[b)] Own estimation based on the case study analyses.
[c)] According to VDI 4800-1 (2016)
[d)] No information available on hardware quantities or power consumption of the software from the company.

[e)] Presumably low contribution; is therefore not included in the calculation.

7.2.8 PA8: Virtual product manufacturing in prototype construction

From the case study of the company **Sanner GmbH** (Appendix 1 A7, p. 239, the production by means of 3D printing implemented there for the production of plastic closure prototypes was investigated as a practical application (Table 33).

Table 33: Characterisation of the practical application PA8

PA8: "Virtual product manufacturing in prototype construction" (Sanner GmbH)	
Description of the practical application	Sanner manufactures plastic packaging and components for pharmaceutical, medical and healthcare products using the injection-moulding process. Before implementing the practical application, specific tools had to be produced for the individual prototypes. Every change to the prototype setup meant that a new master tool had to be developed and manufactured. The final approval by the customer took between six to twelve months. Thanks to the 3D printing technology, the prototypes can be printed directly using a digital model. The release cycles could be reduced so that they now last a few weeks to months. Thus, the injection-moulding process and the complex conventional sample tool manufacturing can be circumvented. Today, only prototype-specific sample tools are produced on customer request.
Introduced since	2014
Used measures	M9: Comprehensive data integration M10: Virtual product development
Vertical integration	- No sample tools are required for the production of a prototype. The tool for series production is created only after acceptance of the digital sample. - The number of tools produced in operation decreases.
Involved departments	Product development, tool technology
Horizontal integration	Since a large part of Sanner's sample tools are produced externally, the reduced number of tool orders has a direct influence on tool manufacturers.
Involved departments	Tool manufacturers

System framework before and after the introduction of the practical application

Before: Besides the CAD drawing, the necessary sample tools for the production process (e.g. injection-moulding tools) are also required for the production of a plastic prototype using the injection-moulding process.

After: PA8 includes measures M9 and M10. The required hardware and software system elements from Table 34 are shown in Figure 19. A 3D printer is used for the production of prototypes. This allows the virtual 3D drawings of the prototypes to be printed directly. Since sample tools are only required for complex functional components or necessary customer requirements, the sample tools are not considered in the further evaluation. Any changes to the prototype structure are made on the digital model.

Functional unit (FU): One unit of a plastic closure prototype is selected as the FU [1 piece of plastic closure].

Table 34: Necessary system elements of PA8

Hardware		
Generic system elements	Concrete components	Relevant to the measure
Printer	3D printer	M10
Software		
Generic system elements	Concrete components	Relevant to the measure
Software (function)	3D printer software	M9, M10

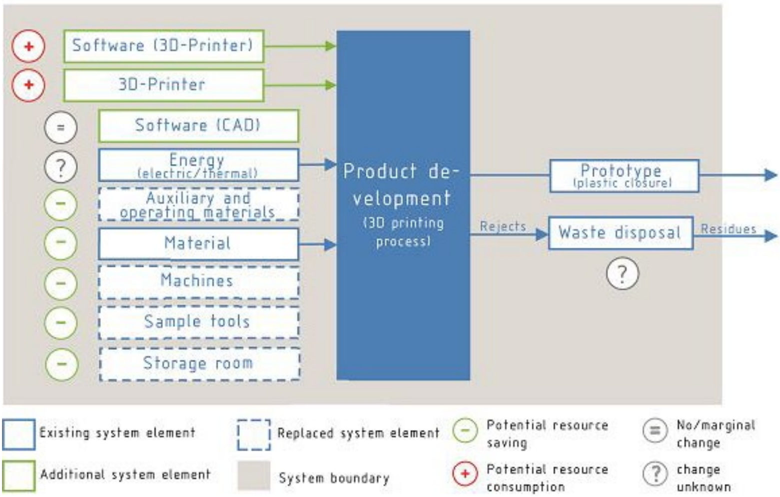

Figure 19: System frame of PA8 ("After") with savings and costs

Identification of savings and costs in tangible operational resources

Table 35 summarises the savings and costs as well as the available information bases.

Table 35: Savings and costs of PA8 [FU: 1 unit of plastic closure]

Savings in terms of FU				
Savings effects		Affected operational material resources	Savings per FU	Affected natural resources[c]
Savings of storage space for sample tools	The sample tools are stored in the factory after a single use. The reduction in the amount of sample tooling produced results in a reduction in the storage space required for these tools.	-	Partial savings in construction costs for the warehouse[b), e)]	-
Material savings through substitution of the conventional manufacturing process	With 3D printing, the process step of prototype production by injection-moulding can be substituted. As a result, not only the required sample tools are saved, but also auxiliary materials and consumables for the injection-moulding equipment.	Tools, materials, operating and auxiliary materials	Sample tools: > 50%[a)] 3D printing process: No information[a)]	Raw materials
Reduction of energy requirements for tool and prototype production	3D printing can save the energy required both for in-house tool production and prototype production via the injection-moulding process.	Electrical energy	No information[a)]	Energy resources
Costs related to the FU				
Hardware[d)]		Software[d)]		
1x 3D printer		3D-CAD[f)] software		

[a)] Questionnaire / case study interviews
[b)] Own estimation based on the case study analyses.
[c)] According to VDI 4800-1 (2016)
[d)] No information available on the power consumption of the software from the company.
[e)] Presumably low contribution; is therefore not included in the calculation.
[f)] CAD – Computer-Aided Design

7.2.9 PA9: Cloud-based manufacturing

From the case study of the company **Sanner GmbH** (Appendix 1 A7, p. 239), the cloud-based manufacturing implemented there is also investigated as a practical application (Table 36). The use of cloud-based services should increase system stability above all and the associated process stability.

Table 36: Characterisation of the practical application PA9

PA9: "Cloud-based manufacturing" (Sanner GmbH)	
Description of the practical application	The company uses the Manufacturing Execution System (MES) as well as the SAP system as a web service on the Internet. Through this practical application, the storage location of the internal company data from the in-house data server is outsourced to a data centre, which is operated by an external IT service provider. The data storage of the in-house MES and SAP system is also carried out by the external service provider in this context. Prior to the incorporation of the practical application, all operating data or software programmes were stored or executed on in-house data servers. For the implementation of the practical application, a second data cable was set up as an emergency line at the site.
Introduced since	2009
Used measures	M9: Comprehensive data integration M11: Cloud computing
Vertical integration	- No change of in-house processes. The application runs completely in the background - Thanks to the practical application, other company sites can now access the data server and thus the current process and operating information.
Involved departments	IT & cloud services
Horizontal integration	The data centre's external service provider handles the storage and provision of in-house data and software programmes.
Involved departments	External service provider of the data centre

System framework before and after the introduction of the practical application

Before: The system frame of the state "before" comprises the production of plastic closures, including the server capacity used for production (data storage, software usage, etc.).

After: PA9 includes measures M9 and M11. The required hardware and software system elements from Table 37 are shown in Figure 20. The considered effects outside of the company (horizontal integration) are only taken into account for the external service provider of the data centre. The "data centre" process module contains the data server required for this purpose as well as the IT infrastructure and the required amount of energy.

Functional unit (FU): A unit of the specific product (e.g. plastic closure) is assumed as the FU for the "before-after" comparison [1 piece of plastic closure].

Table 37: Necessary system elements of PA9

Hardware		
Generic system elements	Concrete components	Relevant to the measure
Server	Data server	M9, M11
Communication technology	Data line	M9, M11
Software		
Generic system elements	Concrete components	Relevant to the measure
Software (function)	Cloud storage	M9, M11
Software (interfaces)	VPN[a] connection	M9, M11

a) VPN – Virtual Private Network

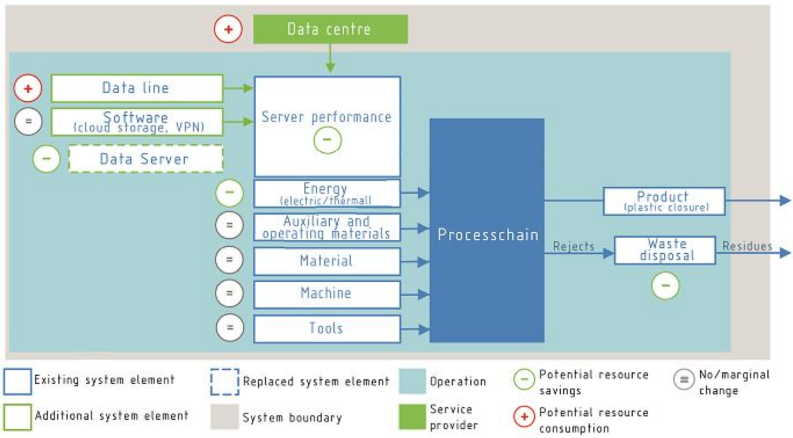

Figure 20: System frame of PA9 ("After") with savings and costs

Identification of savings and costs in tangible operational resources

Table 38 summarises the savings and costs as well as the available information bases.

Table 38: Savings and costs of PA9 [FU: 1 piece of plastic closure]

Savings in terms of FU				
Savings effects		Affected operational material resources	Savings per FU	Affected natural resources [b]
Waste prevention by reducing process losses	In case of problems at the in-house servers, the machines had to be shut down for several days due to the networking of the servers with the production machines, until the problem was solved. Such failures can cause the production line to generate more waste due to existing process instabilities. The outsourcing of the data server results in high reliability of server performance. This increases plant-specific process stability even in the case of unforeseeable events (e.g. power outages).	Material	No information[a]	Raw materials, ecosystem services
Reduction of material usage	Outsourcing the data servers eliminates the need for physical data servers on site. In addition, maintenance and operation of the servers on site are eliminated. The relocation to a data centre enables consolidation of the server capacities.	Material costs for the servers	No information[a]	Raw materials
Reduction of energy consumption	By relocating the server power to an external cloud, electrical power for server operation can be saved during operation. The energy consumption for the server operation was shifted to the external service provider as part of the outsourcing of server provision.	Electrical energy	No information[a]	Energy resources

Costs related to the FU	
Hardware[c]	Software[c]
Data centre	Cloud storage, VPN[d] connection

[a] Questionnaire / case study interviews
[b] According to VDI 4800-1 (2016)
[c] No information available on hardware quantities or power consumption of the software from the company.

[d] VPN – Virtual Private Network

7.2.10 PA10: FoamCreator

From the case study of the company **Wetropa Kunststoffverarbeitung GmbH & Co. KG** (Appendix 1 A10, p. 254 et seqq.), the virtual product development in the form of the so-called "FoamCreator" was investigated as a practical application (Table 39). This virtual product development system allows customers to customise and order foam inserts with a current focus on simple tools.

Table 39: Characterisation of the practical application PA10

PA10: "FoamCreator" (Wetropa Kunststoffverarbeitung GmbH & Co)	
Description of the practical application	Using the FoamCreator developed by the company, the conventional development of foam inserts has been changed to customer-specific virtual product development. The FoamCreator can be used as a web-based programme on a computer or as an application on a smartphone or tablet. In the course of product development of the custom foam insert, the customer can use moulds from a stored database for his insert. He can arrange these individually, or the customer can photograph the object for which an insert is to be made. The "ToolScan" app, also developed for Wetropa, is available for this purpose. With the help of the app, the customer can load the image of his tool into the FoamCreator. After the customer specifies a single dimension of the object and selects specific product configurations (e.g., type and colour of the foam), a simple, digital model of the foam insert is automatically created by the programme. If the customer agrees with the virtual prototype, he confirms this by ordering the foam insert. Subsequently, the offer (including the delivery date) is transmitted to the customer. After acceptance, the order is transferred directly to the company, and the order is integrated into the production planning. Prior to using the FoamCreator and the ToolScan, the customer objects had to be scanned on site and modelled in a CAD programme. The foam insert prototypes were only released for production after coordination and adjustment rounds with the designer and customer.
Introduced since	Study since 2015
Used measures	M1: Networking of sensors and actuators M2: Use of digital object memories M9: Comprehensive data integration M10: Virtual product development
Vertical integration	- After receiving the customer's order, the order is transferred directly into digital production planning through comprehensive data integration. - The actual production process for the production of a foam insert is not changed by the FoamCreator.
Involved departments	Sales, Product Development, Process Planning & Development, Supply Chain Management, Procurement & Purchasing, Production, Logistics & Warehousing, Manufacturing & Assembly, IT & Cloud Services
Horizontal integration	- The digitalised custom design and ordering by the customer accelerate the communication and production chain. - The effects on material resources by the FoamCreator are largely on the company side.
Involved departments	Customer

System framework before and after the introduction of the practical application

Before: The system frame of the “before” state covers the entire external and internal process for the development of the foam insert. As an iterative process, this includes the measurement and recording rounds for the object at the customer’s site, the CAD modelling of the object and the foam insert by the designer, the creation of a prototype, the final acceptance by the customer and the commissioning for production in the company.

After: PA10 includes measures M1, M2, M9 and M10. The required hardware and software system elements from Table 40 are shown in Figure 21. Product development is now carried out virtually by the customer using the FoamCreator. The digitalised development process eliminates the need for physical prototyping and the costs associated with traditional product development, such as transportation between customers and businesses.

Functional unit (FU): A unit of the specific product is assumed as the FU for the “before-after” comparison [1 piece of foam insert]. The absolute amount of foam needed for the insert (final product) is not changed by the application.

Table 40: Necessary system elements of PA10

Hardware		
Generic system elements	Concrete components	Relevant to the measure
Sensors	Camera (customer)	M2, M9, M10
Server	Data server	M9, M10
Mobile device	Smartphone, tablet (customer) each with Wi-Fi [a)]	M1, M2, M10
Computer	Notebooks, workstations, internet-enabled computers	M1, M2, M10
Communication technology	Broadband internet access	M10
Software		
Generic system elements	Concrete components	Relevant to the measure
Communication technology	Internet, WLAN[a)]	M9, M10
Software (function)	ERP[b)]/WMS[c)] and MES[d)] software, CAD[e)]/CAM[f)] software, FoamCreator and ToolScan app	M9, M10
Software (interfaces)	Interface between FoamCreator and production technology	M9, M10

[a)] WLAN – Wireless Local Area Network
[b)] ERP – Enterprise Resource Planning
[c)] WMS – Warehouse Management System
[d)] MES – Manufacturing Execution System
[e)] CAD – Computer-Aided Design
[f)] CAM – Computer-Aided Manufacturing

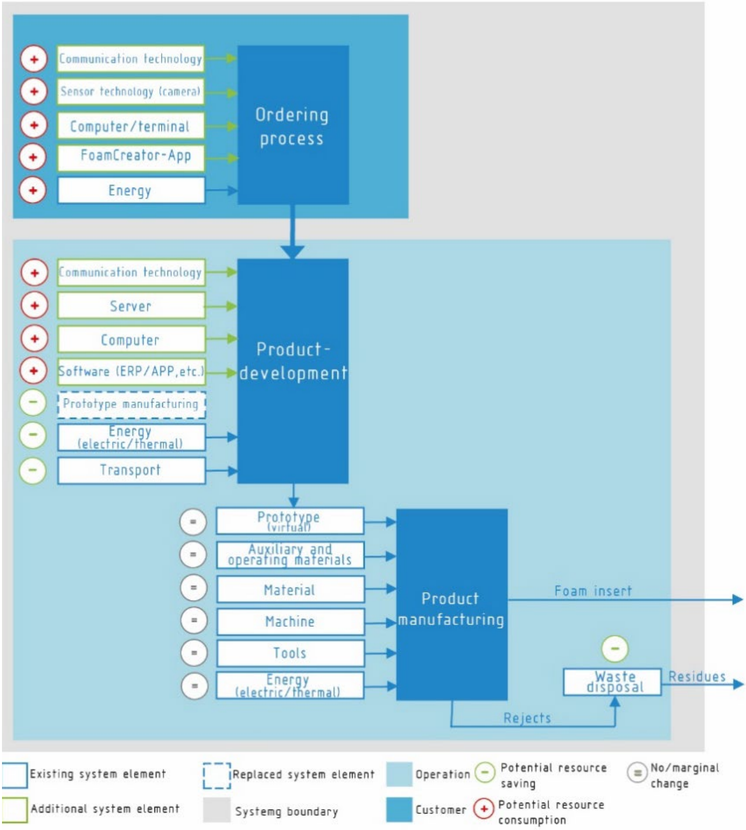

Figure 21: System frame of PA10 ("After") with savings and costs

Identification of savings and costs in tangible operational resources

Table 41 summarises the savings and costs as well as the available information bases.

Table 41: Savings and costs of PA10 [FU: 1 piece of form insert]

Savings in terms of FU				
Savings effects		Affected operational material resources	Savings per FU	Affected natural resources[b]
Elimination of prototypes	With the customer's virtual and custom configuration of foam inserts, physical prototypes no longer need to be developed and manufactured. There are no related expenses.	Material (foam), electr. energy, wear machine / tools	25%[a]	Raw materials, energy resources, ecosystem services
Reduction of transport costs	The digital development process can reduce additional prototype and transportation costs between business and customers.	Electricity, fuel	33%[a]	Energy resources, ecosystem services (emissions, especially CO_2)
Costs related to the FU				
Hardware[c]		Software[c]		
Camera, broadband Internet connection, data server, smartphone/tablet, notebooks/workstations (exact quantities not known)[d]		ERP[d]/WMS[e] and MES[f] software, CAD[g]/CAM[h] software, FoamCreator and ToolScan app, Internet, WLAN[i]		

[a] Questionnaire / case study interviews
[b] According to VDI 4800-1 (2016)
[c] No information available on hardware quantities or power consumption of the software from the company.

[d] ERP – Enterprise Resource Planning
[e] WMS – Warehouse Management System
[f] MES – Manufacturing Execution System
[g] CAD – Computer-Aided Design
[h] CAM – Computer-Aided Manufacturing
[i] WLAN – Wireless Local Area Network

7.3 Summary evaluation of practical applications

The savings effects derived from the practical applications of the study are listed in Table 42. Six effects were identified: Prevention of **wastes** (E1), **energy** savings in the form of electricity (E2), reduction of **failure rate** and the associated rejection (E3), **storage space** savings (E4), reduction of **material use** (E5) and (in-house) **transports** savings (E6). Table 42 lists the resulting effects on operational and natural resources for every savings effect. The last column (Factor / Life Cycle Assessment Data Set) indicates the basic data from which factors can be derived that allow the calculation of natural resources from the consumption of operational material resources.

Table 42: Savings effects as a result of the digital transformation

Savings effects	Operational material resources	Natural resources	Factor / Life Cycle Assessment Data Set
E1: Waste	Material, wear machine / tools	Raw materials, energy resources, ecosystem services	Life Cycle Assessment Data Sets
E2: Energy	Electrical energy	Energy resources, raw materials, ecosystem services	Specific CO_2 emissions of different energy sources; CO_2 and primary energy factors for the German electricity mix
E3: Error rate	Material, wear machine / tools, operating and auxiliary materials	Raw materials, energy resources, ecosystem services	Life Cycle Assessment Data Sets
E4: Storage space	Area usage, operating materials, energy	Area/floor, raw materials, energy resources, ecosystem services	-
E5: Material	Material, wear machine / tools	Raw materials, energy resources, ecosystem services	Life Cycle Assessment Data Sets
E6: Transport	Electrical energy, fuel	Energy resources, ecosystem services (emissions, especially CO_2)	Specific CO_2 emissions of different energy sources; CO_2 and primary energy factors for the German electricity mix

The following individual representations of the practical applications are summarised according to operational savings (Table 43) and operating expenses (Table 44).

Table 43: Operational savings per practical application

Savings effects	Practical applications									
	PA 1	PA 2	PA 3	PA 4	PA 5	PA 6	PA 7	PA 8	PA 9	PA 10
	Optimised business processes	Compressed air leakage app	One Piece Flow	Warehouse management system	Data on a stick	Virtual product simulation	Business warehouse system	Virtual product manufacturing in prototype construction	Cloud-based manufacturing	FoamCreator
Operational savings										
E1: Waste	up to 25%	n. r.	up to 25%	n. r.	up to 25%	n. r.	n. r.	n. r.	not specified	n. r.
E2: Error rate	up to 25%	n. r.	50 - 75%	n. r.	up to 25%	not specified	n. r.	n. r.	n. r.	n. r.
E3: Storage space	n. r.	n. r.	not specified	not specified	n. r.	n. r.	not specified	not specified	n. r.	n. r.
E4: Material	n. r.	not specified	n. r.	not specified	up to 25%	up to 25%	up to 25%	> 50 %[a] not specified[b]	not specified	25%
E5: Electricity	n. r.	up to 50 %	n. r.	n. r.	> 20%	up to 25%	up to 25%	not specified	not specified	n. r.
E6: Transport	up to 25%	n. r.	up to 25%	not specified	n. r.	n. r.	n. r.	n. r.	n. r.	33%
Influence on natural resources										
Raw materials	x	x	x	x	x	x	x	x	x	x
Energy resources	x	x	x	x	x	x	n. r.	x	x	x
Ecosystem services	x	x	x	x	x	x	x	n. r.	x	x
Surface	n. r.	n. r.	x	x	n. r.	n. r.	x	n. r.	n. r.	n. r.

[a] Savings due to the reduced number of sample tools produced
[b] Savings through 3D printing process
not specified: There is no quantitative information on the respective savings effect.
n. r.: The measure is not relevant to the respective savings effect or natural resources.

As described at the beginning of chapter 7.2, the potential savings from Table 43 represent estimates of the surveyed companies resulting from the interviews. These relate to the respectively influenced or primarily perceived effect or objectives of the respective practical application. For example, material savings and avoidance of waste are listed as separate effects, although these are related from a material flow perspective: The material savings (e.g. by the elimination of the production of prototypes) also leads to the reduction of waste and vice versa. Likewise, the effect of reducing the fault rate lies in both material savings and waste savings. Energy savings in production (e.g. electricity) and transport savings were also included. Both ultimately lead to final energy savings in the form of electricity or fuel. The effect of storage space savings was also listed several times. Here, however, it is difficult to assign the consumption of operational material resources, since this is only indirectly conceivable, for example, by avoiding future construction expansion measures.

In general, Table 43 shows that the basic data for quantifying savings is still unsatisfactory. As already described in Chapter 6, the motivation for saving resources in the digitalisation process was not the main focus of the investigated companies. Nevertheless, the companies said that the practical applications described resulted in savings. A self-assessment in terms of the given categories of areas of percentage savings was given in the questionnaires for six of the nine practical applications. Additional information describing the savings was often not available to the contact persons in the practical examples. This applies, for example, to the area of transports, where there was generally no information on transport distances or means of transport. Also in the case of material savings, there was often a lack of more detailed information on the material used – or the information was not allowed to be published.

Table 44: Operating expenses per practical application

Generic system elements		Practical applications									
		PA 1	PA 2	PA 3	PA 4	PA 5	PA 6	PA 7	PA 8	PA 9	PA 10
		Optimised business processes	Compressed air leakage app	One Piece Flow	Warehouse management system	Data on a stick	Virtual product simulation	Business warehouse system	Virtual product manu-facturing in prototype	Cloud-based manufacturing	FoamCreator
Hardware	Sensors	x	x	x	x	n. r.	n. r.	x	n. r.	n. r.	x
Hardware	Actuators	n. r.	x	n. r.	x	n. r.	n. r.	x	n. r.	n. r.	n. r.
Hardware	Server	x	x	x	x	x	n. r.	x	n. r.	x	x
Hardware	Computer	x	x	x	x	x	n. r.	x	n. r.	n. r.	x
Hardware	Mobile devices	n. r.	x	x	x	n. r.	n. r.	x	n. r.	n. r.	x
Hardware	3D printer	n. r.	n. r.	n. r.	n. r.	n. r.	n. r.	n. r.	x[a]	n. r.	n. r.
Hardware	Microcontrol-ler	n. r.	n. r.	n. r.	x	n. r.	n. r.	x	n. r.	n. r.	n. r.
Hardware	Communication technology	n. r.	n. r.	x	n. r.	x	n. r.	x	n. r.	x	x
Software	Communication technology	n. r.	x	n. r.	x	n. r.	n. r.	x	n. r.	n. r.	x
Software	Software (function)	x	x	x	x	x	x	x	x	x	x
Software	Software (in-terface)	x	x	x	x	x	n. r.	x	n. r.	x	X

[a] Amount used: 1x 3D printer
n. r.: The generic system element is not relevant for the respective practical application.

Table 44 shows the overview of the costs mentioned in the practical applications in the form of hardware and software (described here as generic system elements). Only qualitative and predominantly general information was available, with one exception (PA8: Purchase of a 3D printer cf. p. 112); for example, only a few details were given on the nature of the sensors used.

The company-external effects of the practical applications were cited by the companies only for direct suppliers and customers and are presented in a descriptive manner without the estimation of quantities. These effects, in terms of the individual practical applications, included:

- Simplified data exchange (PA1, PA5, PA6)

- Networking with customers (PA2, PA10)
- Custom production according to customer requirements (PA3, PA10)
- Data access for customers on WMS (PA4)
- Networking with subsidiaries and suppliers (PA7)
- Immediate influence on tool manufacturers due to reduced number of tool orders (PA8)
- Provision of in-house data and software programmes by service providers (PA9)

7.4 Estimation of resource efficiency potentials

7.4.1 Procedure

The above representations show that the basic data for the quantitative REP determination by comparing savings and costs for the specifically examined practical applications are partly not given at present. This has two main reasons:

- Savings were estimated as a percentage. The required reference values for the calculation of absolute numbers, which allow a comparison of the respective applications, were not familiar to the companies. For example, information on the annual electricity consumption of individual machines / production lines or on annual transport distances were not available.
- In terms of costs, the companies had little information on the number and type of hardware components used (except in simple cases such as a laptop or smartphone). For example, no information could be provided on the type and quantity of sensors used/installed for a specific practical application. Manufacturing companies usually do not have such information. The contact persons for these purposes are mostly IT experts of the respective specialist companies / IT suppliers.

Nevertheless, in order to be able to derive statements on REP, the following procedure was chosen: The percentage figures obtained in the case studies were linked to the absolute consumption data from, e.g., statistics[206] or from the life cycle assessment database Ecoinvent.

Due to a lack of factual assignments and statistical data, “comparable” practical applications could not be determined in most cases. In two cases, initial estimates of the REP could be calculated on the basis of practical applications.

The information on hardware costs is based on own assumptions or has been estimated based on literature. Energy indicators were used in order to make savings and expenditures comparable (final energy and the CO_2 emissions resulted from the German electricity mix). The necessary factors which may be used to calculate such information from operational material resources, were taken out of LCA databases or the publications mentioned in Chapter 5.2 (p. 58 et seqq.).

The first statements for two practical applications regarding the ratio of savings to costs could be derived in this way. It is important to point out the large uncertainties, because it was necessary to work with assumptions and approximations on several levels:

- At the operational level, only the margins of the percentage savings based on estimates from the companies surveyed could be used.
- Missing information was replaced by assumptions with regard to the statistics.
- LCA datasets were often only available for generic components. In the literature, for example, there is only one record to a specific sensor. This was generally used to map the resource consumption of sensors, knowing that there are a large number of very different sensors.
- The determination of natural resources was limited to the core size of the energy expenditure (final energy electricity) of the production and utilisation, since all further environmental effects would have required a more in-depth investigation and are not reproducible with the described basic

[206] Cf. UBA (2017).

data. The conversion into CO_2 emissions was carried out with the German electricity mix.

7.4.2 Extrapolations for Germany

7.4.2.1 Practical application "Compressed air leakage app" (Mader GmbH & Co. KG)

Findings from the case study analysis

While in some companies compressed air leaks can still be detected by listening to the distribution system (listening for hissing noises in production-free periods) or other manual leak testing procedures, appropriate measuring equipment is used at other production sites for this process.[207] The company Mader GmbH & Co. KG currently offers on-site compressed air leakage tests with ultrasonic measuring devices as a service to the customer. A special feature is the digital documentation of the test procedure and the evaluation of the measured data using the compressed air leakage app developed by Mader (Figure 22).

Figure 22: Monitoring of pressure and temperature by means of a sensor (left) and the compressed air leakage app for mobile devices (right) (Source: Mader GmbH & Co. KG)

[207] Cf. IHK Nürnberg für Mittelfranken (2012).

The data are evaluated in real-time on the basis of economic and environmental criteria (costs or savings in kWh, CO_2 emissions and euros) and prioritised according to their resolution urgency. In the future, the company plans to fully test and control the compressed air system at the customer's site using sensors that are integrated directly into the pipeline. Subsequently, the data measured by the sensors will be forwarded directly to the application and processed, as mentioned above. The compressed air leakage app of Mader GmbH & Co. KG in conjunction with the integration of sensors in the distribution network thus enable optimised compressed air system monitoring and prompt detection of leaks. Leaks are understood here to be only avoidable leaks within the pressurised air or distribution network, not system-related losses at the actuator. According to Mader's experience, customers can save up to 35% of their compressed air. This corresponds to a reduction of the electricity requirement for compressed air production by as much as 35%.[208]

General relevance of the practical application of the case study

The compressed air leakage app (including the integration of sensors) or comparable digital applications of other companies can generally be used by all compressed air users regardless of the industry sector. In Germany alone, 17.29 TWh of final energy (electricity) were spent on industrial compressed air production in recent years (2005 - 2014).[209] Compressed air is considered inefficient compared to other forms of energy, as only 4 to 7% system efficiencies can be achieved due to the high conversion losses from electrical to mechanical energy (unless waste heat is integrated into the compressed air generation process). It is precisely this that makes the economical and efficient use of the medium necessary from a resource perspective[210] as well as regular leakage tests on the distribution network. The combination of a compressed air leakage app and integrated sensors enables simple and continuous monitoring of the compressed air distribution network so that the loss of compressed air can be largely avoided if leaks are detected promptly. This also leads to significant cost savings for the operation. The following REP

[208] Information extracted from interview/questionnaire with the company Mader GmbH & Co. KG.
[209] Cf. UBA (2017).
[210] Cf. HMWVL (2011).

determination is carried out in accordance with the above-mentioned advantages for the customer's use of the compressed air leakage app in connection with the integration of the sensor technology, which was not yet implemented in the practical application (Cf. PA2, p. 90).

Estimation of the REP for Germany

Operational savings in compressed air or electricity through similar digital applications, such as Mader's Compressed air leakage app, are conservatively set at 10% and optimistically, according to the case study findings, at 35%. Based on the above-mentioned total consumption of compressed air or electricity in Germany and assuming that only a proportional 50% offsetting takes place,[211] this results in savings of the final energy electricity in the amount of 0.86 to 3.03 TWh per year for Germany. This can be used to calculate savings in terms of the associated CO_2 emissions [212] from 462,508 to 1,618,776 tonnes of CO_2 emissions per year.

The expenses in the form of hardware (smartphone, computer and sensors) for the use of a compressed air leakage app are predominantly borne by the user, i.e. the customers of Mader GmbH & Co. KG or companies offering similar digital applications as the compressed air leakage app. Here, the user (customer) needs a smartphone, a computer or a laptop to run the application. These expenses are estimated on the basis of literature data as follows: Conservatively, the assumption is made that users use both a computer and a smartphone to run the compressed air leakage app, although one of the end-devices would be sufficient for the application. In addition, it is assumed that the computer and the smartphone are exclusively for the application in use and not proportionately counted for other uses. The period of use of the smartphone and the computer is assumed to be three years, based on the depreciation period of a notebook.[213] Under these assumptions, using LCA data, the energy requirement for one year of operation can be calculated as

---

[211] It is assumed that only this energy expenditure share results from inadequate control of compressed air systems. The remaining 50% of the total energy consumption is attributed to compressed air systems, which are constantly and carefully controlled or maintained.

[212] In 2015, an average of 535 g of carbon dioxide was emitted in the generation of one kilowatt hour of electricity (German electricity mix) (Cf. UBA (2016).

[213] Cf. BMF (2000).

follows: Computer 248 kWh per year[214, 215] and smart phones 6 kWh per year[216, 217, 218]. If it is assumed that, within Germany, half of the SMEs from the manufacturing industry (101,216 companies[219]) carry out continuous compressed air system monitoring, the sum of the expenditure [220] for the production and one-year use of all computers and smartphones can amount to 0.026 TWh per year or 13,753 tonnes of CO_2 emissions per year. The expenses associated with the use of the software or application are also borne by the user. It is assumed that a query within the application has the same final energy consumption as a Google query (0.0003 kWh per query)[221], and users make five queries each day to control the compressed air system[222]. For 101,216 users, an additional final energy demand for Germany of 55.42 MWh per year can be calculated. The resulting CO_2 emissions amount to 30 tonnes of CO_2 emissions per year.

In addition, sensors are integrated into the respective compressed air distribution network. The company Mader usually installs volumetric flowmeters and pressure sensors at compressor stations and in production halls. Average power values of these sensors are 3.3 W for volumetric flowmeters and 0.45 W for pressure sensors. Conservatively, the assumption is made for the extrapolation that only volumetric flowmeters are integrated into the systems. Since the number of sensors required depends on the size of the compressed air system and on the measurement accuracy desired by the customer, it is not possible to make a precise statement regarding the average amount of sensors required. For this reason, it is assumed hypothetically that five to 50 sensors (volumetric flowmeters) are integrated into the system per company.[223] Taking into account the proportion of companies classified as

[214] Cf. Ecoinvent (2016b).

[215] Assuming that the end-device is operated eight hours a day, 365 days a year.

[216] Cf. Andrae, A. S. G. and Andersen, O. (2010).

[217] Assuming that the end-device is operated eight hours a day, 365 days a year.

[218] The data includes both the manufacturing and the utilisation phase of the end-devices.

[219] Cf. Söllner, R. (2014).

[220] It should be noted that in the methodology of the life-cycle approach, the costs of production are calculated as the sum of the costs of all processes of the production chain. Most of these processes take place abroad.

[221] Cf. Google (2009).

[222] 365 days a year.

[223] Cf. Mader (2017).

relevant, it is possible to calculate an additional annual energy requirement of 0.004 to 0.044 TWh of final energy for the utilisation phase in relation to Germany.[224] The resulting additional CO_2 emissions amount to 2,372 to 23,718 tonnes of CO_2 emissions per year.

Comparison of savings and costs

For the observation period of one year, 0.86 to 3.03 TWh of final energy savings (or 462,508 to 1,618,776 tonnes of CO_2 emissions) are offset by 0.03 to 0.07 TWh of final energy (or 16,154 to 37,500 tonnes of CO_2 emissions) in expenditure. Based on CO_2 emissions, this calculates a difference of 446,353 to 1,581,276 tonnes of CO_2 emissions. By implementing the “compressed air leakage app” practical application, net savings for Germany as a business location can be expected under the conservative assumptions used in the example calculation.

7.4.2.2 Practical application "Data on a stick" (Sensitec GmbH)

Findings from the case study analysis

The practical application “Data on a stick” by Sensitec GmbH enables the conversion to a paperless production process within the company’s own wafer production line (microelectronic) by using data carriers (USB sticks). According to Sensitec, the conversion will save between 6,000 and 10,000 sheets of specialty paper per year for cleanroom applications. In addition, according to the company, the integration of data carriers and the resulting real-time control of the manufacturing process has reduced the electrical energy requirements of the production line. There is an energy-saving potential of up to 20% by switching on and off the process-relevant systems in a targeted manner.[225] Digital storage also allowed the company to reduce the error rate, which was largely attributed to the entry of external substances into the sterile production area via the documentation material. Since no estimates were made by the company, this is not taken into account.

---

[224] Assuming that the sensors are operated 24 hours a day, 365 days a year.

[225] Information was obtained from interview/questionnaire with Sensitec GmbH.

General relevance of the practical application of the case study

Paperless manufacturing approaches are rarely implemented in industrial production processes.[226] In principle, a general transferability of paperless manufacturing approaches is possible across industries. However, the practice of Sensitec is specific in two aspects. On the one hand, the savings concern high-quality cleanroom paper, which is needed in the production line for wafer processing[227]. On the other hand, Sensitec implemented a real-time control for the production line. The introduction does not necessarily have to take place simultaneously, but it may be a useful option and enables additional energy savings by switching on and off system components in a targeted manner. In the following, both effects are considered together for the wafer processing sector using cleanroom paper. According to Sensitec, a total of 20 to 50 companies in the electrical industry are processing wafer slices into the finished product in a similar way to Sensitec. The proportion of companies which already operate wafer processing without paper is assumed to be 10%, and the other companies still use cleanroom paper.[228] This identifies 18 to 45 production-related companies to which this practical application is transferable.[229]

Estimation of the REP for Germany

The savings on cleanroom paper based on Sensitec's experience is conservatively estimated at 6,000 and optimistically at 10,000 sheets of cleanroom paper per company per year.[230] If this is done in conjunction with the above-mentioned total number of manufacturers of wafers, the potential savings for Germany is 108,000 to 450,000 sheets per year. In order to make this information comparable, life cycle assessment data are used to calculate the costs of paper production in the form of the required final energy demand and CO_2 emissions. A dataset for coated paper is used[231, 232] as information especially

[226] Cf. Handelsblatt (2016).
[227] The company buys wafer slices externally and processes them at its own production site. The discs are structured so that microchips can be integrated.
[228] This is based on the statement that paperless manufacturing tends to be unusual for smaller companies and more common for larger companies.
[229] Company information of Sensitec GmbH.
[230] Information was obtained from interview/questionnaire with Sensitec GmbH.
[231] Cf. Ecoinvent (2016c).
[232] DIN A4, single sheet 80 g/m².

for cleanroom paper is not available. The final energy consumption for the production of the annually required amount of paper is therefore 189 to 786 kWh per year. The associated CO_2 emissions, which can be calculated using the factor of the German electricity mix[233], amount to 0.10 to 0.42 tonnes of CO_2 emissions per year.

Electricity savings through real-time control of the production line are estimated between 10 and 20% based on Sensitec's experience.[234] It is assumed that the electrical energy requirement for the entire production of a wafer amounts to 30 kWh per m² of wafer.[235] However, since Sensitec only processes the wafer slices without actually producing the polycrystalline (semiconductor-)blanks, the hypothetical assumption is made that this production step accounts for 1 to 10% of the total energy needs of the whole production chain. In addition, it is assumed that the companies process 1,750 wafers per year [236]and that they have an average size of 0.0243 m²[237]. Each year, 43 m² of wafers are processed per company. With respect to the already-mentioned assumptions, an annual business-related energy savings potential of 1 to 26 kWh per year can thus be calculated. The potential for Germany amounts to between 23 and 1,148 kWh per year. This amount of electricity (final energy), offset by the German electricity mix factor[238], leads to savings of 0.01 to 0.61 tonnes CO_2 emissions per year.

The costs involved in the conversion to a paperless production line on part of the company are mainly due to the use of USB sticks, the proportional use of a server and in the use of a computer[239], including the required software. The estimate conservatively assumes that the USB sticks and the computer are only in use for the application in question. Using data from the LCA database Ecoinvent, the final energy consumption for the production and use

[233] Cf. UBA (2016).
[234] Information was obtained from interview/questionnaire with Sensitec GmbH.
[235] Cf. Ecoinvent (2016a).
[236] Company information of Sensitec GmbH.
[237] Cf. Ecoinvent (2016a).
[238] In 2015, an average of 535 g of carbon dioxide was emitted in the generation of one kilowatt hour of electricity (German electricity mix). Cf. UBA (2016).
[239] This also includes an LCD monitor, a mouse and a keyboard.

of a computer, which has been converted to one year, equals 248 kWh.[240, 241] The number of data carriers required per year to be integrated into the production line for the paperless process is 500 units. The USB sticks are reused for various production processes and repeatedly overwritten. The final energy demand for the use of all USB sticks in the company is calculated to be 0.4 Wh to 18 kWh per year.[242,243] Information on the production of USB sticks was not available. Also, there is no information about the share of the server capacity accounted for by the converted production line. Hypothetically, between 1 and 5% of in-house server capacity is used for this purpose. In total, this translates into an annual final energy consumption of 56 to 279 kWh.[244] Thus, the in-house costs amount to an additional annual total energy requirement of 304 to 546 kWh. With regard to Germany and the production-related companies, an energy expenditure of 5,473 to 24,557 kWh per year can be calculated. From this, CO_2 emissions[245] of between 3 and 13 tonnes CO_2 emissions per year can be calculated using the factor of the German electricity mix. For simplicity, it has been neglected that the production of the USB sticks and the server has not been evaluated.

Comparison of savings and costs

Within the observation period of one year, the savings in the form of clean-room paper (108,000 to 450,000 sheets per year), energy expenditure (212 to 1,935 kWh per year) and CO_2 emissions (0.1 to 1 tonnes CO_2 emissions per year)thus face the expenses in form of additional energy requirements (5,473 to 24,557 kWh per year) and associated CO_2 emissions (2.9 to 13 tonnes of CO_2 emissions per year). Based on the CO_2 emissions, this results in a difference of 2.8 to 12 tonnes CO_2 emissions.

The implementation of the practical application "Data on a stick" thus leads to low net expenses under the conservative assumptions used in the example

[240] Cf. Ecoinvent (2016b).
[241] Assuming that the end device is operated eight hours a day, 365 days a year, and based on a computer's period of depreciation, the period of use is three years (Cf. BMF (2000).
[242] The calculation is based on an average power consumption of a data carrier of 0.1 to 0.9 W for each read or write operation. In this case, information is transmitted to the data carrier or retrieved from the data carrier 0.01 to 50 times per hour (information from Sensitec GmbH). It is assumed that a read or write operation takes one second.
[243] Assuming that the USB sticks are in operation eight hours a day, 365 days a year.
[244] Cf. LaCie (2017).
[245] Cf. UBA (2016).

calculation, which mainly result from the power requirement of the integrated system elements (computer / USB sticks / server, pro-rata). In view of the large uncertainties of the calculation using rough estimates, this result can only be assessed as a preliminary statement that savings and costs are of approximately equal magnitude. It should be noted that the impact of the reduced error rate could not be accounted for. In addition, the example calculation with the indicators energy and CO_2 emissions does not include other impact categories or effects of paper production on the environment that could possibly lead to other statements in the context of a comparison of material and energy savings.

7.4.3 Qualitative potential analysis

In this chapter, the findings on increasing resource efficiency through digital transformation and the findings from the literature review and case study analysis are brought together and discussed.

As a general finding from the analysis of literature, it should first be noted that the concept of resources in the aforementioned studies is generally not clearly defined and is rarely used in the sense of a comprehensive consideration of natural resources. Many studies are mainly concerned with energy efficiency and the contribution to climate protection. Likewise, the literature describes the data in terms of supplies and raw material efficiency as rather patchy, although the cost of materials in the manufacturing sector represents the largest cost factor.[246] This can be partially confirmed by the results of this study, because, as already mentioned, the data in the case studies are generally incomplete. However, there were no differences in terms of energy and material (e.g. reduction of error rates or overproduction) (Table 43, p. 125).

According to a new study, the material savings potential for the manufacturing industry in Germany is estimated at 3 to 4%, corresponding to a value of just under two billion euros.[247] As part of a company survey, savings potential averaging 15% was determined specifically for energy consumption; in

[246] Cf. Behrendt, S. and Erdmann, L. (2010), pp. 7 and 14.
[247] Cf. Neligan, A. and Schmitz, E. (2017), p. 3.

sectors such as vehicle or machine manufacture, a greater savings potential is expected.[248] This statement is basically consistent with the picture of the case studies: **The companies surveyed ranked the reduction in energy consumption (electrical energy) achieved through digital transformation measures predominantly in the range of up to 25%.**

In the special context of digital transformation, a study by Roland Berger states that [...] the topic of the efficient use of raw material and supplies is only slowly becoming viewed as a relevant building block in the context of Industry 4.0. Although digitalisation plays a key role in large enterprises, especially in terms of manufacturing processes and the use of new techniques, according to a study by the German Economic Institute, the possibilities of digital networking are hardly used or only used to a very limited extent to exploit existing REP.[249]

In addition, the literature also contains statements regarding some individual aspects on which the case studies have provided insights.

For instance, it is pointed out that there are fundamental advantages in terms of resource efficiency through the use of sensors for direct monitoring of the raw material quality, energy consumption or material quality and quantity. During the production process, a direct interventions are possible if faults or bottlenecks occur. Corresponding measures were found in practical application PA5: Data on a stick (Sensitec) (Chapter 7.2.5, p. 101).

Through the use of sensors, it is also possible to provide a supply of required precursors or materials on demand. In this way, overcapacities can be detected and reduced. This was the case in practical application PA1 (Chapter 7.2.1, p. 87). As a result of the reduced overproduction and the magnesium material, the current stock could be reduced by up to 25%.

The literature also deals specifically with interdisciplinary technologies such as pumps or compressed air systems, which have great relevance for energy

[248] Cf. Schröter, M., Weißfloch, U. and Buschak, D. (2009), p. 6.
[249] Cf. Neligan, A. and Schmitz, E. (2017).

consumption. In addition to more effective technologies and peripherals, the use of electronic ballasts, for example, can also help to save energy.[250] For existing compressed air systems, the identification of leaks is vital to increasing the efficiency of a system.[251]

The experience gained from the practical application PA2 compressed air leakage app (Chapter 7.2.2, p. 90) is even above this estimate. The company Mader GmbH & Co. KG stated that the maximum value of the savings achieved by its own customers was up to 35% savings of the previously used compressed air and the corresponding power consumption.

The literature also indicates that the production and use of the required ICT technologies and devices, such as PCs and notebooks, are likely to consume a large amount of resources. In 2007, about 30 million tonnes of CO_2 were emitted in Germany through the use of ICT due to the ICT-related electricity consumption. In the next few years, a significant increase is expected, which will be caused, in particular, by cloud computing.[252, 253, 254]

A study by the German Economic Institue Cologne also points out that the costs associated with digitalisation are so far largely unknown in companies.[255]

250 Cf. Emec, S. (2013), p. 52.
251 Cf. Schmitt, R., Brecher, C., Nau-Hermes, M. and Berners, T. (2015), p. 29.
252 Cf. eLife (2017).
253 Cf. BMWi (2015b).
254 Cf. German Bundestag (2011).
255 Cf. Neligan, A. and Schmitz, E. (2017).

8 MEASURES OF DIGITAL TRANSFORMATION

In the previous chapters, eleven measures of the digital transformation (Chapter 5.3.2, p. 69) were identified, which where validated in the practical applications of the case studies (Chapter 7.2, p. 86). The measures can be used independently or in combination to promote the digital transformation in the company while at the same time-saving resources.

In order to make it easier for companies to select the measure, each of the eleven measures is described below in a compact, action-oriented profile that presents the prerequisites, challenges and opportunities in a tabular form. Subsequently, an overview of the resource savings potential is given. In addition, references are made to the practical applications (Chapter 7.2, p. 86) as well as the case studies described in Appendix 1 (p. 213 et seqq.).

8.1 M1: Networking of sensors and actuators

The networking of sensors and actuators forms the basis for creating digital value and determining potential savings (Table 45). Therefore, the networking of sensors and actuators should be a central component of the digitalisation strategy of a manufacturing company. The data collection over a longer period of time and the subsequent evaluation, as well as extended viewing and analysis of combined data sources, can reveal potential savings. In addition, coordinated data acquisition of existing sensors and actuators creates an integrated view of ongoing processes in production through increased transparency.

Table 45: Challenges and opportunities through networking of sensors and actuators

Requirements	Challenges	Opportunities
Hardware: - sensors and actuators - microcontroller - communication interface	Integration of heterogeneous sensors and actuators Qualification requirements for employees	Basis for many digitalisation measures of higher order Monitoring and analysis of collected sensor data
Conditions: - low energy - error robust - scalable - mobile	Data security Environmental effects Disruptions in wireless communication	Process transparency Derivation of new possibilities for planning and optimisation of processes
Safety requirements: - availability - reliability - data integrity - data authenticity	Network attacks	Basis for measures such as condition monitoring or predictive maintenance

Potential for saving natural resources

The networking of sensors and actuators is the basis for further measures and thus a basic component for the saving of resources. It is the basic prerequisite for data collection, which in turn enables data analysis, the discovery of potential and transparency.

Reference to practical applications and case studies

PA2 "Compressed air leakage app" (Mader GmbH & Co. KG): In the future, automatically controlled actuators may close compressed air line areas when ultrasonic sensors detect leaks there and report it to the system. Currently this is not yet implemented.

PA3 "One piece flow" (J. Schmalz GmbH): In this PA, mould images of foam parts are automatically transferred to the cutting machine according to the custom order by the customer using CAD files. The production orders are transmitted directly to the respective machine, and the existing sensors and actuators are automatically adjusted accordingly. This produces the required foam part overnight, which is then installed directly in the gripper.

8.2 M2: Use of digital object memories

By providing physical objects of production, such as products, machines and field devices, with a digital object memory, the storage and use of relevant data (e.g. production data) can be made possible directly on the product.

Thus, the digital object memory offers a direct assignment of relevant production data to the resource consumption of the respective component of production. Continuous monitoring also makes it possible to detect deviations from the requirements of normal operation. Table 46 summarises the prerequisites, challenges and opportunities of using digital object memory.

Table 46: Challenges and opportunities through the use of digital object memory

Requirements	Challenges	Opportunities
Comprehensive data integration	Lack of standards	Ensuring product quality
Smart sensor networks	High network complexity	Customised production
Machine-to-machine communication (M2M)	High amount of data	Paperless production
Semantic technologies	Real-time capability	Documentation of performed maintenance operations
Embedded systems	Marking the components	Automation of logistics processes
Sufficient storage capacity Expandability of memory		Information on origin, composition, quality, storage conditions, etc., are available directly on the product
Quick access to the contents of the memory		Information provision for end users (e.g. through interaction with mobile devices)
Standardised interoperable hardware		Tracking and tracing
Small space		Basis for measures such as decentralised control, assistance systems, modularity, condition monitoring and predictive maintenance
Low cost		Use of digital object memories for the qualification of processes and for product-related quality certificates
Flexible architecture and data structure		

Potential for saving natural resources

Digital object memories allow a direct allocation of resource consumption to the components. Processes, for example, can be optimised by monitoring fluctuations. Since the relevant data (production data, documentation) are available directly on the product, paperless production can also be achieved. In this way, the entry of external materials is reduced, which leads to the reduction of the risk of contamination in sensitive production sites (cleanrooms) and thus also to the reduction of faulty production. Energy can also be saved thanks to the optimised tool service life on the basis of individual tool histories stored in, e.g., an object memory. In production, object memories thus lead to savings in raw materials, energy resources and ecosystem services (waste). On the sales side, there is another advantage: The customer can be easily provided with information about the resource footprint of a product, which can influence his or her purchase decision.

Reference to practical applications and case studies

PA2 “Compressed air leakage app” (Mader GmbH & Co. KG): The central compressed air leakage management system (server) stores all relevant data for each compressed air leakage site, such as size and pressure. These data are processed further and made available to the respective app users in the company (employees, energy managers, managing directors, etc.) in real-time.

PA4 “Warehouse management system” (MAINCOR Rohrsysteme GmbH & Co. KG): Integration of production-relevant data is achieved by using a warehouse management system based on optical identification. In addition to product-related data, quantity and time-related data are also stored. These are provided as needed for process optimisation in warehousing.

PA5 “Data on a stick” (Sensitec GmbH): By attaching USB sticks to the workpiece carrier, the company has turned it to an information carrier. This enabled paperless production. Furthermore, it is no longer necessary to digitalise the data from the paper for error analysis.

8.3 M3: Decentralised control

The smart workpiece becomes an important building block in the decentrally controlled manufacturing and value network. It is equipped with a digital object memory (M2), has knowledge of its properties and keeps information about its production and its goal ready. This allows the product to be manufactured to independently control the production process. Companies that adopt a decentralised approach can optimise resource efficiency control parameters, such as short production routes, high machine utilisation and automatic shutdown of system components (Table 47)

Table 47: Challenges and opportunities through decentralised control

Requirements	Challenges	Opportunities
Networking of sensors and actuators Comprehensive data integration Use of digital object memories Standardised machine-to-machine communication Structure of an architecture that enables a combination of centralised and decentralised control Match the machine and system characteristics to the decentralised control: Machines must be able to recognise components and retrieve information	Changeover from central deterministic planning Integration of the latest Enterprise Resource Planning systems (ERP systems) Differentiation between centralised and decentralised control	Flexible, decentralised control networks instead of the rigid structure of the automation pyramid Reduction of the planning complexity of production processes Enabling high product diversity with small batch sizes Local optimisation of tasks and order sequences Use of digital object memories as a sensible requirement for decentralised control. Decentralised control in turn allows modularisation

Potential for saving natural resources

When decentralised control is used, the dependencies of the individual production steps are reduced. Innovative production systems are networked and decentrally organised, so each component of the production system (sensor, actuator, control unit) communicates with other components of the (corporate) network without centralised control. This helps to avoid malfunctions, detect errors early and identify potentials for optimising the efficiency of production and product. Overall, this can lead to a reduction in misproduction, resulting in savings of raw materials, energy resources and ecosystem services (waste).

Reference to practical applications and case studies

PA5 "Data on a stick" (Sensitec GmbH): Using the data carriers (USB sticks) integrated into the production process and the subsequent paperless production line, it was possible to simplify and speed up information and communication processes with regard to wafer production.

PA7 "Business warehouse system" (Hermos AG): The central storage and processing of all customer orders and the product- and process-spanning information enabled optimised planning and implementation of company-specific production.

8.4 M4: Measures for staff support and assistance

Multimodal assistance systems can assist staff with a wide range of tasks in production and assembly through tailor-made instructions on mobile devices or through sensors that are integrated into the workplace (Table 48). Systems integrated into the workplace can be used to assist the staff, such as pick-by-light or laser specifications for optimum material utilisation in punching and cutting processes. These support the staff in production, and at the same time, lead to more efficient utilisation of supplies and raw material savings. In a future expansion stage, machine and plant manufacturers can deliver their products directly with self-developed software for staff assistance (e.g. in the form of apps), for example, to support the operators who are employed by their customers in machine operation and maintenance.

Table 48: Challenges and opportunities through measures for staff support and assistance

Requirements	Challenges	Opportunities
Practical terminal equipment	Lack of acceptance of staff	Acceleration of orientation processes
Suitable software systems	High dependence on IT	Improvement of productivity
Networking of Product Life Cycle Management systems (PLM systems)	High support and maintenance effort	Simplification of variant mastery
Develop concepts for augmented reality applications	No uniform standards	Error reduction/avoidance
Open, easily accessible interfaces	Lack of compatibility of various assistance systems	Increasing safety at work
	Low application flexibility	Cost reduction through consumer products
	Training expenses	Improvement of ergonomics
		Targeted support for older staff

Potential for saving natural resources

Tailored instructions for the staff reduce misproduction and rejects, as well as more efficient material utilisation and maintenance. Thus, assistance systems can contribute to savings of raw materials, energy resources and ecosystem services (waste).

Reference to practical applications and case studies

PA2 "Compressed air leakage app" (Mader GmbH & Co. KG): The compressed air leakage app was originally used as a staff support measure. The compressed air leakage recording and logging was carried out using the app, which further processed and provided the data in real-time.

PA4 "Warehouse management system" (MAINCOR Rohrsysteme GmbH & Co. KG): By providing stored warehouse data, the company Maincor is able to employ logistics staff more efficiently and optimise warehousing processes.

8.5 M5: Dynamically cooperating systems and modularisation

Modern manufacturing facilities can be composed of interchangeable and extensible cooperating systems. There is a flat automation hierarchy between the field, coordination and control levels, and the boundaries are partially blurred. Each functional unit encapsulates certain functionalities that can be integrated into the production process or simply removed again when they are not needed (paradigm of plug-and-produce). As a result, several product variants can be produced, where the product itself can control itself through production, among other things. Likewise, stand-by losses can be avoided by switching off unneeded systems. Table 49 has an overview of requirements, challenges and opportunities of dynamically cooperating systems and modularisation.

Table 49: Challenges and opportunities through dynamically cooperating systems and modularisation

Requirements	Challenges	Opportunities
Decentralised control	Standards	Increased flexibility
Modularisation of manufacturing systems	Suitable interfaces	Lower construction or conversion times
Standardisation of the modules	Compatibility of modules	Increase of productivity
Compact design of the modules	Commissioning strategies	Efficient production of small quantities
Mobility of modules		Scalability of production
		Shortened start-up times
		Shutdown of unused modules
		High reusability of the modules
		By linking upstream and downstream states of a digitally defined object, these can be included in consideration of product development

Potential for saving natural resources

Modularisation makes the adaptation of production processes easier and can be implemented by exchanging individual modules. It is also possible to switch off systems and system components when not in use. This results in a better utilisation of plants and plant components. Modular production also means that a product does not have to go through the entire production line. This results in possible savings in raw materials, energy resources and ecosystem services (waste).

Reference to practical applications and case studies

PA7 "Business warehouse system" (Hermos AG): After receiving the customer's order, the business warehouse system makes it possible to automatically carry out the digital creation of circuit diagrams, the programming of product-specific software and the ordering of required components from the respective suppliers.

8.6 M6: Introduction and use of positioning and localisation systems

Positioning and localisation systems make it easier to find and assign manufactured products and machines in the factory. They offer the opportunity to increase the transparency of the transport flow and thus avoid unnecessary transports (Table 50). Using this approach, machines, workpiece carriers and transport systems can locate themselves, navigate autonomously and cooperate with one another (e.g. robot-robot cooperation). The processes and procedures along the entire supply chain can be taken into consideration.

Table 50: Challenges and opportunities by introducing and using positioning and localisation systems

Requirements	Challenges	Opportunities
Localisation infrastructure: - Marking objects to be located - Transmitting and receiving units	Selection of suitable systems Real-time capability of the positioning systems	Optimisation of operations along the entire manufacturing process Reduction or elimination of errors and non-value adding processes Tracking and tracing of components and machines Transparency and optimisation of the transport flow Reduction of warehousing Antitheft Geofencing Simplification of recall actions through improved traceability

Potential for saving natural resources

This measure exerts a direct influence on the internal or external transport. Transport routes can be e.g. analysed and optimised. Products, tools, etc., can be found more easily, which can reduce overproduction. As a result, raw materials and ecosystem services (waste, CO_2) can be saved.

Reference to practical applications and case studies

PA1 "Optimised business processes" (C & C Bark Metalldruckguss und Formenbau GmbH): Within the framework of this PA, a function of the implemented ERP system enables the accurate and real-time location and traceability of all product batches during production.

PA5 "Data on a stick" (Sensitec GmbH): The company has created an "indirect" localisation system by introducing USB sticks. By registering the USB stick on the machine, it is known where the task is currently located. Before the implementation of the practical application, when the orders were still printed on paper, they had to be laboriously searched by the staff when needed.

8.7 M7: Condition monitoring

Thanks to the continuous monitoring and analysis of the data from sensors and actuators, deviations from a reference state can be detected and corrected at an early stage. For example, deviations caused by wear could be registered and indicated early on. In addition, the monitoring of the operating states of systems and processes enables early detection of incorrect settings, improper use and incorrect operation by the staff or the machine operator.

Table 51: Challenges and opportunities through condition monitoring

Requirements	Challenges	Opportunities
Networking of sensors and actuators	Selection of suitable data and measuring points	Continuous status, process and quality monitoring
Comprehensive data integration	Capture, storage and processing of large amounts of data	Predictive maintenance
Regular collection of meaningful data	Data handling with continuous acquisition	Transparent production (also in terms of resource use)
Identification for condition assessment of suitable data	Beneficial analysis of the data	Error analyses based on well-founded data
Corresponding hardware and software	Correlation to process parameters	Reduction of rejects by monitoring process stability
		Provides predictive maintenance
		Basis for assistance systems

Potential for saving natural resources

Condition monitoring allows wear parts to be used up to their actual usage limit instead of replacing them at fixed intervals. It can also prevent machine failures with the resulting damage situations and rejects. The detection of deviations and the elimination of untypical errors also lead to the reduction of misproductions. As a result, raw materials, energy resources and ecosystem services (waste) can be saved.

Reference to practical applications and case studies

PA1 "Optimised business processes" (C & C Bark Metalldruckguss und Formenbau GmbH): The introduced ERP system has a feature that allows networking of machines with the system. Operation and machine data are reported to the system in real-time. This thus allows condition monitoring.

PA2 "Compressed air leakage app" (Mader GmbH & Co. KG): This PA represents a digital condition monitoring tool. The condition of compressed air systems (primarily pipes) is monitored from ultrasound sensors to mobile devices, and information is provided in real-time.

PA3 "One piece flow" (J. Schmalz GmbH): The machining centres are equipped with condition monitoring software. Possible disruptions are then evaluated in part directly by the machine suppliers in order to optimise their maintenance work.

PA5 "Data on a stick" (Sensitec GmbH): By developing its own manufacturing execution system (MES), machines and, in particular, critical consumables (e.g. chemicals) can be monitored.

8.8 M8: Predictive maintenance

Predictive maintenance systems predict machine failures (e.g. machine failures or malfunctions) depending on the condition. Consequently, companies are able to carry out repairs as needed. Service life due to wear parts can be optimally utilised. The purchase of spare parts takes place only when they are needed, thereby eliminating their storage. Preventative maintenance measures and timely repairs reduce breakdowns and machine downtime.

Table 52: Challenges and opportunities through predictive maintenance

Requirements	Challenges	Opportunities
Condition monitoring	Threshold determination for different components, machines and plants	Avoidance of production losses Increased machine availability Predictable maintenance measures during planned business interruptions Possibility to order spare parts and task repair personnel in advance Early detection of damage / prevention of consequential damage Use of wear parts up to the limit of use

Potential for saving natural resources

Predictive maintenance systems are designed to monitor and identify wear and resource consumption early (e.g., find leakage, monitor rejects). Additionally, maintenance aspects can be included in the consideration. The detection of deviations and the elimination of untypical errors lead to the reduction of misproduction and rejects. As a result, raw materials, energy resources and ecosystem services (waste) can be saved.

Reference to practical applications and case studies

PA3 "One piece flow" (J. Schmalz GmbH): The company uses software for the condition monitoring of its machining centres, which is in part evaluated directly by suppliers in real-time. This is an excellent example of predictive maintenance.

PA5 "Data on a stick" (Sensitec GmbH): By monitoring the condition and quality history of critical consumables (e.g. chemicals), the consumable can be changed before it leads to a reject.

8.9 M9: Comprehensive data integration

Comprehensive data integration forms the basis for uniform access to different data structures from heterogeneous data sources in both existing and new plants. The combination and evaluation of these data makes it possible to determine the presence of any correlations. Production errors can be reduced by detecting and correcting deviations and errors between planning and production. The improved traceability across system boundaries prevents overproduction, the processing of defective products and unnecessary material purchases.

Table 53: Challenges and opportunities through comprehensive data integration

Requirements	Challenges	Opportunities
Meaningful preparation and aggregation of the data	Compatibility of different interfaces	Networking of operating areas, e.g., shop floor with management areas (uniform systems)
Interfaces for exchange	High complexity due to inconsistent data structures and formats	Uniform viewing and evaluation of information
Information model for mapping and consolidating the data	Collection and processing of large amounts of data	Basis for almost all higher order digitalisation measures
Comprehensive data management structure	Control of data quality	Traceability of data on life cycles of products and plants
	Operational effort when collecting data from different business areas	High transparency of processes
	Real-time requirement	Decisions based on data
	Scalability of the system	Time savings
	Different technology levels of the machinery	Reduction of errors
	Safety requirements	Data on resource consumption from the utilisation phase and the end of life can be used by the manufacturer for product optimisation
	Resolution or avoidance of data silos	Creation of industry-specific standards as a guide in the digitalisation process

Potential for saving natural resources

According to a study by the IMPULS Foundation, the majority of SMEs surveyed already collect machine and process data in some form.[256, 257] Half of these companies use such collected data to optimise resource consumption. However, a complete logging of machine and process data is still extremely rare in companies. Through comprehensive data integration, raw materials, energy resources, ecosystem services (waste, CO_2) and area can be saved.

[256] Cf. Lichtblau et al. (2015), p. 37.

[257] Survey of the members of the German Mechanical Engineering Industry Association (VDMA).

Reference to practical applications and case studies

PA1 "Optimised business processes" (C & C Bark Metalldruckguss und Formenbau GmbH): The introduced ERP system enables company-wide networking of machines and systems as well as data exchange. It transfers operating and machine data to the system in real-time.

PA2 "Compressed air leakage app" (Mader GmbH & Co. KG): The fact that the compressed air leakage app itself provides data about a compressed air system in real-time enables continuous data integration.

PA3 "One piece flow" (J. Schmalz GmbH): There is a comprehensive data integration in the One Piece Flow production area. Here, the production is coupled to order management, and the ordering process is supplied with digital data at an early stage.

PA7 "Business warehouse system" (Hermos AG): Comprehensive data integration enables both increased transparency and the optimisation of order processing as well as automated costing.

PA10 "FoamCreator" (Wetropa Kunststoffverarbeitung GmbH & Co): By changing the business model, product development is now done by the customer. The resulting data can be routed to production.

8.10 M10: Virtual product development

Virtual product development, in combination with virtual simulation, enables product testing to be performed on virtual test objects. This reduces the need for physical prototypes. The prototypes that are still needed can often be created by additive methods, such as 3D printing.

Table 54: Challenges and opportunities through virtual product development

Requirements	Challenges	Opportunities
Data infrastructure and management	Training of employees	Fast development cycles
	Product data management	Early feedback
Accessibility of process and project data	Administrative expenses	Frontloading
System integration	High software costs	Simulation studies
Employee know-how		Sound decision basis
High computing power		Conserving resources through fewer last-minute design changes and virtual prototypes
		Quality improvement
		Process optimisation (release/change)
		Avoidance of media breaks
		3D data exchange with customers/suppliers
		Additive manufacturing (3D printing)

Potential for saving natural resources

Virtual product development in prototype production requires significantly fewer resources, compared to traditional subtractive manufacturing processes: Firstly, quantitatively less raw materials are needed for them; secondly, tools for the production of prototypes and their maintenance are eliminated. An integrated digital CAD process chain also saves additional resources by avoiding media discontinuities. Content no longer needs to be entered manually or converted using tools. Overall, this results in savings in raw materials, energy resources and ecosystem services (waste).

Reference to practical applications and case studies

PA3 "One piece flow" (J. Schmalz GmbH): 3D printing is used for the production of prototypes of plastic parts as well as customised solutions.

PA8 "Virtual product manufacturing in prototype construction" (Sanner GmbH): Products are first digitally developed, and then the prototype production takes place by 3D printing. This eliminates the costly iterative tool production. In addition, this method offers the possibility of quickly presenting the prototypes to the customer.

PA10 "FoamCreator" (Wetropa Kunststoffverarbeitung GmbH & Co): Product development was outsourced to the customer through the provision of an app and internet platform. Production data can be routed by the customer directly to the production or to the machines.

8.11 M11: Cloud computing

Moving complex applications or production and manufacturing data into cloud-based solutions makes data exchange easier and reduces administration efford. The data and applications stored in the cloud can be accessed worldwide from different computers around the clock.

Table 55: Challenges and Opportunities from cloud computing

Requirements	Challenges	Opportunities
Reliable broadband internet connection Data security Legal certainty Interoperability of the cloud services with the existing IT infrastructure	Ensuring the data security of sensitive company data Sufficient performance for liquid processes Establishment of reliability and failure protection	Improved energy and resource efficiency through optimised utilisation of IT capacities Dynamic access to IT capacities Billing according to flexible payment models Low administrative effort Mobile availability Availability guaranteed by cloud provider Shift long-term capital expenditure to operational costs Empowering cross-company partner networks Simplification of maintenance tasks by direct control of field devices

Potential for saving natural resources

Moving computing power and data storage from in-house servers to more energy-efficient external data centres results in energy savings, as larger centres can operate more efficiently. Accordingly, servers and the subsequent infrastructure of cooling systems and storage solutions as well as their own production, which consists of a wide variety of raw materials and critical materials, can be saved. Therefore, there is a potential to save energy and raw materials.

Reference to practical applications and case studies

PA9 “Cloud-based manufacturing” (Sanner GmbH): An ERP system with MES functionalities has been outsourced to an external service provider. In addition, data is stored at a cloud provider. As a result, the company’s own IT infrastructure was shut down, resulting in energy savings and increased availability.

9 RECOMMENDATIONS FOR ACTION FOR SMES, POLITICS AND SCIENCE

The essential components of this study are a structured literature review, the consideration of a systematic methodology for the evaluation of resource efficiency potentials and the investigation of practical examples in companies. This information basis was supplemented by a workshop and a conference with participants from industry, science, associations and the administration. Based on the results of the study, approaches for action for SMEs as well as for politics and science are derived in the following.

9.1 Recommendations for action for SMEs

In SMEs, there are two main challenges in order to realise resource efficiency potential: On the one hand, companies must select suitable measures for their own operations. On the other hand, they should make use of the new possibilities of digitalisation in a targeted manner to generate data on resource consumption in the company and in the value chain, thus creating a strategic information basis for identifying savings potentials and testing the effectiveness. The recommendations for action for SMEs (HK) are structured according to these objectives below.

9.1.1 HK1: Determination of the maturity of digitalisation and selection of measures

Recommendation for action

The digital transformation measures identified in the study can be used across industries to increase resource efficiency. Which measure is selected and to what extent it is implemented must be individually adapted to the boundary conditions of each company.

Companies should carry out a “readiness check” with the aim of determining the current degree of maturity of digitalisation. Based on the determined degree of maturity, the corresponding measures M1 to M11 and their development stages can be selected. Resource efficiency potentials should be taken into account consistently.

Every digital transformation measure (Chapter 8, p. 141) exists in several maturity levels (Chapter 5.3.3, S. 72). It can be applied depending on the stage of development and the digitalisation stage of the company. However, due to the technical requirements, some measures should only be used at an advanced stage (Figure 23). For example, the concept of digital object memory (M2) can be used in different stages of development. At the I4.0 Advanced level, e.g., manufacturing data can be logged in detail on a digital, rewritable storage medium. As an I4.0 Expert or I4.0 Pioneer, it is also possible to use this complex measure, e.g., in the form of a cyber-physical system with wireless network connection, to increase the efficiency of production.

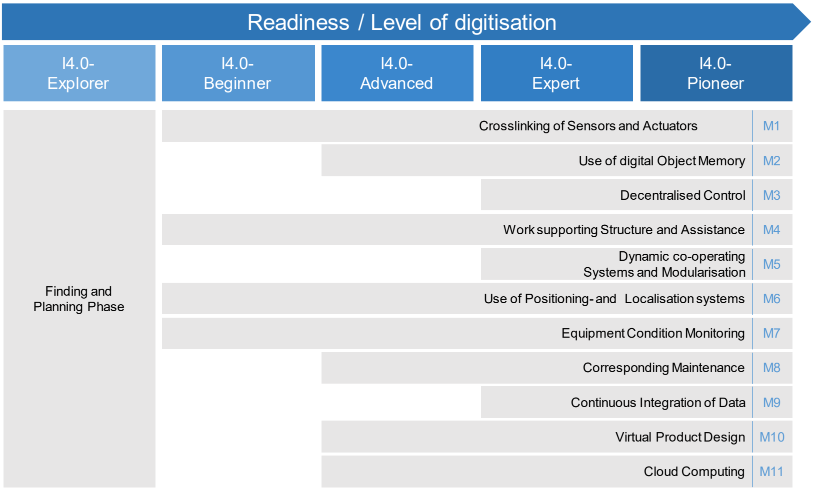

Figure 23: Assignment of measures according to the digitalisation status

In order to classify suitable measures or their transferability for one's own company, it is recommended to determine one's own digitalisation status. The readiness check developed by the Competence Centre for SME 4.0 Kaiserslautern, for example, is ideal for this purpose.[258] The readiness check uses 25 questions to determine the level of Industry 4.0 maturity of a company and assigns it to one of five levels – from the I4.0 Explorer to the I4.0 Pioneer. The digital transformation measures could then be selected and implemented in accordance with the determined Industry 4.0 maturity level.

[258] Cf. Competence Centre for SME 4.0 Kaiserslautern (Mittelstand 4.0-Kompetenzzentrum Kaiserslautern, no date).

The potentials for saving resources (Chapter 8, p. 141) should be taken into account consistently.

9.1.2 HK2: Collection and evaluation of resource data

Recommendation for action

Industry 4.0 offers new possibilities for plant- and process-related logging and evaluation of data on operational resource consumption. It is essential to identify the relevant operational parameters and use the ICT components introduced as part of digitalisation to record them.

It is recommended that companies use Industry 4.0's ability to create a plant- and process-based database of the specific resource consumptions of their processes. Further processing and analysis of the data enable the identification of resource efficiency potentials and the targeted success controlling of future measures. The resource self-assessment tool (ReSET) developed in the study offers assistance in this respect.

According to the study "Unlocking the potential of applying 'Industry 4.0' in SMEs",[259] a lot of data are collected in SMEs, but data analysis is usually neglected. In addition, the data collection process is not systematic. A clear strategy is lacking as to which data should be included in order to gain relevant insights. This was confirmed by the experience gained in this study.

In the following, a tool is presented that especially helps SMEs to use the digital transformation in the company for systematic data collection and analysis. Furthermore, it should enable companies to independently derive further steps for their specific application and to be able to estimate the resulting resource potential. The tool was developed on the basis of the Toolbox Industry 4.0[260] published in the Guideline Industry 4.0.

[259] Cf. Bischoff, J. (2015).
[260] Cf. Anderl, R. (2015).

Resource self-assessment tool (ReSET)

The present resource self-assessment tool (ReSET) shows six operational material resources in six stages of data collection and analysis.

Figure 24 shows the generalised version of the resource self-assessment tool. For the six tangible operational resources electrical energy, thermal energy, raw materials, consumables, specific emissions and waste for disposal, six development stages of digitalisation were defined in a comprehensive manner.[261] These range from left to right: From a non-existent data collection on resource usage, to acquisition with an ever-higher resolution, to fully automated systems that capture and analyse data that are able to independently implement derived optimisation measures.

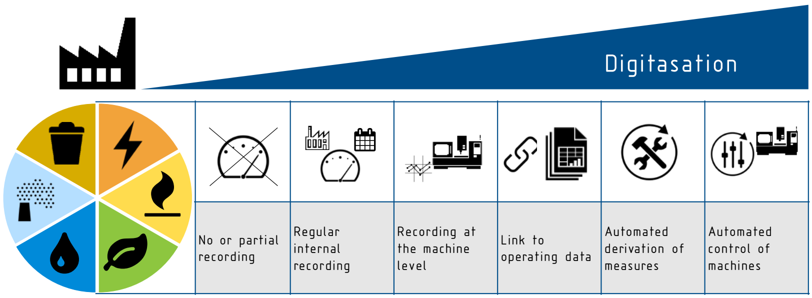

Figure 24: Generalised version of the resource self-assessment tool (ReSET)

At **level 1**, only unordered or irregular data are logged for the respective resource. Even without the use of modern sensors, data on the use of resources are generated, e.g., from purchase orders or utility invoices. However, these remain within their respective organisational units and are not used for a holistic consideration of resource efficiency.

Companies at **level 2** regularly record and structure the relevant reference values at the company level. An awareness of the use of resources is created. The data can be extracted from the existing data records or specifically collected manually. The initial use of sensors for automated data collection is conceivable, but is accompanied by high demands on the IT infrastructure of

[261] The relationship between operational and natural resources described in Chapter 2.2 makes it possible to deduce the natural resources from the six operational material resources.

the company. The collected data can be used to create time trends, identify seasonal fluctuations and derive initial optimisation measures.

At **level 3**, the resolution is intensified by recording the resource data at the machine level. Automated data collection and vertical data integration are targeted at this stage. The granularity of the database is increased. Specific measures for individual machines or production areas can be derived. The resulting knowledge about the use of resources can be incorporated into the work preparation.

The first three stages describe the path from a non-existent collection of resource data to an increasing awareness of the use of resources by gathering the relevant data and then increasing both the frequency and the reference points. This creates growing transparency of the processes in the company in terms of resource efficiency and forms the foundation for further digitalisation steps.

At **level 4**, the recorded resource data is linked with operating data, i.e. machine or process data. An intensive analysis of the coupled data leads to new insights into the connection between production and resource use and allows the derivation of further optimisations to increase resource efficiency.

With the help of machine learning, patterns and laws in the processes can be identified at **level 5**. Algorithms learn from continuously acquired data and make predictions about future events based on it. The artificial system can thus react to unknown data and independently derive optimisation measures to increase resource efficiency. These are then proposed to the employees to be implemented.

The highest level of digitalisation development (**level 6**) is formed by autonomous systems, which independently implement the machine-derived optimisation measures. A seamless networking of sensors, artificial intelligence and actuators is a prerequisite for this. The use of autonomous systems opens up many new opportunities that cannot yet be fully assessed based on current knowledge.

While the underlying technologies of levels 1 to 4 are generally state of the art, but have not yet been implemented comprehensively, the technologies of stages 5 and 6 are objects of current research projects that have little or no application in industrial practice, especially in SMEs. The levels were nevertheless included to reflect the vision of complete digitalisation. A detailed description of the resource self- assessment tool can be found in Appendix 2 (p. 258).

9.1.3 HK3: Development of strategies for resource efficiency in the company

Recommendation for action

Resource efficiency is currently a secondary objective of digital transformation for SMEs. It should be more widely viewed by companies as an independent opportunity to increase resource efficiency.

Companies should develop a targeted strategy for resource efficiency measures as part of their digital transformation.

Further information on measures M1 to M11 can be obtained from the partners involved in this study and their networks. In the medium term, the advisory services of existing competence centres should be networked (see HP1, p. 165). The ReSET tool and the readiness check can be used as a starting point, among other things.

9.2 Recommendations for action for politics

The right political framework is of particular importance for the success of digital transformation in manufacturing SMEs. Thus, politics is currently driving forward the progress of the digital transformation through the expansion of the network infrastructure. This benefits especially smaller businesses in rural areas. In the future, it can be assumed that companies will have the infrastructure available for digital transformation regardless of their region and size, and will also be able to use the opportunities to increase resource efficiency. The government can promote this above all to businesses through supporting targeted counselling services and assistance for companies.

At the same time, polictitians have the task of keeping an eye on the risks posed to society and businesses by the Internet and digitalisation. This concerns predominantly the following points:

- IT systems and their infrastructures are now integral components of almost all products and services of the German economy. Accordingly, special attention should be paid to data protection and data security. Greater awareness must be developed for the security of data and the protection of critical infrastructures. It is important to know and safeguard the vulnerability and weaknesses in the provision of data, gas, electricity and water in order to ensure supply to the population and thus also to domestic production. Confidence in IT infrastructures and systems must be created so that SMEs can boldly take the step towards digitalisation. Operational and data security should always be considered an integral part of the networking of production sites or of machines and plants as well as their sensors and actuators.

- Artificial intelligence makes it possible to first unearth “hidden” information in data through data analysis (correlation analysis) and make it visible. This goes hand in hand with the question of ownership of the digital data of a product, which are generated in the manufacturing and utilisation phase: Who can view and (continue to) use them? Awareness for such issues must be raised.

- With regard to the introduction of positioning and localisation systems, policymakers should set the legal framework for the use of such systems. As these can potentially also be used to monitor employees. Such misuse must be prevented by appropriate laws.

- In addition, policymakers should look to the legal protection of infrastructure and promote cloud solutions at the EU level, and strive for standardisation and interoperability between cloud providers in order to avoid vendor lock-in.

In the following, the most important recommendations for politics (HR) are described, which are prerequisites for realising the potential of digital transformation in terms of increasing resource efficiency in manufacturing SMEs.

9.2.1 HP1: Networking and promotion of advisory services on Industry 4.0 and resource efficiency

Recommendation for action

There are publicly funded institutions at the federal level and some regional levels that offer support for SMEs as well as advisory and training measures both in the area of Industry 4.0 and in the field of resource efficiency. At the federal level, these include the Competence Centres for SME 4.0 of the BMWi and the Resource Efficiency Competence Centre of the BMUB, which is based at VDI ZRE. Corresponding advisory services are also available for this in individual federal states.

A key recommendation for action is the networking of these counselling services with the aim of developing a uniform toolkit to support SMEs in identifying and realising resource efficiency potentials in the context of Industry 4.0 (Resource Efficiency 4.0).

Starting situation

Many SMEs in the manufacturing sector are still in their early stages of implementing digitalisation measures. On the other hand, the case studies have shown that aspects of resource efficiency play a secondary role in the implementation of such measures. However, as shown in the previous chapters, digital transformation can offer great potential in increasing resource efficiency in enterprises. It is important that the material and energy efficiency aspects are integrated into the digitalisation measures right from the start.

Implementation

Experience has shown that advisory and information measures for SMEs are only successful if they are clear and easy to handle for the companies. It is therefore important to develop a uniform set of advisory and information services that can be used by all advisory agencies of the federal and state governments alike. For this purpose, it is proposed that a task force consisting of representatives of the Competence Centres for SME 4.0 and the VDI ZRE should, as a first step, develop a joint **roadmap for the development of a Resource Efficiency 4.0 Toolkit**. This can then be coordinated with the advisory agencies of the countries accordingly. And it shall ensure that all matching competences and experiences are taken into account. The Resource Efficiency 4.0 Toolkit could, for example, contain tools, qualification modules or best practice examples. New tools could be developed, e.g., from existing online tools of the VDI ZRE (resource checks, process chains, etc.) and the resources self-assessment tool presented in Chapter 9.1.2 using methodology for evaluating resource efficiency presented in Chapter 2.2 and Chapter 5 of this study. The establishment of a common digital platform with links to the different elements of the toolkit would appear to be a useful connecting element.

With the aid of the Resource Efficiency 4.0 Tool Kit, a cross-regional and content-wide network on resource efficiency and Industry 4.0 can be established with a **standardised information and advisory service** for SMEs.

9.2.2 HP2: Marking/labelling of electricity consumption values of ICT and Internet services

Recommendation for action

Operational measures of digital transformation require ICT hardware and software and rely on services offered on the Internet. This will require natural resources in the form of raw materials for hardware and power for operation, which must be considered when assessing resource efficiency. In particular, several studies have pointed out the increasing demand for electricity due to the increasing use of Internet services.

Politics should therefore encourage the use of marking and labelling systems for ICT manufacturers or providers of Internet-based services to indicate electricity consumption during utilisation and production.

Starting situation

The electricity consumption through the use of ICT hardware and software (in-house) and services offered on the Internet (off-site) is often unknown to companies. These consumptions can therefore not be taken into account in operational efficiency measures.

Implementation

Existing regulations on energy-related products (ErP Directive or Ecodesign Directive (2009/125/EC)) should be extended to include relevant ICT product groups for companies (e.g. sensors) and to especially include data on the consumption of specific software as well as Internet or cloud services, and equip them with a consumption label or a label for the consumption of electricity. These should show how much electricity is consumed per unit of use. Such labels/markings could also be linked to the "Software as a service" business model, in which only the use of a service (pay-per-use or pay-per-MB), e.g. a cloud service, is charged. Thus, in addition to the costs, the associated electricity consumption (electricity consumption per MB) or the emitted greenhouse gas emissions (CO_2 equivalent per MB) would be shown. The indication of consumption values leads to a direct comparison of suppliers, enables companies to choose the most energy-efficient component or service and thus strengthens competition in the field of ICT energy efficiency. In addition, greenhouse gas compensation models could be added to the consumption value labels, as is currently the case in the transport sector.

In the context of the development of labels, the following aspects could be included in labelling in addition to electricity consumption: Life cycle costs, annual workload of systems, reparability, transparency of information, particularly on rechargeable batteries (e.g. capacity indicators). Necessary methodological procedures and parameters can be developed within the framework of research projects.

9.2.3 HP3: Orientation of research promotion to link Industry 4.0 with resource efficiency

Recommendation for action

The research promotion of the federal ministries addresses topics related to Industry 4.0 and resource efficiency.

It is recommended that these programmes integrate specific issues for realising the potential of digital transformation to increase resource efficiency. In addition, future priority topics of research promotion should be devised or developed to advance technologies and generate new knowledge.

Starting situation

Concrete recommendations for action for science to bring together Industry 4.0 and resource efficiency are specified in Chapter 9.3. However, previous recommendations for action also refer to research in various aspects.

Implementation

The need for research and the topics of research promotion can be divided into two areas. On the one hand, from the point of view of resource efficiency, the focus continues to be technologically oriented research on ICT, combined with questions of the framework conditions (access to infrastructure, data security, etc.). On the other hand, a broader interdisciplinary and transdisciplinary approach will be needed in the future to provide more advanced methodological approaches for assessing the impact on natural resources and to develop new digitalisation applications, e.g., in the circular economy, together with stakeholders in these operational fields.

9.3 Recommendations for action for science

Science can promote the direction of digital transformation in increasing resource efficiency in different ways. Thus, ICT-related research can identify specific aspects of resource conservation. In addition, it should focus on systemic complex effects and explore the societal impact of digital transformation.

In futuristic research factories – “Future Factories” – researchers will collect data from control and production, and the machines will independently provide information on the quality of the manufactured products as well as the operating conditions of the plant and current consumption, of, e.g., lubricants, energy and compressed air. All production data will be presented in human-machine interfaces, understandable to the user. In this way, the interaction of modular production and the corresponding material flow, as well as the use of energy and consumables, will be documented and displayed in tables and diagrams.

Much research and development is needed to realise this vision. In general, the following priorities are particularly important:

- Science must raise the awareness of SMEs to the vulnerability of the IT infrastructure (electricity and water supply) so that the topic of security and protection of IT systems and data structures is given higher visibility. It must also present solutions and procedures that act as barriers to attacks on the networked infrastructure. This is necessary to build trust in IT solutions. Because the digital shift and thus the digital transformation only have a chance, if the respective decision-makers have confidence in IT solutions. Science should improve the transferability of approaches and representation formats and conduct research to increase the security of IT systems and data structures.

- Science needs to drive the evolution of cyber-physical systems and direct integration with manufacturing modules. As a result, software agents could control more flexible manufacturing – decentralised from different computer systems. The main focus in developing modular approaches should be on resource conservation (e.g. by reducing scrap).

- As an orientation for the introduction of digitalisation solutions in the context of Industry 4.0, more and more companies are demanding standards, norms and certifications. Methods, representation formats and foundations for a consistent resource efficiency indicator system need to be developed especially in terms of data. Only then can a standardisation process begin. One possible research topic is the standardised transfer of product development data to production planning data and machine codes in order to directly start the manufacture.

In the following, action recommendations for science (HW) with a special relevance for resource efficiency are discussed in more detail.

9.3.1 HW1: Data acquisition, evaluation, presentation through approaches of artificial intelligence

Recommendation for action

Appropriate acquisition, evaluation and representation of production data can be useful for process control and monitoring as well as for maintenance to save resources. However, existing data collection and analysis methods are not suitable for the quantity and complexity of the expected data sources.

Science should develop methods for data collection, evaluation and presentation through artificial intelligence approaches (machine learning technologies such as deep learning), as well as promote the derivation of specific automated action strategies.

Potential for saving natural resources

When evaluating data by means of machine learning, it is important to learn from the history of typical courses of events and to identify outliers and atypical courses of events, as well as to display them at an early stage. Typical processes are then represented by tolerance ranges or (partially) automated threshold definitions in a series of measurements.

In addition, procedures for easier processing and evaluation of CAD datasets should be developed. The transfer to standardised representation formats for further evaluation by means of learning methods (deep learning) also offers a lot of research potential.

A search for resource-intensive processes through a series of measurements that are recorded, e.g., in the company's own manufacturing plant, is followed by an analysis and consideration of costs for supplies and raw materials, in order to identify significant savings potential. For storing the series of measurements, it is possible to use plant-specific and product-specific data structures and logging them in digital object memories (Measure M2, p. 142). This allows a realistic assessment of the resource consumption of the product or plant during the utilisation phase. Such a solution follows the overarching concept of comprehensive data integration (Measure M9, p. 152) and creates transparency in production. The actual real data can be continuously compared with predicted resource consumption. From this, specific automated action strategies can be developed.

9.3.2 HW2: Linking operational indicators with natural resources

Recommendation for action

Depending on the industry and the process used by a company, different tangible operational resources and, consequently, natural resources are influenced. Companies that want to make a meaningful contribution to resource conservation through their actions must be equipped to determine the contribution of operational measures to different natural resources and, if appropriate, to the respective indicators of the sustainability strategy.

Therefore, factors to translate operational indicators into sustainability strategy indicators should be identified, and their measurement should be integrated into Industry 4.0 solutions. To this end, collaboration between research and I4.0 enablers is considered to be particularly important for the development of a consistent methodology. Tools can then be implemented according to this methodology.

Potential for saving natural resources

Companies see resource efficiency as part of their sustainability policy and are motivated to orient themselves to social objectives within the framework of environmental and sustainability management. So far, however, there is a lack of tools that companies can use to quantify the relationship between operational measures and their impact on natural resources and the relevant indicators of German sustainability policy. Different areas of research must be addressed in order to make this possible: As groundwork, a (further) development of the methodology for a consistent indicator is required, which identifies relevant operational parameters and links them to the methodology of German sustainability indicators with reference to natural resources. Furthermore, basic data have to be created that are not known to the companies themselves. These involve issues such as material content of ICT hardware that can be incorporated into the operational-level tools mentioned above.

Appropriate tools can take advantage of the future capabilities of Industry 4.0, which enables automated capture and intelligent analysis of data. Thus, the relevant operational parameters for natural resources can be collected and evaluated automatically for the representation of resource consumption. Such tools will enable companies to strategically align the development of measures and corporate environmental policy with societal objectives, and to contribute as effectively as possible to reducing the overall consumption of natural resources.

9.3.3 HW3: Knowledge transfer through the development of practical applications from technology demonstrators

Recommendation for action

The prototypical implementation of technology demonstrators is a major component of many research projects, since a practical implementation of a system can yield numerous insights, both positive and negative. Possible environments for the implementation of technology demonstrators can be, for instance, the test centres sponsored jointly by the BMWi and the BMBF, or the training facilities for energy and resource efficiency at various technical universities.

The participating scientific institutions have the role of transferring the resulting findings (best practice examples) in terms of increasing resource efficiency under Industry 4.0 into practical applications and applying them in cooperation with industry (transfer of research in companies).

Potential for saving natural resources

The practical applications and technology demonstrators presented in this study demonstrate the potential of digital transformation to save resources and serve as a model for companies to carry out their own technological implementations.

9.3.4 HW4: Identification of material flows and their synergies

Recommendation for action

The digital transformation can create value networks and cross-company processes, e.g., in industrial parks (“industrial symbiosis”).

Science should help to identify suitable material flows and their synergies with each other. In the process, science will examine to what extent this can be achieved with digital platforms (or with the help of digital tools). The same applies to energy efficiency measures, such as waste heat recovery. Technological and ICT-related issues also need to be addressed to clarify the economical and legal aspects of cooperation models and data accessibility/data security issues.

Potential for saving natural resources

There are many possibilities for resource savings. The consideration of several companies in a value network enables the bundling of synergy potentials for the recycling, cascade use, “piggyback strategies” or comparable possibilities. The data exchange here may include, for example, information about the generated waste that can be used by other companies as raw materials. Another possibility would be the sharing of data on expected energy consumption (peak load regulation) or waste heat in the network so that the process planning in the individual companies can be adapted accordingly.

Possible fields of applications are, e.g., zero-emission commercial areas or industrial symbiosis projects.

9.3.5 HW5: Consideration of resource efficiency in product development and in recycling

Recommendation for action

In product development, large companies have long been working with life cycle assessments in order to optimise products in terms of environmental aspects. However, the amount of work involved in determining the resource consumption of products is very high and often impossible for SMEs.

Continuous data integration capabilities should be further developed to allow a direct assessment of the resource efficiency of product variants during the product development process. Furthermore, research is needed in order to use information from a digital life cycle dossier throughout the value chain and especially in the disposal phase.

Potential for saving natural resources

The action recommendation is integrated into the concept of comprehensive data integration M9 (p. 152). Moreover, in combination with measure M2 (p. 142), the use of a digital product memory allows the use of production data for product-related information. Further research is necessary here to manage this information, e.g., in a “digital life cycle dossier”, and thus make knowledge from the entire value chain available while integrating the utilisation and disposal phases. Companies – including SMEs – can then use this knowledge to optimise the use of resources across the entire value chain. It is also conceivable to generate product information that the consumer can access via a mobile device.

Completely new possibilities can also be opened up for the recycling sector, if material information is available for future recovery or re-use of individual functional components: Options such as deposit systems or leasing of products can be supported here. The area of the “circular economy”, as an example of future opportunities for Industry 4.0, was discussed in an expert workshop as part of a recent study for the German Council for Sustainable Development[262].

New possibilities are also opening up for designing custom products offered by the digital transformation: A comparison of the predicted resource consumption of different designs of a product already during the development makes it possible to select the (probably) most resource-efficient variant. Real resource consumption of the product during the utilisation phase by the customer can then be compared with the resource consumption forecast stored in the digital object memory of the product M2 (p. 142). These considerations, in turn, can be fed back into the development phase and thus feed into a possible overhaul of the product.

9.3.6 HW6: Investigation of the digital transformation on the macroeconomic and social level

Recommendation for action

The transformation of processes and production lines through digital transformation can lead to completely new value chains and business models. The social impact cannot be sufficiently recognised from the corporate perspective combined with the restriction to direct repercussions on suppliers or customers.

It is considered useful to investigate the effects of digital transformation in companies on a macroeconomic and societal level in future research work. A broad interdisciplinary perspective (e.g. effects on consumer behaviour) should be addressed in this context.

Potential for saving natural resources

Influences of the digital transformation on system innovations in completely new value chains and on social processes can have extensive consequences with impacts on resource consumption. In particular, this raises the question of possible rebound effects, if, e.g., products can be made more efficient and thus cheaper through digitisation. Such questions require further research,

[262] Cf. RNE (2016).

including the development of new methodological approaches to identify the overall economic impact of aggregated resource use, and to associate this with social implications.

10 SUMMARY AND CONCLUSION

The present study examines the implementation of digital transformation measures to increase resource efficiency. The focus is on SMEs in the manufacturing sector.

In accordance with the motivation and objectives formulated in **Chapter 1**, this study is particularly concerned with investigating the relationships between digital transformation and resource efficiency, identifying the state of development and deducing recommendations for action for SMEs, politics and science.

The necessary basics and concepts are defined and explained in **Chapter 2**. In addition to the definition of Industry 4.0, the need for a holistic approach to the consideration of resource efficiency is also highlighted here. In the context of Industry 4.0, this topic has been examined so far with two approaches: Individual studies look at the expected macroeconomic potential and draw conclusions for the entire economy or for specific sectors. Other studies examine individual companies or concrete production technologies in the form of case studies for the savings of operational resources, usually without considering expenditures (e.g. power consumption of digital technologies) or influences outside of the enterprise. A holistic view, however, requires the inclusion of the savings as well as the consumptions that are achieved by Industry 4.0 solutions while taking into account the entire life cycle.

In order to examine the impact of the digital transformation on the resource efficiency of industrial processes and technologies, **Chapter 3** presents the status and perspectives of Industry 4.0 regarding relevant technologies. Existing standardisation bodies and architectural models are also briefly described. Decisive factors for the effects of digitalisation measures on resource efficiency are the system framework considered and the level at which the measures are implemented (process, company, value chain).

Chapter 4 presents practical solutions and application cases, where the technologies presented in Chapter 3 can already make a concrete contribution to saving resources in companies. The examples include individual solutions at the process level, as well as system solutions at the enterprise level, within the supply chain as well as the entire life cycle of a product. Furthermore, existing research and development activities are presented. The measures and application examples show that positive effects of the digital transformation on the efficient use of resources are already recognisable. The fluid developmental stages of this transformation make it even more difficult at the present time to point out direct connections between the use of technological components or solutions that promote Industry 4.0 and a direct increase in resource efficiency. Interactions are therefore only partially identified. However, the described information, automation and control measures for holistic Industry 4.0 solutions in practice can enable a more transparent and efficient use of resources.

Chapter 5 presents the approach of the scientific investigation of resource efficiency potentials through Industry 4.0 solutions. To determine resource efficiency potential, a methodological procedure based on the VDI Guideline 4800 is developed, taking into account the standards for life cycle assessment (DIN EN ISO 14040/44). This methodology shows how the savings of natural resources can be determined from operational parameters (e.g. fuel consumption or energy input), taking into account ICT expenses. For a better classification, eleven measures of digital transformation and five levels of digital maturity of a company are defined.

Chapter 6 identifies relevant sectors and presents a selection of ten case studies based on these. The electrical and plastics industries, as well as machine manufacture, are the industries with the highest relevance within the manufacturing sector in terms of the criteria considered. The selected companies are all based in the four federal states that act as co-sponsors of the study. The transferability of the results is given by the general account of the measures of the digital transformation within the study.

In **Chapter 7**, the selected case studies are qualitatively examined according to the methodology developed in Chapter 5. Two case studies are also subjected to a quantitative assessment.

The investigated case studies show that digital transformation measures have an influence on **operational resources savings**: In addition to the reduction of electricity consumption and the use of materials, these also include, for example, the avoidance or reduction of waste, the (intra-company) transport savings, the reduction of defective parts and thus rejects, and the savings from required storage space. Only a few companies could give estimates of the extent of the savings. These are in most cases in a **range of up to 25%**, and above that in only a few cases. There are also indications from the case studies that further specific effects may exist at the company level, which, however, would require a deeper examination of the individual framework conditions of each specific production chain. It should also be noted that in many cases, the companies investigated also made savings on intangible operational resources, e.g. capital. Measures of the digital transformation have **an impact on resources** and thus the consumption of natural resources: On the one hand, by the use of additional hardware components and the associated higher raw material consumption; and on the other hand, by the power consumption of the use of hardware and software.

In order to determine resource efficiency potentials, first **sample calculations** are performed by combining information from the case studies with data from literature and statistics. The results show that the ratio of savings to cost can vary widely in terms of the net savings generated by a measure. It should generally be noted that the type of material has a major influence on the assessment. This is because the expected savings in natural resources are higher for those materials that require a great deal of energy and raw materials for their production.

The following **conclusion from the case studies** can be drawn:

- Measures of digital transformation are implemented in companies in the form of different practical applications. They contribute to saving operational resources, especially in the form of reduced error rates, scrap and waste volumes, and saved electrical energy.

- The resource-related expenditures of digitalisation, in particular, the volume requirements for specific hardware and the associated power consumption, are so far largely unknown at both the in-house and the off-site level.

- Initial sample calculations based on the developed methodology show that the consideration of expenses can reduce the net savings of measures and that they must be included for the determination of resource efficiency.

The companies surveyed attach great importance to the digital transformation for the future, even if they are presently only in the early stages of digital transformation. The main motivation is to improve competitiveness.

The increase in resource efficiency is seen in most cases as a side effect of using digital technologies that are associated with, e.g., process automation. **Therefore, there is no systematic control of success to track and quantify resource savings**. The companies lack the information basis on their operational resource consumption, which they could use to derive targeted measures. **The systematic measurement and evaluation of resource consumption are therefore an essential prerequisite for the identification and implementation of all resource efficiency potentials within the company.**

In **Chapter 8**, the eleven measures validated in practical applications were presented in detail: **M1:** Networking of sensors and actuators, **M2:** Use of digital object memories, **M3:** Decentralised control, **M4:** Measures for staff support and assistance, **M5:** Dynamically cooperating systems and modularisation, **M6:** Introduction and use of positioning and localisation systems, **M7:** Condition monitoring, **M8:** Predictive maintenance, **M9:** Comprehensive data integration, **M10**: Virtual product development and **M11**: Cloud computing. This figure is intended to assist SMEs in selecting suitable measures. These form the basis of practical applications of digital transformation, whose targeted use can save resources.

In **Chapter 9**, based on the results of the study, recommendations for action are developed for the industry, particularly SMEs in the manufacturing sector, politics and science.

Three recommendations for action are addressed to **SMEs**:

- **HK1:** Companies are advised to select the measures described in Chapter 8 depending on the state of digitalisation. In the first step, **a readiness check** is proposed to determine the company's own degree of maturity of the digitalisation. Based on the result, **measures matching the degree of maturity and their stages of development can be** selected.

- **HK2:** The possibilities of digitalisation for plant and process-related **collection and analysis of data on operational resource consumption** should be the focus of companies **as a strategic task** in the future. Corresponding information bases are essential for the identification of resource efficiency potentials and the success controlling. The resource self-assessment tool (ReSET) developed in the study offers assistance in this regard.

- **HK3: Digital transformation** should be seen to a greater extent **as an opportunity to increase resource efficiency**. Companies should develop a targeted strategy for this purpose.

From the results of the study, **three recommendations for politics** have been prepared:

- **HP1:** Most of the SMEs are at the beginning of the digital transformation. This creates the opportunity for resource efficiencies to be taken into account right from the start and integrated into Industry 4.0 solutions. For this purpose, a uniform advisory service is required. An important step towards this would be the **networking of existing advisory services for SMEs** with the aim of developing joint advisory services. Such a proposal can be seen in the implementation of a **Resource Efficiency 4.0 Toolkit**.

- **HP2:** Measures of digitalisation contribute to the increase in energy consumption, especially through the use of in-house ICT hardware and software and through the use of services on the Internet. Politicians should promote the **development of labels / labelling systems** to indicate the energy consumption for ICT manufacturers or Internet service providers, as consumption data for resource efficiency is often not available.

- **HP3:** Research promotion should integrate **specific issues for the realisation of the potentials of digital transformation to increase resource efficiency** into their programmes as outlined in the recommendations for action for science.

The following **six recommendations of action for science** are derived from the study results:

- **HW1: Central methods for data acquisition, evaluation and presentation** through artificial intelligence technologies (self-learning algorithms) should be further explored and further developed with respect to supporting resource efficiency. With the help of digital object memories and comprehensive data integration, specific automated action strategies can be developed.

- **HW2:** Optimising operational processes to reduce the consumption of natural resources requires establishing relationships between operational metrics and corresponding indicators. To achieve this, the development **of a consistent methodology and the development of tools in collaboration between research and Industry 4.0 enablers** are particularly important.

- **HW3:** With the goal of improving the transfer of research results to companies, the **findings on resource efficiency gained in technology demonstrators** should be **applied in cooperation with industry** within the framework of Industry 4.0. The participating scientific institutions play an essential role here.

- **HW4:** The digital transformation can support **industrial symbioses within value networks**. For this, research is needed with regard to the identification of suitable material flows, the development of synergies and the implementation with digital platforms and digital tools. In doing so, **economical and legal aspects** must also be clarified.

- **HW5:** The workload for forecasting resource consumption in the development phase of future products is very high and often impossible for SMEs. Therefore, possibilities of digitalisation, such as comprehensive data integration, should be further developed with the goal of an **efficient assessment of resource consumption already in the product development process**. This also applies to the effect of product variants on recycling.

- **HW6:** The study of the societal effects of digitalisation must go beyond the company level and also include consequences on consumer behaviour. From an interdisciplinary perspective, future research should, in particular, address **questions relating to consumer and user behaviour that can only be predicted to a limited extent**.

Businesses, including those in the SME sector, see digital transformation as a key topic of the future. At the same time, the topic of resource efficiency is present in many companies in the form of energy and environmental goals in corporate policy. However, a strategically oriented connection of both areas hardly ever takes place in practice.

The study shows that companies can implement measures at various stages of the digital transformation that enable operational resource savings, for example, in the form of avoidance of misproduction and waste or reduction of electricity consumption. At the same time, it is clear that the basic data for identifying such potential savings within companies are currently still insufficient. The chances of digitalisation lie precisely in changing this with the new information technology possibilities: The goal must be for companies to have specific data on resource consumption available at the company level as a strategic planning basis in the future. Consulting and training services could help companies build operational information and controlling tools using digitalisation technologies.

Overall, it can be said that realising the opportunities of Industry 4.0 to reduce societal consumption of natural resources is a very complex challenge. This should be tackled strategically in the next few years and through networking of different spheres of action as well as efforts at the levels of businesses, politics and science.

11 GLOSSARY

Term	Specification
Actuator	"Technical element that changes the physical world according to the specifications of information processing with the increase in auxiliary energy. By using manufacturer-specific interfaces, the system is also able to forward the information obtained to humans or to mechatronic systems."[263]
Artificial Intelligence	Artificial intelligence is a branch of information technology. It seeks to create methods that enable a computer to solve tasks that, when solved by humans, require intelligence.[264]
Big Data	Big Data is data that is too big or too complex to be evaluated by traditional processes or methods of data processing and is subject to rapid, continuous change. This goes hand in hand with an inversion of IT priorities: Since the data is too big, the programme now has to be flexible and mobile.[265]
Business model	"A business model is a simplified representation of a business and an abstraction of how its business and value-added operate to ultimately make money. It describes organisation, cost structures, financial flows, value chain and products of a company in a compact way. The process of defining a business model is part of the business strategy."[266]
Cyber Physical Production System (CPPS)	"Application of cyber-physical systems in the manufacturing industry and thus the ability to consistently consider the product, means of production and production

[263] Lucke, D. et al. (2014), p. 43 et seq.
[264] Cf. Gabler Wirtschaftslexikon (2017).
[265] Cf. Lichtblau, K. et al. (2015), p. 66.
[266] Promotorengruppe Kommunikation (2013), p. 85.

Term	Specification
	systems, taking into account changing and changed processes."[267]
Cyber Physical Systems (CPS)	"CPS consist of embedded systems, production, logistics, engineering, coordination and management processes as well as Internet services, which use sensors to directly record physical data and act on physical processes via actuators, are interconnected via digital networks, use data and services available worldwide, and have multimodal man-machine interfaces. Cyber-Physical Systems are open socio-technical systems that enable a range of novel features, services and features."[268]
Data security	"The protection of data and services in (digital) systems against misuse, such as unauthorised access, alteration or destruction. The objectives of security measures against attacks are to increase confidentiality (restricting access to data and services to certain technical/human users), integrity (correctness/soundness of data and correct functioning of services) and availability (measure of a system's ability to perform a function in a given amount of time). Depending on the specific technical system and the data and services it contains, security from attacks forms both the basis for data protection (information privacy), i.e. the protection of individuals against infringement of their personal rights in relation to personal data, as well as a measure for know-how-protection (intellectual property rights protection)."[269]
Digital factory	"Digital factory is the generic term for a comprehensive network of digital models, methods and tools – including simulation and three-dimensional visualisation –

[267] Promotorengruppe Kommunikation (2013), p. 84.
[268] Promotorengruppe Kommunikation (2013), p. 84.
[269] Promotorengruppe Kommunikation (2013), p. 51.

Term	Specification
	which are integrated through integrated data management. Its goal is to carry out the holistic planning, evaluation and continuous improvement of all essential structures, processes and resources of the real factory in connection with the product."[270]
Digital transformation	Transition to the integrated networking of all economic sectors and adaptation of the stakeholders to the new circumstances. Decisions in networked systems include data exchange and analysis, calculation and evaluation of options, and initiation of actions and consequences. These new tools will fundamentally change many established business models and value processes.[271]
Digitsation	Digitisatio makes it possible for the richest data to be available anytime, anywhere and at acceptable cost, in the quality and quantity needed.[272]
Embedded system	"Hardware and software components integrated into a comprehensive system to implement system-specific features."[273]
Engineering, System Engineering	"Interdisciplinary approach to design, systematically develop and implement complex technical systems as needed (e.g. Industrial Engineering: Relies on specialised knowledge and skills in mathematics, physics, computer science, social sciences, etc., along with the principles and methods of technical analysis and design to implement or improve integrated systems of people, technical components, materials, and information, as well as equipment and energy)."[274]

[270] VDI 4499 Part 1: 2008-02, p. 3.
[271] Cf. Roland Berger Strategy Consultants (2015).
[272] Cf. Computer Sciences Corporation (2015).
[273] Promotorengruppe Kommunikation (2013), p. 85.
[274] Promotorengruppe Kommunikation (2013), p. 85.

Term	Specification
Enterprise Resource Planning Systems (ERP systems)	ERP systems offer integrated software solutions for administration as well as planning and controlling of operational value creation processes and thus form the basis for information processing in the company. The focus of current ERP systems is on the expansion of functionalities by integrating various functionally specialised systems. This is done using the term APS (Advanced Planning and Scheduling).[275]
Fieldbus system	"Wired serial bus systems with which sensors (field devices) and actuators are connected to control devices and host computers, via which the data exchange between the components takes place."[276]
Functional unit (FU)	"Quantified performance of a product system for use as a reference unit."[277] The FU is an instrument for quantifying the benefit for use as a unit for comparison, which is fundamental to a resource efficiency assessment.
Horizontal integration	Horizontal integration of a value chain comprises the networking of all machines, devices and employees at a company level and links them within the value chain, i.e., between companies. Horizontal integration via value networks, which goes beyond the individual factory location, also enables the creation of dynamic value networks.
Human Machine Interface (HMI)	"Components of an interactive system (software and hardware) that provide information and controls necessary for the user to complete a specific work task with the interactive system."[278]

[275] Cf. Lichtblau, K. et al. (2015), p. 66.
[276] Lucke, D. et al. (2014), p. 43 et seq.
[277] Cf. DIN EN ISO 14040: 2009-11, p. 10.
[278] Lucke, D. et al. (2014), p. 43 et seq.

Term	Specification
Industry	"Business sector for the extraction of raw materials, the preparation and processing of raw materials and semi-finished products, the manufacture of end products as well as for the assembly and repair work. Industrial enterprises are mainly characterised by mechanical production, extensive division of labour and mass production usually in larger premises. In economic statistics, the industry in the narrower sense is also referred to as the manufacturing sector, and the industrial sector differs to the agricultural sector and the service sector as a producing sector."[279]
Industry 4.0	"The term 'Industry 4.0' stands for the fourth industrial revolution, a new step in organising and managing the entire value chain across the life cycle of products. This cycle is geared to the increasingly individualised customer desires and extends from the idea, the order to the development and production, the delivery of a product to the end customer to recycling, including related services. The basis for this is the availability of all relevant information in real-time through networking of all entities involved in the value process as well as the ability to derive the optimum value flow from the data at any given time. The combination of people, objects and systems creates cross-company value networks that are dynamic, real-time optimised and self-organising, which can be optimised based on different criteria such as costs, availability and resource consumption."[280]

[279] Duden Wirtschaft (2016).
[280] VDI/VDE-Gesellschaft (2014), p. 2.

Term	Specification
Industrial symbiosis	"Industrial symbiosis is a form of brokering to bring companies together in innovative collaborations, finding ways to use the waste from one as the raw materials for another."[281]
Information and communication technologies (ICT)	Information and communication technologies encompass all those technical devices and equipment that can digitally convert, process, store and transmit information of all kinds.[282]
Internet of Things	"Linking of physical objects (things) to a virtual representation on the Internet or an Internet-like structure. The automatic identification via RFID is a possible form of the Internet of Things, while sensor and actuator technology can be used to extend the functionality to include the acquisition of states or the execution of actions."[283]
Internet of Things (IoT)	s. Internet of Things
Interoperability	"Ability for active, targeted collaboration of different components, systems, techniques or organisations."[284]
IP capability	"Internet Protocol (IP) is a network protocol and is the foundation of the Internet. An IP-capable device can be addressed in the network and thus reached."[285]
Life cycle	Successive and interconnected stages of a product system from raw material extraction or raw material production to final disposal.[286]

[281] FISSAC (no date).
[282] Cf. Lichtblau, K. et al. (2015), p. 67.
[283] Promotorengruppe Kommunikation (2013), p. 85.
[284] Fraunhofer IOSB (2016c), keyword: Interoperability.
[285] Lucke, D. et al. (2014), p. 43 et seq.
[286] Cf. DIN EN ISO 14040: 2009-11, p. 8.

Term	Specification
Machine-2-Machine Communication (M2M)	Machine-2-Machine Communication (M2M) stands for the automated exchange of information between technical systems with each other or with a central station. Typical applications are remote monitoring and control. M2M links information and communication technology and forms the so-called “Internet of Things”.[287]
Manufacturing Execution Systems (MES)	“A Manufacturing Execution System is an IT system operating in the technical production process. It stands out against similarly effective systems for enterprise planning (so-called Enterprise Resource Planning Systems) by the direct connection to the distributed systems of the process control system and allows the navigation, guidance, control and monitoring of the production in real-time. This includes classic data acquisition and processing such as production data acquisition, machine data collection and personnel data logging, but also all other processes that have a real-time impact on the technical production process.”[288]
Manufacturing industry	Manufacturing industry “covers the mechanical, physical or chemical transformation of substances or parts into goods. These are raw materials or primary materials from agriculture, forestry, fisheries and fish farming, mining, quarrying, as well as products of this sector itself. The substantial change or re-processing of goods is generally regarded as the manufacture of goods and assigned to the manufacturing sector.”[289]
Operating materials	Operating materials include substances that make production possible in the first place, such as power, compressed air etc.

[287] Cf. Lichtblau, K. et al. (2015), p. 67.
[288] Promotorengruppe Kommunikation (2013), p. 85.
[289] Statistisches Bundesamt (2008), p. 186.

Term	Specification
Plug and Produce	"Create, modify, or resolve interoperation between two or more people with minimal effort."[290]
Practical application	It describes the combination or manifestation of different measures found in the real enterprise.
Primary raw material	"Raw material extracted from nature."[291]
Product Life Cycle Management (PLM)	"Concept/strategy for managing product-related information about the life cycle of a product. PLM goes beyond managing production data and describes a broader process that includes not only development and design, but also purchasing, manufacturing, assembly, service, and marketing. PLM considers the pursuit for a digital manufacturing or factory in the context of the product life cycle. In this context, Internet technology plays an essential role as a communication platform."[292]
Product system	"All the processes associated with a product throughout its entire life cycle, as well as the associated material and energetic flows."[293]
Process	Corresponds in this sense to the "process module" of DIN EN ISO 14040, which represents the smallest component of a life cycle assessment and for which input and output data have to be quantified.[294]
Radio Frequency Identification (RFID)	Radio Frequency Identification Tags are identification and information carriers for modern automatic data acquisition via invisible and contactless data transmission based on electronic waves that even go through physical

[290] Fraunhofer IOSB (2016b).
[291] UBA (2012), p. 17.
[292] Blien R. (2011).
[293] UBA (2012), p. 19.
[294] Cf. DIN EN ISO 14040: 2009-11, p. 10.

Term	Specification
	barriers. Potentials can be found in production, for material tracking, order picking, warehousing, transport, goods receipt and dispatch, stock control or shelf optimisation.[295]
Raw materials, critical	"Economically important raw materials whose supply is considered critical."[296]
Real-time	In information and communication technology, real-time is the time in which a given action takes place. The action can take place simultaneously for the viewer, without appreciable time delay, for the technical equipment it runs according to predetermined and guaranteed delay times.[297]
Real-time capability	"Real-time capability is an essential requirement that many industrial applications demand. If a system can react correctly and in good time to all occurring events under all operating conditions, then it is real-time capable. If a communication system satisfies the qualitative and time requirements for the data exchange of the components of a specific application, it is real-time capable in relation to this application."[298]
Real-time requirement	The real-time requirement is a guiding concept in Industry 4.0 that refers to the decision support from data analytics, where data must be available at the time it is needed. This does not necessarily have to be "now" without any time delay.[299]
Resource consumption	"Form of resource use that transforms natural resources in such a way that they are no longer able to be re-used

[295] Cf. Syska, A. (2006).
[296] EU (2014).
[297] ITWissen (2016).
[298] Virtuelle Software-Engineering-Kompetenzzentrum (2016).
[299] Cf. Lichtblau, K. et al. (2015), p. 66.

Term	Specification
	(e.g. loss of biodiversity, soil erosion, combustion or dissipative losses). The term energy consumption is also used in this sense."[300]
Resource, natural	Resource that is part of nature. These include renewable and non-renewable primary raw materials, physical space (area), environmental media (water, soil, air), flowing resources (e.g. geothermal, wind, tidal and solar energy) and biodiversity. It is irrelevant whether the resources serve as sources for the production of products or as natural sinks to absorb emissions (water, soil, air).[301]
Resource, operational, intangible	Other operational resources (i.e. without material resources), e.g. time or costs.
Resource, operational, tangible	Operational resources that have a direct impact on the consumption of natural resources. These include materials (including raw materials and water), energy, emissions, waste and area.
Resource, operational	From the point of view of a company, resources can be regarded as consumables, supplies, capital, personnel, know-how and time. An operational resource can be tangible or intangible.
Resource efficiency	"ratio between a certain benefit or result and the resource use required for it"[302]
Resource Efficiency Potential (REP)	The REP refers to the potential increase in resource efficiency through digital transformation for a particular benefit or outcome compared to a reference state defined for that benefit or outcome.

[300] UBA (2012), p. 26.
[301] Cf. UBA (2012).
[302] VDI 4800 Part 1: 2016-02, p. 9.

Term	Specification
Resource input	"Use of [natural] resources in processes."[303]
Secondary raw material	"Raw material extracted from waste or production residues. It can replace primary raw materials."[304]
Sensor	"Technical component that can quantify certain physical or chemical properties qualitatively or as a measured quantity."[305]
Services	"In information technology, the bundling of technical functions of a programme; in networks, the provision of a programme on a server; and in telecommunications, the transmission of data. The term 'service' is used synonymously. Services refer to the provision of services to meet a defined need."[306]
Small and Medium-Sized Enterprises (SMEs)	SMEs are defined in EU Recommendation 2003/361. According to this, a company is considered to be an SME if it has no more than 249 employees and has an annual turnover of no more than EUR 50 million or a balance sheet total of up to EUR 43 million.[307] In addition, in this study, the term SME also refers to locations in sectors that are characterised by SMEs and correspond to SMEs. This refers to companies in certain locations that, by virtue of being part of a larger company, are no longer SMEs, as defined by the EU, but have an SME-like structure (staff, turnover, balance sheet total).
System boundary	Set of criteria for determining which process modules are part of a product system.[308]

[303] UBA (2012), p. 24.
[304] UBA (2012), p. 33.
[305] Promotorengruppe Kommunikation (2013), p. 86.
[306] Promotorengruppe Kommunikation (2013), p. 85.
[307] Cf. EU (2003).
[308] Cf. DIN EN ISO 14040: 2009-11, p. 12.

Term	Specification
System innovations	"System innovations are technologically-based innovations that can translate into economically viable and socially acceptable products or services, provided it is possible to integrate the necessary components and competenciesinto functioning system architectures. They transcend organisational and technical boundaries, are characterised by an effective cooperation between different stakeholders along the value creation processes, and enable business models that can only be successful if they are accepted by the relevant players and stakeholders."[309]
System solution	"Service that includes (especially in the field of IT) the complete required system components and their integration to solve a problem or fulfil a customer request."[310]
System frame	s. System boundary
Vertical integration	Vertical integration stands for the complete networking between all company levels.[311] It therefore consists of networking production resources, e.g., automation devices or services with each other.
Value chain	"Model of value added as a sequential, graded sequence of activities or processes, from development and production to marketing and services."[312]
Value network	"Decentralised polycentric network characterised by complex interrelationships between autonomous, legally independent stakeholders. It forms an interest group from potential value-added partners who interact

[309] Institut für Innovation und Technik (2016).
[310] Duden (2016).
[311] Cf. Malanowski, N. and Brandt, J. C. (2014), p. 6.
[312] Promotorengruppe Kommunikation (2013), p. 87.

Term	Specification
	in joint processes as needed. The emergence of value networks is geared towards sustainable economical added value. Special features of value networks are called Business Webs."[313]
Value creation process	"Process that creates a valuable commodity for customers."[314]
Waste	"Mobile objects, materials that the owner discards, wants to discard or must discard."[315]

[313] Promotorengruppe Kommunikation (2013), p. 87.

[314] Fraunhofer IOSB (2016a) [Keyword: Value creation process].

[315] § 3 para. 1 KrWG.

BIBLIOGRAPHY

Abele, L.; Ollinger, L.; Heck, I. und Kleinsteuber, M. (2012): A Decentralized Resource Monitoring System Using Structural, Context and Process Information. In: Trends in Intelligent Robotics, Automation and Manufacturing. Intelligent Robotics, Automation and Manufacturing (IRAM-2012), 28 - 30. November, Kuala Lumpur, Malaysia, Vol. 330. Springer Verlag, Berlin, Heidelberg, Communications in Compute, p. 371-378.

acatech – Deutsche Akademie der Technikwissenschaften und Arbeitskreis Smart Service Welt (2015): Smart Service Welt – Umsetzungsempfehlungen für das Zukunftsprojekt Internetbasierte Dienste für die Wirtschaft- Abschlussbericht. acatech – Deutsche Akademie der Technikwissenschaften, Berlin.

Anderl, R. (2015): Leitfaden Industrie 4.0. Orientierungshilfe zur Einführung in den Mittelstand, VDMA-Verlag, Frankfurt am Main.

Andrae, A. S. G. (2012): Comparative Micro Life Cycle Assessment of Physical and Virtual Desktops in a Cloud Computing Network with Consequential, Efficiency, and Rebound Considerations. Journal of Green engineering, Vol. 3, p. 193 – 218.

Andrae, A. S. G. und Andersen, O. (2010): Life cycle assessments of consumer electronics — are they consistent? [online]. International Journal of Life Cycle Assessment, 8. Jul. 2010 [retrieved on 4 February 2017], available at: www.researchgate.net/publication/224777494_Life_cycle_assessments_of_consumer_electronics-are_they_consistent_Int_J_Life_Cycle_Assess

Apple (2009): iMac Environmental Report [online]. 3. März 2009. [retrieved on 4 February 2017], available at: www.apple.com/environment/reports/docs/iMac-20-inch-Environmental-Report.pdf

Apple (2014): iPad Air 2 Environmental Report [online]. 16. Okt. 2014. [retrieved on 20 February 2017], available at: images.apple.com/environment/pdf/products/archive/2014/iPadAir2_PER_oct2014.pdf

BDEW (2015): Entwicklung der Energieversorgung 2014 [online]. BDEW Bundesverband der Energie- und Wasserwirtschaft e.V., Berlin, 10. März 2015 [retrieved on 14 February 2017], available at: www.bdew.de/internet.nsf/id/0CDCAA69F51E56CFC1257E0C0047C7E3/$file/Entwicklung_der_Energieversorgung_2014.pdf

Behrendt, S. und Erdmann, L. (2010): Querschnittstechnologien - Innovationssprünge für Ressourceneffizienz – Eine Explorationsstudie. Institut für Zukunftsstudien und Technologiebewertung; VDI Zentrum Ressourceneffizienz GmbH, Berlin.

Bischoff, J. (2015): Erschließen der Potenziale der Anwendung von ‚Industrie 4.0' im Mittelstand. agiplan GmbH; Fraunhofer IML; ZENIT GmbH, Mülheim an der Ruhr.

Blien R. (2011): Stichwort: Produktlebenszyklusmanagement. [online]. CAD-Glossar [retrieved on 21 June 2017], vavailable at: www.blien.de/ralf/cad/db/plm.htm

BMBF (2013): Zukunftsbild Industrie 4.0. Bundesministerium für Bildung und Forschung, Bonn, auch verfügbar als PDF unter: www.bmbf.de/pub/Zukunftsbild_Industrie_4.0.pdf

BMF (2000): AfA-Tabelle für die allgemein verwendbaren Anlagegüter („AV"). Bundesministerium der Finanzen, also available as PDF at: www.bundesfinanzministerium.de/Content/DE/Standardartikel/Themen/Steuern/Weitere_Steuerthemen/Betriebspruefung/AfA-Tabellen/2000-12-15-afa-103.pdf?__blob=publicationFile&v=1

BMUB (2016a): Deutsches Ressourceneffizienzprogramm II – Programm zur nachhaltigen Nutzung und zum Schutz der natürlichen Ressourcen. Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit (BMUB), Berlin.

BMUB (2016b): Kurzinfo Ressourceneffizienz [online]. Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit (BMUB) [retrieved on 3 February 2017], available at: www.bmub.bund.de/themen/wirtschaft-produkte-ressourcen-tourismus/ressourceneffizienz/kurzinfo/

BMWi (2010): Energieeffizienz – Made in Germany – Energieeffizienz im Bereich Industrie, Gebäudeanwendungen und Verkehr. Bundesministerium für Wirtschaft und Technologie (BMWi), Berlin.

BMWi (2015a): Industrie 4.0 -Volks- und betriebswirtschaftliche Faktoren für den Standort Deutschland – Eine Studie im Rahmen der Begleitforschung zum Technologieprogramm AUTONOMIK für Industrie 4.0. 1st edition, Bundesministerium für Wirtschaft und Energie (BMWi), Berlin.

BMWi (2015b): Entwicklung des IKT-bedingten Strombedarfs in Deutschland – Abschlussbericht [online]. Bundesministerium für Wirtschaft und Energie [retrieved on 13 February 2017], available at: www.bmwi.de/Redaktion/DE/Downloads/E/entwicklung-des-ikt-bedingten-strombedarfs-in-deutschland-abschlussbericht.pdf?__blob=publicationFile&v=3

BMWi (2015c): Industrie 4.0 und digitale Wirtschaft. [online] Bundesministerium für Wirtschaft und Energie (BMWi), Berlin, [retrieved on 3 February 2017], available at: www.bmwi.de/Redaktion/DE/Publikationen/Industrie/industrie-4-0-und-digitale-wirtschaft.pdf?__blob=publicationFile&v=3

Bonvoisin, J.; Lelah, A.; Mathieux, F. und Brissaud, D. (2012): An environmental assessment method for wireless sensor networks. Int. J. of LCA. Volume 33, September 2012, S. 145 – 154.

Bonvoisin, J.; Lelah, A.; Mathieux, F. und Brissaud, D. (2014): An integrated method for environmental assessment and ecodesign of ICT-based optimization services. Int. J. of LCA, 68, Januar 2014, S. 144 – 154.

Bryzek, J. (2014): Trillion Sensors: Foundation for Abundance, Exponential Organizations, Internet of Everything and mHealth [online]. Sensor Magazin, Mai 2014, volume 5 [retrieved on 20 February 2017], available at: www.sensormagazin.de/dateien/smonline/redaktion/fachartikel/fachartikel2_sm5_14.pdf

Bundesregierung (2016): Deutsche Nachhaltigkeitsstrategie- Neuauflage 2016. Eversfrank Berlin GmbH, Berlin.

Büscher, C. und Schippl, J. (2013): Die Transformation der Energieversorgung: Einheit und Differenz soziotechnischer Systeme. TATuP Nr. 2, 22. Jahrgang, Karlsruhe.

Cisco (2015): The Internet of Everything is the New Economy [online]. Cisco letztes Update, 29. Sep. 2015 [retrieved on 20 February 2017], available at: www.cisco.com/c/en/us/solutions/collateral/enterprise/cisco-on-cisco/Cisco_IT_Trends_IoE_Is_the_New_Economy.html

Computer Sciences Corporation (2015): Digitale Agenda 2020. 1st edition, Computer Sciences Corporation (CSC).

Daiyue, H.; Chao, L. und Puel G. (2015): Spatial Environmental Balance to Information and Communication Technology products in different regions of China by using LCA [online]. Journal of Cleaner Production 91, p. 128 – 135.

Deutscher Bundestag (2011): Energieeffizienz bei Breitbandtechnologien [online]. Deutscher Bundestag, 26. Okt. 2011, Drucksache 17/7472 [retrieved on 3 February 2017], available at: dipbt.bundestag.de/dip21/btd/17/074/1707472.pdf

DIHK (2015): Wirtschaft 4.0: Große Chancen, viel zu tun- Das IHK-Unternehmensbarometer zur Digitalisierung. Deutscher Industrie- und Handelskammertag (DIHK), Berlin.

DIN (2015a): Industrie 4.0: ISO richtet Strategiegruppe ein [online]. Deutsches Institut für Normung e. V (DIN), 14. Juli 2015 [retrieved on 27 April 2017], available at: www.din.de/de/forschung-und-innovation/industrie4-0/industrie-4-0-iso-richtet-strategiegruppe-ein-66482

DIN (2015b): Deutsche Normungs-Roadmap Industrie 4.0. Version 2, DIN Deutsches Institut für Normung e. V.; DKE Deutsche Kommission Elektrotechnik Elektronik Informationstechnik in DIN und VDE, Berlin.

DIN EN ISO 14040:2009-11: DIN Deutsches Institut für Normung e. V. Umweltmanagement - Ökobilanz - Grundsätze und Rahmenbedingungen (ISO 14040:2006). Beuth Verlag GmbH, Berlin.

Dückert, E.; Schäfer, L.; Schneider, R. und Wahren, S. (2015): Analytische Untersuchung zur Ressourceneffizienz im verarbeitenden Gewerbe. VDI Zentrum Ressourceneffizienz GmbH, Berlin.

Duden (2016): Stichwort: Systemlösung [online]. Hrsg. Verlags Bibliographisches Institut GmbH [retrieved on 21 February 2016], available at: www.duden.de/rechtschreibung/Systemloesung

Duden Wirtschaft (2016): Duden Wirtschaft von A bis Z: Grundlagenwissen für Schule und Studium, Beruf und Alltag. 6. Aufl., Lizenzausgabe Bonn, Bundeszentrale für politische Bildung, Bibliographisches Institut Mannheim, 2016.

EBAM (2015): Ökodesign / Energielabel [online]. Bundesanstalt für Materialforschung und -prüfung (EBAM) [retrieved on 7 April 2017], available at: www.ebpg.bam.de/de/richtlinie/

Ecoinvent (2016a): Name des Datensatzes: single-Si wafer production, for electronics | single-Si wafer, for electronics | cut-off, U – RER.

Ecoinvent (2016b): Name des Datensatzes: operation, computer, desktop, with liquid crystal display, active mode | operation, computer, desktop, with liquid crystal display, active mode | APOS, U – Europe without Switzerland.

Ecoinvent (2016c): Name des Datensatzes: paper production, woodfree, coated, at integrated mill | paper, woodfree, coated | APOS, U – RER.

EIDOdata GmbH i.G. (kein Datum): Die EIDOdata-Software und welcher Nutzen daraus gezogen werden kann? [online]. EIDOdata GmbH i.G [retrieved on 4 April 2017], available at: www.eidodata.de/produkte

eLife (2017): Ständig unter Strom: So viel verbraucht das Internet [online]. eLife Vattenfall [retrieved on 4 February 2017], available at: elife.vattenfall.de/trend/energieverbrauch-internet/

Emec, S.; Stock, T.; Bilge, P.; Tufinkgi, P.; Kaden, C. und Seliger, G. (2013): Analyse von Potenzialen der Material- und Energieeffizienz in ausgewählten Branchen der Metallverarbeitenden Industrie. VDI Zentrum Ressourceneffizienz GmbH, Berlin.

EU (2003): Empfehlung der Kommission vom 6. Mai 2003 betreffend die Definition der Kleinstunternehmen sowie der kleinen und mittleren Unternehmen (2003/361/EG (2003)). Europäische Kommission, 20. Mai 2003.

EU (2005): Thematische Strategie für eine nachhaltige Nutzung natürlicher Ressourcen. Kommission der Europäischen Gemeinschaften, Brüssel.

EU (2008): METADTATA Statistische Systematik der Wirtschaftszweige in der Europäischen Gemeinschaft. Rev. 2., Hrsg. European Commission [retrieved on 23 February 2016], available at: ec.europa.eu/eurostat/ramon/nomenclatures/index.cfm?TargetUrl=LST_NOM_DTL&StrNom=NACE_REV2&StrLanguageCode=DE

EU (2009): Richtlinie 2009/125/EG des Europäischen Parlaments und des Rates vom 21. Oktober 2009 zur Schaffung eines Rahmens für die Festlegung von Anforderungen an die umweltgerechte Gestaltung energieverbrauchsrelevanter Produkte), Amtsblatt der Europäischen Union.

EU (2014): Große Herausforderung für die Industrie der EU: 20 kritische Rohstoffe (Pressemitteilung) [online]. [retrieved on 29 March 2017], available at: europa.eu/rapid/press-release_IP-14-599_de.htm

EU (2015a): Preparatory study for implementing measures of the Ecodesign Directive 2009/125/EC - DG ENTR Lot 9 - Enterprise servers and data equipment. Task 5: Environment & Economics. Final Report, Jul. 2015 [online]. Bio by Deloitte, Fraunhofer IZM; Europäische Kommission.

EU (2015b): Preparatory study for implementing measures of the Ecodesign Directive 2009/125/EC - DG ENTR Lot 9 - Enterprise servers and data equipment. Task 3: User. Final Report, Jul. 2015 [online]. Bio by Deloitte; Fraunhofer IZM; Europäische Kommission.

Fichter, K. (2007): Zukunftsmarkt Energieeffiziente Rechenzentren. Umweltbundesamt (UBA), Dessau-Roßlau.

FISSAC (kein Datum): Was ist industrielle Symbiose? [online]. Fostering Industrial Symbiosis for a Sustainable Resource Intensive Industry across the extended Construction Value Chain (FISSAC) [retrieved on 7 April 2017], available at: fissacproject.eu/de/was-ist-industrielle-symbiose/

Forschungskuratorium Maschinenbau (2016): Effizienzfabrik. Innovationsplattform für die Produktion [online]. Forschungskuratorium Maschinenbau e.V. im VDMA [retrieved on 15 June 2016], available at: www.effizienzfabrik.de/de/

Fraunhofer IOSB (2016a): FA7.21 Begriffe - Allgemein [online]. Hrsg. Fraunhofer IOSB [retrieved on 21 February 2016], available at: i40.iosb.fraunhofer.de/FA7.21%20Begriffe%20-%20Allgemein

Fraunhofer IOSB (2016b): FA7.21 Begriffe - Industrie 4.0 [online]. Hrsg. Fraunhofer IOSB [retrieved on 21 June 2016], available at: i40.iosb.fraunhofer.de/FA7.21%20Begriffe%20-%20Industrie%204.0

Fraunhofer IOSB (2016c): FA7.21 Begriffe - IKT [online]. Hrsg. Fraunhofer IOSB [retrieved on 21 June 2016], available at: i40.iosb.fraunhofer.de/FA7.21%20Begriffe%20-%20IKT

Fraunhofer IPA (2016): Forschungsprojekt - Die Ultraeffizienzfabrik im urbanen Umfeld [online]. Fraunhofer IPA [retrieved on 10 June 2016], available at: www.ipa.fraunhofer.de/ultraeffizienzfabrik0.html

Fraunhofer IPA und Dr. Wieselhuber & Partner GmbH (2015): Geschäftsmodell-Innovation durch Industrie 4.0 - Chancen und Risiken für den Maschinen- und Anlagenbau. Dr. Wieselhuber & Partner GmbH, München.

Fraunhofer-Gesellschaft (2014): Leitprojekt E³-Produktion - Projektbroschüre. Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e.V., München.

Gabler Wirtschaftslexikon (2017): Stichwort: Künstliche Intelligenz (KI) [online]. In: Gabler Wirtschaftslexikon, Springer Gabler Verlag [retrieved on 4 April 2017], available at: wirtschaftslexikon.gabler.de/Archiv/74650/kuenstliche-intelligenz-ki-v12.html

GE (2014): Industrial Internet Insights report for 2015 [online]. General Electric Company [retrieved on 20 February 2017], available at: www.ge.com/digital/sites/default/files/industrial-internet-insights-report.pdf

GHGP (2013): GHG Protocol Product Life Cycle Accounting and Reporting Standard ICT Sector Guidance, Chapter 7, Software, Draft v2.9 [online. Green House Gas Protocol (GHGP), [retrieved on 22 February 2017], available at: www.ghgprotocol.org/files/ghgp/GHGP-ICT-Software-v2-9-26JAN2013.pdf

Google (2009): Powering a Google search [online]. Google, 11. Jan. 2010 [retrieved on 2 March 2017], available at: googl-blog.blogspot.de/2009/01/powering-google-search.html

Handelsblatt (2016): Digitale Produktion: Papier war gestern [online]. Handelsblatt GmbH, 15. Dez. 2016 [retrieved on 7 March 2017], available at: unternehmen.handelsblatt.com/digitale-produktion.html

Hellge, V. (2017): Readiness Check Digitalisierung - Ergebnisse der Online-Selbstbewertung Januar 2017 [online]. Kaiserslautern [retrieved on 14 March 2017], available at: kompetenzzentrum-kaiserslautern.digital/wordpress/wp-content/uploads/2017/03/Kurzbericht_Ergebnisse_Readiness_Check_Januar2017.pdf

Hering, E. und Schönfelder G. (2012): Sensoren in Wissenschaft und Technik. Funktionsweise und Einsatzgebiete. Hering, E. und Schönfelder G., Vieweg und Teubner, Wiesbaden, 2012.

Hilty, L. M.; Lohmann, W; Behrendt, S; Evers-Wölk, M.; Fichter, K. und Hintemann, R. (2015): Grüne Software. Schlussbericht zum Vorhaben: Ermittlung und Erschließung von Umweltschutzpotenzialen der Informations- und Kommunikationstechnik (Green IT). Studie im Auftrag des Umweltbundesamtes, Berlin.

Hirschnitz-Garbers, M.; Srebotnjak, T.; Gradmann, A.; Lutter, S. und Giljum, S. (2014): Further Development of Material and Raw Material Input Indicators – Methodological Discussion and Approaches for Consistent Data Sets. Input paper for expert workshop. 26. May 2014.

Hischier, R.; Achachlouei, A. M. und Hilty, L. M. (2014): Evaluating the sustainability of electronic media: Strategies for life cycle inventory data collection and their implications for LCA results. Environmental Modelling & Software, Vol. 56, p. 27 – 36.

HMWVL (2011): Praxisleitfaden Energieeffizienz in der Produktion. 2nd edition, HA Hessen Agentur GmbH, Wiesbaden.

HPE (2017): HPE ProLiant MicroServer Gen8 [online]. Hewlett-Packard GmbH [retrieved on 5 January 2017], available at: www.hpe.com/de/de/product-catalog/servers/proliant-servers/pip.hpe-proliant-microserver-gen8.5379860.html

IHK NRW (2015): Digitale Transformation und Industrie 4.0 - Unternehmen und Forschungseinrichtungen aus NRW zeigen Best Practice. IHK Innovationsberater, die Industrie- und Handelskammern in Nordrhein-Westfalen e.V. (IHK), Düsseldorf.

IHK Nürnberg für Mittelfranken (2012): Druckluft effizient nutzen. Praxisleitfaden für Energieeffizienz und Kosteneinsparung der Industrie- und Handelskammer Nürnberg für Mittelfranken [online]. Industrie- und Handelskammer Nürnberg für Mittelfranken [retrieved on 6 March 2017], available at: www.ihk-nuernberg.de/de/media/PDF/Innovation-Umwelt/Energie/leitfaden-druckluft-effizient-nutzen.pdf

Institut für Innovation und Technik (2016): Systeminnovationen [online]. Hrsg. Institut für Innovation und Technik (iit) [retrieved on 21 June 2016], available at: www.iit-berlin.de/de/themenfelder/systeminnovationen

ITWissen (2016): Stichwort: Echtzeit [online]. Hrsg. ITWissen [retrieved on 21 June 2016], available at: www.itwissen.info/definition/lexikon/Echtzeit-RT-realtime.html

Knüpffer, G. (2016): Wie man mit dem digitalen Schatten die Produktion vorhersehen kann [online]. Produktion, 10. März 2016 [retrieved on 28 April 2017], available at: www.produktion.de/nachrichten/unternehmen-maerkte/wie-man-mit-dem-digitalen-schatten-die-produktion-vorhersehen-kann-117.html

KrWG (2012): Gesetz zur Förderung der Kreislaufwirtschaft und Sicherung der umweltverträglichen Bewirtschaftung von Abfällen (Kreislaufwirtschaftsgesetz - KrWG).

LaCie (2017): LaCie 8big Rack Thunderbolt™ 2 [online]. Seagate Technology GmbH [retrieved on 6 March 2017], available at: www.lacie.com/de/de/professional/rackmount/8big-rack-thunderbolt-2/

Lichtblau, K.; Stich, V.; Bertenrath, R.; Blum, M.; Bleider, M.; Millack, A.; Schmitt, K.; Schmitz, E. und Schröter, M. (2015): Industrie 4.0-Readiness. IMPULS-Stiftung für den Maschinenbau, den Anlagenbau und die Informationstechnik, Frankfurt.

Loskyll, M.; Heck, I.; Schlick, J. und Schwarz, M. (2012): Context-based Orchestration for Control of Resource-efficient Manufacturing Processes. Future Internet, MDPI, Vol. 4, Nr. 3, p. 737 – 761.

Lucke, D.; Görzig, D; Kacir, M.; Volkmann, J.; Haist, C.; Sachsenmaier, M. und Rentschler, H. (2014): Strukturstudie „Industrie 4.0 für Baden-Württemberg“ - Baden-Württemberg auf dem Weg zu Industrie 4.0. Stuttgart.

Malanowski, N. und Brandt, J. C. (2014): Innovations- und Effizienzsprünge in der chemischen Industrie? Wirkungen und Herausforderungen von Industrie 4.0 und Co. Druckerei Bonifatius, Paderborn.

Marscheider-Weidemann, F.; Langkau, S.; Hummen, T.; Erdmann, L.; Espinoza, L. T.; Angerer, G.; Marwede, M. und Benecke S. (2016): Rohstoffe für Zukunftstechnologien 2016. Auftragsstudie. 28 DERA Rohstoffinformationen. Deutsche Rohstoffagentur (DERA), Berlin.

Matsuno, Y.; Takahashi, K.I. und Tsuda, M. (2007): Eco-Efficiency for Information and Communications Technology (ICT): The State of Knowledge in Japan [online]. In: Proceedings of the 2007 IEEE International Symposium on Electronics and the Environment, [retrieved on 4 February 2017], available at: ieeexplore.ieee.org/document/4222845/

McKinsey Digital (2015): Industry 4.0 - How to navigate digitization of the manufacturing sector. McKinsey & Company, München.

Merkel, W. (2010): Systemtransformation - Eine Einführung in die Theorie und Empirie der Transformationsforschung, 2nd, revised and extended edition, VS Verlag für Sozialwissenschaften, Wiesbaden.

Meyer, L. und Reker, J. (2016): Industrie 4.0 im Mittelstand. Deloitte, also available as PDF at: www2.deloitte.com/content/dam/Deloitte/de/Documents/Mittelstand/industrie-4-0-mittelstand-komplett-safe.pdf

Mittelstand 4.0-Kompetenzzentrum Kaiserslautern (kein Datum): Readiness Check – Möchten Sie wissen, wie weit Ihr Unternehmen digitalisiert ist? [online] Mittelstand 4.0-Kompetenzzentrum Kaiserslautern [retrieved on 20 April 2017], available at: komzkl.de/wordpress/readiness-check/

Neligan, A. und Schmitz, E. (2017): Digitale Strategien für mehr Materialeffizienz in der Industrie - Ergebnisse aus dem IW-Zukunftspanel. Institut der deutschen Wirtschaft Köln, IW-Report 3/2017, Köln.

Plass, C. (2015): Industrie 4.0 als Chance begreifen. Unity AG, Berlin.

Plattform Industrie 4.0 (2013): Umsetzungsempfehlungen für das Zukunftsprojekt Industrie 4.0 – Deutschlands Zukunft als Produktionsstandort sichern - Abschlussbericht des Arbeitskreises Industrie 4.0. Frankfurt am Main.

Plattform Industrie 4.0 (2015): Umsetzungsstrategie Industrie 4.0 - Ergebnisbericht. Bitkom; VDMA; ZVEI, Berlin.

Plattform Industrie 4.0 (2016): Deutsche Industrie startet Normungsinitiative für Industrie 4.0 [online]. BMWi, 21.April 2016 [retrieved on 27 April 2017], available at:
www.plattform-i40.de/I40/Redaktion/DE/Pressemitteilungen/2016/2016-04-21-deutsche-industrie-startet-normungsinitiative-fuer-i40.html

Plattform Industrie 4.0 (2017): Normen & Standards – Eine gemeinsame Sprache für Industrie 4.0-Technologien [online]. BMWi und BMBF [retrieved on 18 January 2017], available at: www.plattform-i40.de/I40/Redaktion/DE/Standardartikel/handlungsfelder-normen-standards.html

Promotorengruppe Kommunikation (2013): Umsetzungsempfehlungen für das Zukunftsprojekt Industrie 4.0. Abschlussbericht des Arbeitskreises Industrie. Promotorengruppe Kommunikation der Forschungsunion Wirtschaft – Wissenschaft, Frankfurt.

Reuter, M. A. (2016): Digitalizing the Circular Economy - Circular Economy Engineering defined by the metallurgical Internet of Things - 2016 TMS EPD Distinguished Lecture Award. TU Bergakademie Freiberg, Freiberg.

RNE (2016): Industrie 4.0 und Nachhaltigkeit: Chancen und Risiken für die Nachhaltige Entwicklung. Rat für nachhaltige Entwicklung.

Roland Berger (2016): Die Digitalisierung in der GreenTech-Branche. Roland Berger GmbH, München.

Roland Berger Strategy Consultants (2014): Industry 4.0 - The new industrial revolution - How Europe will succeed. München.

Roland Berger Strategy Consultants (2015): Die digitale Transformation der Industrie. Was sie bedeutet. Wer gewinnt. Was jetzt zu tun ist. 1st edition, Bundesverband der Deutschen Industrie e.V. (BDI), auch verfügbar als PDF unter: bdi.eu/media/presse/publikationen/information-und-telekommunikation/Digitale_Transformation.pdf

Roth, A. (2016): Einführung und Umsetzung von Industrie 4.0 –Grundlagen, Vorgehensmodell und Use Cases aus der Praxis. Springer Verlag, Berlin, Heidelberg.

Schebek, L.; Abele, E.; Campitelli, A.; Becker, B. und Joshi, M. (2016): Praxisleitfaden: Ressourceneffizienz in der Produktion - Zerspanungsprozesse. 1st edition, Hessen Trade & Invest. GmbH, Wiesbaden, Band 17 der Schriftenreihe der Technologielinie Hessen-Umwelttech.

Schmitt, R.; Brecher, C.; Nau-Hermes, M. und Berners, T. (2015): Material- und Energieeffizienzpotenziale durch den Einsatz von Fertigungsdatenerfassung und -verarbeitung. VDI Zentrum Ressourceneffizienz GmbH, Berlin.

Schröter, M.; Lerch, C. und Jäger, A. (2011): Materialeffizienz in der Produktion: Einsparpotenziale und Verbreitung von Konzepten zur Materialeinsparung im Verarbeitenden Gewerbe. 1st edition, Fraunhofer ISI, Karlsruhe

Schröter, M.; Weißfloch, U. und Buschak, D. (2009): Energieeffizienz in der Produktion - Wunsch oder Wirklichkeit? Energieeinsparpotenziale und Verbreitungsgrad energieeffizienter Techniken. Fraunhofer-Institut für System- und Innovationsforschung ISI, Karlsruhe, Modernisierung der Produktion; Mitteilungen aus der ISI-Erhebung.

Schuh, G.; Anderl, R.; Gausemeier, J.; ten Hompel, M. und Wahlster, W. (2017): Industrie 4.0 - Maturity Index. Die digitale Transformation von Unternehmen gestalten, also available as PDF at: www.acatech.de/fileadmin/user_upload/Baumstruktur_nach_Website/Acatech/root/de/Publikationen/Projektberichte/acatech_STUDIE_Maturity_Index_WEB.pdf

Siemens Aktiengesellschaft (2015): Digitalisierung im Maschinenbau - Der digitale Zwilling [online]. Siemens AG [retrieved on 4 April 2017], available at: www.siemens.com/customer-magazine/de/home/industrie/digitalisierung-im-maschinenbau/der-digitale-zwilling.html

Söllner, R. (2014): Die wirtschaftliche Bedeutung kleiner und mittlerer Unternehmen in Deutschland. Statistisches Bundesamt, Wiesbaden, Jan. 2014, also available as PDF at: www.destatis.de/DE/Publikationen/WirtschaftStatistik/UnternehmenGewerbeanzeigen/BedeutungKleinerMittlererUnternehmen_12014.pdf?__blob=publicationFile

Statistisches Bundesamt (2008): Klassifikation der Wirtschaftszweige mit Erläuterungen. Statistisches Bundesamt (Destatis), Wiesbaden.

Statistisches Bundesamt (2015a): Umwelt - Abfallentsorgung 2013. korrigierte Version des 10. August 2015, Statistisches Bundesamt (Destatis), Wiesbaden, Fachserie 19 volume 1.

Statistisches Bundesamt (2015b): Umweltnutzung und Wirtschaft - Tabellen zu den Umweltökonomischen Gesamtrechnungen 2015 - Teil 2: Energie. Version des 8. Dez. 2015, Statistisches Bundesamt (Destatis), Wiesbaden.

Statistisches Bundesamt (2015c): Umweltnutzung und Wirtschaft - Tabellen zu den Umweltökonomischen Gesamtrechnungen 2015 - Teil 3: Anthropogene Luftemissionen. Version des 8. Dez. 2015, Statistisches Bundesamt (Destatis), Wiesbaden.

Statistisches Bundesamt (2016a): Produzierendes Gewerbe. Kostenstruktur der Unternehmen des Verarbeitenden Gewerbes sowie des Bergbaus und der Gewinnung von Steinen und Erden 2014. Version des 03. Jun. 2016, Statistisches Bundesamt (Destatis), Wiesbaden, Fachserie 4 Reihe 4.3.

Statistisches Bundesamt (2016b): Umweltnutzung und Wirtschaft - Tabellen zu den Umweltökonomischen Gesamtrechnungen – Teil 2: Vorbericht Energie. Berichtszeitraum 1995 – 2014. Version des 14. April 2016, Statistisches Bundesamt (Destatis), Wiesbaden.

Statistisches Bundesamt (2016c): Betriebe, Tätige Personen und Umsatz des Verarbeitenden Gewerbes sowie des Bergbaus und der Gewinnung von Steinen und Erden nach Beschäftigtengrößenklassen 2015. Version des 1. Juni 2016, Statistisches Bundesamt (Destatis), Wiesbaden, Fachserie 4 Reihe 4.1.2

Statistisches Bundesamt (2016d): Umweltnutzung und Wirtschaft - Tabellen zu den Umweltökonomischen Gesamtrechnungen 2015 - Teil 4: Rohstoffe, Wassereinsatz, Abwasser, Abfall. korrigierte Version des 8. März 2016, Statistisches Bundesamt (Destatis), Wiesbaden.

Synology (2017): RackStation RS815+/RS815RP+ [online]. Synology [retrieved on 5 January 2017], available at: www.synology.com/de-de/products/RS815+#spec

Syska, A. (2006): Produktionsmanagement. Das A – Z wichtiger Methoden und Konzepte für die Produktion von heute. 1st edition, Gabler, Wiesbaden.

Tränkler, H.-R. und Reindl L. M. (2014): Sensortechnik - Handbuch für Praxis und Wissenschaft. 2nd edition, Springer Verlag, Berlin, Heidelberg.

UBA (2012): Glossar zum Ressourcenschutz [online]. Umweltbundesamt (UBA), Dessau-Roßlau [retrieved on 2 Decembre 2016], available at: www.umweltbundesamt.de/sites/default/files/medien/publikation/long/4242.pdf

UBA (2014): Energieverbrauchsrelevante-Produkte-Richtlinie/Ökodesign-Richtlinie (2009/125/EG), Energieverbrauchskennzeichnungs-Richtlinie (2010/30/EG), Übersicht über den Stand der Prozesse zur Verabschiedung von Durchführungsmaßnahmen. Umweltbundesamt, 18. Dez. 2014.

UBA (2015): Rohstoffnutzung und ihre Folgen [online]. Umweltbundesamt (UBA), Dessau-Roßlau, [retrieved on 30 March 2017] available at: www.umweltbundesamt.de/daten/rohstoffe-als-ressource/rohstoffnutzung-ihre-folgen

UBA (2016): Entwicklung der spezifischen Kohlendioxid-Emissionen des deutschen Strommix in den Jahren 1990 bis 2015. Umweltbundesamt, Dessau-Roßlau, Climate Change 26/2016, also available as PDF at: www.umweltbundesamt.de/sites/default/files/medien/378/publikationen/climate_change_26_2016_entwicklung_der_spezifischen_kohlendioxid-emissionen_des_deutschen_strommix.pdf

UBA (2017): Datenbasis zur Bewertung von Energieeffizienzmaßnahmen in der Zeitreihe 2005 – 2014 – Endbericht. Umweltbundesamt, Dessau-Roßlau, Climate Change 01/2017, also available as PDF at: www.umweltbundesamt.de/sites/default/files/medien/1968/publikationen/2017-01-09_cc_01-2017_endbericht-datenbasis-energieeffizienz.pdf

UTBW (2016): Baden-Württemberg sucht: 100 Betriebe für Ressourceneffizienz [online]. Umwelttechnik und Ressourceneffizienz Baden-Württemberg GmbH [retrieved on 10 June 2017], available at: pure-bw.de/de/100betriebe/overview

VDI 4499 Blatt 1:2008-02: Verein Deutscher Ingenieure e. V., Digitale Fabrik - Grundlagen. Beuth Verlag GmbH, Berlin.

VDI 4600: 2012-01: Verein Deutscher Ingenieure e. V., Kumulierter Energieaufwand (KEA) – Begriffe, Berechnungsmethoden. Beuth Verlag GmbH, Berlin.

VDI 4800 Blatt 1: 2016-02: Verein Deutscher Ingenieure e. V., Ressourceneffizienz - Methodische Grundlagen, Prinzipien und Strategien. Beuth Verlag GmbH, Berlin.

VDI 4800 Blatt 2: 2016-03: Verein Deutscher Ingenieure e. V., Ressourceneffizienz – Bewertung des Rohstoffaufwands [Entwurf]. Beuth Verlag GmbH, Berlin.

VDI ZRE (2014a): Perfekter Stoffkreislauf für Aluminium [online]. VDI Zentrum Ressourceneffizienz GmbH, Berlin [retrieved on 4 April 2017], available at:
www.ressource-deutschland.tv/themen/metallverarbeitung/perfekter-stoffkreislauf-fuer-aluminium/

VDI ZRE (2014b): Wettbewerbsvorteil Ressourceneffizienz - Definitionen, Grundlagen, Fakten und Beispiele. 2nd edition, VDI Zentrum Ressourceneffizienz GmbH, Berlin.

VDI ZRE (2014c): Schnell, genau und effizient mit Datenmonitoring – Ressourceneffizienz [online]. VDI Zentrum Ressourceneffizienz GmbH, Berlin [retrieved on 4 April 2017], available at:
www.youtube.com/watch?v=sNPdkFR1HT4&index=17&list=PLVS82M2ywurdlbzKZkhmGDvezoW4Qf1vB

VDI/VDE-Gesellschaft und ZVEI (2015): Referenzarchitekturmodell Industrie 4.0 (RAMI4.0)- Statusreport. Verein Deutscher Ingenieure e.V.; VDI/VDE-Gesellschaft; ZVEI –Zentralverband Elektrotechnik und Elektronikindustrie e.V., Düsseldorf.

Virtuelle Software-Engineering-Kompetenzzentrum (2016): Begriffsdefinition: Echtzeitfähigkeit, Rechtzeitigkeit, Gleichzeitigkeit, Jitter, Determinismus [online]. Hrsg. Virtuelle Software-Engineering-Kompetenzzentrum (VSEK) [retrieved on 21 June 2016], available at: www.software-kompetenz.de/servlet/is/28612/?print=true

WGP (2016): WGP-Standpunkt Industrie 4.0 [online]. Wissenschaftliche Gesellschaft für Produktionstechnik WGP e. V. (WGP), Juni 2016 [retrieved on 4 June 2016], available at: www.wgp.de/uploads/media/WGP-Standpunkt_Industrie_4-0.pdf

Wittbrodt, B. T.; Glover, A. G.; Laureto, J.; Anzalone, G. C.; Oppliger, D.; Irwin, J.L. und Pearce, J.M. (2013): Life-cycle economic analysis of distributed manufacturing with open-source 3-D printers [online]. Mechatronics, Sep. 2013, Volume 23, Issue 6, S. 713 – 726.

Yin, R. (2014): Case Study Research - Design and Methods. 5th edition, SAGE Publications, Inc., Los Angeles, ISBN 978-1-4522-425.

Zarnekow, R. und Kolbe L. M. (2013): Green IT: Erkenntnisse und Best Practices aus Fallstudien. Springer Verlag, Berlin, Heidelberg.

Zettl, E.; Hawthorne, C.; Joas, R.; Lahl, U.; Litz, B.; Zeschmar-Lahl, B. und Joas A. (2014): Analyse von Ressourceneffizienzpotenzialen in KMU der chemischen Industrie. VDI Zentrum Ressourceneffizienz GmbH, Berlin.

APPENDIX 1: CASE STUDY PORTRAITS

A1: Case study portrait C & C Bark Metalldruckguss und Formenbau GmbH

C&C Bark
Metalldruckguss und
Formenbau GmbH

Company

Already in its third generation, C & C Bark Metalldruckguss und Formenbau GmbH with its 70 employees in Schömberg near Rottweil focuses on the production of magnesium die-cast parts for various applications. The company offers the entire process chain, from support in the development and design phase to casting, surface treatment and machining. Depending on requirements, it is possible to choose between hot and cold chamber pressure die casting. In addition, cast-related processes such as punching, milling, deburring, vibratory finishing and manual deburring complete the service scope. CNC machining steps such as thread milling, machining of fits or printing on individual parts (e.g. by pad printing) are also carried out.

The company's customers include motorcycle and power tool manufacturers (such as hammer drill housings) and the optics industry. With this, a turnover of 7.5 million euros was achieved in 2015. For the C & C Bark foundry, it is particularly important to deal with sustainability and environmental issues within the scope of its possibilities and to set a good example, especially because it belongs to an industry with high emissions.

Resource efficiency

In addition to increasing effectiveness in all areas, resource efficiency at C & C Bark also plays an important role. On the one hand, the topic of material efficiency in the magnesium foundry represents an important savings lever, and on the other hand, the reduction of energy consumption, especially of the melting furnaces, is an important topic.

Thus, material circulation was reduced through the introduction of an ERP system across all production processes all the way to sales. This saves stock. Likewise, it is possible to intervene more quickly in the case of last-minute changes to the product, as each batch can now be located more easily. This in turn has positive effects on the reduction of rejects and rework. Indirectly, the material use of magnesium can be made more effective.

C & C Bark gave consideration to material savings in the direction of technological innovations. Accordingly, an innovative method for hot chamber pressure die-casting is used, which ensures a smaller sprue, thereby saving material. Thanks to the FGS (Frech Gating System) process developed in cooperation with Oskar Frech GmbH + Co. KG, 45 - 80% of the usual circulation material could be avoided. Depending on the article, C & C Bark, as co-developer of the FGS, saves about 50 g of magnesium per cast part. The lower material usage also leads to energy savings, since less material has to be melted per part. Due to contamination by oxides or release agent residues, it is not possible to melt the sprue in the foundry itself again. As a result, the sprue material and any rejects are externally recycled and melted, which in turn adds extra cost and energy consumption. The FGS process is thus more environmentally friendly than conventional hot chamber casting processes and also leads to cost savings.

In terms of energy, C & C Bark introduced a peak load management system. This queries the temperature of the crucible in the furnaces using sensors. The system then knows exactly which furnaces have reached their optimum temperature and which have not. So it can decide which furnaces need to be heated up. For this purpose, an algorithm has been developed, which prevents all furnaces from being heated up at the same time. This in turn means that a certain peak load, which determines the price basis for a whole year of operation, is not exceeded.

Even simple organisational measures, such as a more resource-efficient break scheme, have already contributed to a resource-efficient operation at C & C Bark. The fact that the employees take breaks alternately means that the machines do not have to be shut down. The re-start of the machines is eliminated, which consumes less energy and also less waste is produced, since fewer starting parts are produced.

Of course, the driving factors to implement such conversions are driven primarily by the efficiency ideas. Nevertheless, it is also important for the company, for reasons of external perception, to get away from the prejudices of foundries as “dirty, dangerous and high-emission”. Potential competitive advantages through the more efficient use of resources are also included in the considerations.

Digital transformation

In addition to its commitment to resource conservation, C & C Bark integrated a consistent ERP system in 2015. Data is collected and linked in all areas from customer order collection in sales, to production planning and control (PPS), and to storage location booking to purchasing. In addition, the ERP system is also connected via financial accounting, which promotes efficient work.

All important machine and process data are also automatically recorded via WLAN. On workshop monitors, these can be accessed at any time to draw conclusions about production. Information about machine running time, machine interruptions and causes of disruption can be evaluated in the same way as the rework rate. For data acquisition, older machines (some more than 30 years old) were converted, i.e. equipped with pulse interfaces and sensors on the doors. The capacity planning module of the ERP system automatically proposes production plans, e.g., for better machine utilisation and more appropriate use of resources, but self-optimisation of the machines is not yet possible. Although customers have not made any specific demands on C & C Bark with regard to digitalisation, the transparency of customer details is essential. Thanks to the ERP system, it is always possible to have the information on the location and quantity of parts of a batch, even if they are located off-site for coating or are already in the consignment warehouse. This traceability also brings with it some security, including when faulty parts need to be identified or for recalls. In the future, C & C Bark sees the potential of digital transformation as being able to produce faster, with more flexibility and more efficiency through greater transparency.

According to C & C Bark, the use of simulation tools would not be worthwhile as part of their work, since each casting is physically different and cannot be interfered with during the extremely short process. However, the company can imagine using new manufacturing processes in the near future – in the context of digital transformation – such as the 3D printing process. Networked sensors and actuators are also already being used by the SME. For example, a linear gripping system can remove a part in the machine and hold it in front of a camera. If this is detected as faulty via the optical sensor, it will give the actuator command “Stop”. This will ensure that the part is not further processed. As a result, energy and material can also be saved.

The main goal of the implementation of the ERP system was to reduce throughput times and increase productivity. Before the system was introduced, it was not always clear where certain parts were located, and over- or underproduction was more frequent. The production of family moulds presents a challenge when it comes to correctly capturing the parts and mapping the process through the ERP system. For example, a blank can be turned into four finished parts, i.e., an order corresponds to the four finished parts. C & C Bark is currently developing a reasonable solution for this. In addition to increasing the effectiveness, the data generated via the ERP system can also be used for the employee rating system. In this way, finer performance-oriented key figures can be mapped, and human resources can be optimally used.

Interactions between digital transformation and resource efficiency

The interaction between digital transformations and resource efficiency can be found in the area of energy management at C & C Bark. The positive correlation can be seen in the peak load management, where the automatic furnace temperature query prevents high energy consumption. Consistent data integration via the ERP system also helps to reduce material inventories. The transparency of the ERP system leads to less waste, less stock and a lower risk of overproduction. Material can be saved indirectly, in this case magnesium.

Highly specialised digitalisation, however, is easier to implement in large foundries due to the available capacities and resources, according to C & C Bark.

The SME C & C Bark is an example of how even small steps towards digitalisation can have a major impact on production and resource efficiency.

A2: Case study portrait Mader GmbH & Co. KG

MADER

Company

Based on its decades of experience, the SME expert for compressed air from Baden-Württemberg, Mader GmbH & Co. KG, offers services and products for the complete compressed air process – in compressed air supply as well as in the control and application of compressed air – from compressed air generation right up to pneumatics. At the heart of the product and service portfolio are energy-optimised compressed air and pneumatic systems, as well as a compressed air leakage app. The company, headquartered in Leinfelden-Echterdingen, was voted one of the top 3 most sustainable German SMEs in the 2015 German Sustainability Award and employs around 85 people at two locations. In the name of sustainability, Mader GmbH regularly publishes a sustainability report and is certified according to the most important management standards, including DIN EN ISO 9001: 2015, DIN EN ISO 14001: 2009 and DIN EN ISO 50001: 2011.

Resource efficiency

The company, which is very committed to sustainability measures, has already implemented a series of measures to increase resource efficiency. Starting with the **environmental and energy certifications**, for example, the entire lighting at the main site was switched to LED, and the number of computer servers was reduced by virtualisation. All measures resulted in a reduction of energy consumption of about 85% between 2011 and 2015, although energy costs are less relevant for the company. This was also the result of a corporate policy approach, namely raising the awareness of the workforce for the consumption of resources within the company, e.g., via an economical use of electricity. Each generation of apprentices also receives an energy-saving project at the site at the beginning of their activity, such as the identification of power waste. Another measure is the internal competition per app regarding fuel consumption in the field. At the top of the list of the internal measures in increasing resource efficiency is the establishment of a very innovative and resource-saving energy management concept for a newly planned company building. According to the management, the motivation for these measures lies in the company's own motivation to strengthen the credibility of the SME. The main advantages resulting from this, according to the management, include the development of unique selling points and the identification of differentiation potentials. A positive experience in the implementation of these measures is, for example, a better perception of the external corporate image through the regular publication of a sustainability report.

Mader GmbH is also active in the direction of material efficiency. Currently, in cooperation with a customer, a test is being carried out for **self-controlling effluent free manufacture and reuse** of packaging systems – plastic containers for steel cylinders. Even though the willingness on the part of the customers is limited and the economic conditions required are large order volumes, management as a whole is convinced that the SME is on the right path towards sustainability and resource efficiency.

Digital transformation

The SME is not only committed to sustainability, but is also innovatively positioned. The Innovation Management organisational unit ensures that both the product and service portfolio, as well as the internally planned and implemented measures, remain constantly efficient and state-of-the-art.

Internally, the SME uses a system for **enterprise resource planning** (ERP), and on its SharePoint server, data are stored digitally and processed both for order management as a customer request for a paperless order processing as well as for customer-specific measurements taken from pressurised air leakage. There is also digital networking with the customers, who have access to the data recorded via their mobile devices or computers around the clock by identifying the respective IP address.

In addition, the **service process** is now **digital**, with maintenance plans, service reports on the history of repairs, checklists, lists of materials and operating instructions for machines and equipment being managed in digital form, paperless and via mobile devices. The provision of information but also the recording of working hours take place independent of location, accurately and in real-time. In addition, the ERP system provides the material needed for a specific service using the digital material lists. All this saves time and resources and thus brings more efficiency into the process. The company is thus more productive and accurate. By digitalising the service process and linking the ERP system, the recorded data is automatically collected, checked and billed. The data collected includes both working hours and materials used, even during unplanned maintenance operations. As a result, the company strives for, among other things, an optimal use of internal resources. Compressed air leakages are systematically recorded by means of modern ultrasonic positioning technology.

The top of the product and service portfolio, however, is currently the **compressed air leakage app for mobile devices** that creates transparency.

It manages, quantifies and prioritises digitally the detected leakages – in terms of location, type, size, pressure loss, photos – and also provides a real-time, up-to-date and customer-specific overview of losses and wastes in terms of energy and costs, as well as prioritised repair recommendations and cost estimates. Originally developed in 2015 as a digital tool exclusively for internal employee support in the recording of compressed air leaks, the app is now being used as a supplement to the services and even as a stand-alone product. By managing and remedying the leaks with the help of the app, the compressed air losses were reduced on average by about 30 - 35%. This will also enable predictive maintenance, among other things, both in-house and on the customer's premises.

However, introducing such measures also presents challenges and disadvantages. This is mainly about the staff. A corresponding acceptance of the employees of the digitalisation measures must first be established. A more accurate and location-independent work time recording in real-time can, for example, easily cause displeasure. As a result of the digital transformation, jobs are also undergoing a shift towards the need for higher qualifications. Further training or retraining of employees is another challenge. Finding suitable professionals, especially for app development programming activities, can also be difficult. In addition, the lack of experience with potentially emerging digital business models may be a significant challenge for businesses. Connected to this is the need for clarification of other aspects, such as regarding the status of ownership of the data on the values measured on the customer's premises: Who owns the data and how long? Who has access to it and how?

The digital transformation in machine manufacture – compressed air generation – thus leads not only to increased productivity and error prevention, but also to energy savings and thus to a cost reduction, especially if the life cycle costs, e.g., from compressed air generation plants, are taken into consideration: 12% investment, 6% maintenance and 82% energy consumption. In addition, such approaches and measures may lead to digitalisation and dematerialisation of business models.

Interactions between digital transformation and resource efficiency

As the most important basis of the digital transformation, data collection at Mader GmbH is largely done with the purpose of increasing resource and energy efficiency, both within the company and among its customers. Among other things, plant-, process-, and site-specific consumptions, losses and waste are recorded in the form of digital data. Thus, a step is taken to increase resource efficiency: Creation of transparency about the compressed air system and the associated losses.

A3: Case study portrait J. Schmalz GmbH

SCHMALZ

Company

J. Schmalz GmbH is the world's leading supplier of automation, handling and clamping technology and offers customers from numerous industries innovative and efficient solutions in vacuum technology. The family-run company with more than 1,100 employees produces a wide range of products. It ranges from individual vacuum components and complete systems for gripping and clamping in automated processes to handling devices for designing ergonomic workstations. The Schmalz-developed assembly workstation "Pick-by-Shutter" was awarded the prize for the „Beste Montage-Idee 2011" (Best Assembly Idea 2011). The innovative workplace solution sustainably improves working conditions and shortens assembly, set-up and testing times. In addition to certification by environmentally relevant management standards such as DIN EN ISO 14001: 2009 and DIN EN ISO 50001: 2011, J. Schmalz GmbH regularly publishes a sustainability report. The head office of J. Schmalz GmbH in Glatten, in the Black Forest, was investigated, where more than 750 employees work.

Resource efficiency

As a family business, J. Schmalz GmbH has been driven by sustainability and resource efficiency goals for decades. As in most machine manufacture companies, material costs are very important to J. Schmalz GmbH. With that background, the company pursues several approaches to increase material efficiency. On the one hand, this is the approach of **material substitution**: The main goal here is to replace aluminium in some components with plastic in order to save both costs and weight. The latter is particularly important where these components have a mobile function in the product (e.g. on the robot arm). Lighter components thus save energy for the customer, especially during the utilisation phase. On the other hand, J. Schmalz GmbH focused on measures to save material in production. These savings were achieved through **process changes** – turning and sawing instead of milling – as well as raw material selection – use of hollow material. In total, it was thus possible to save over one tonne of plastic per year.

Another aspect concerns the **recycling of production waste**. In order to achieve a high level of recycling, recyclables are separated into more than 40 different fractions. In particular, metal waste is collected in its own containers. As a result, only dry chips are discarded, and the cooling lubricants are returned into the material cycle.

Energy efficiency is also very important to J. Schmalz GmbH. All new buildings in Glatten now have LED lighting. One of the motivations for it was to reduce the high internal heat load due to conventional lighting in combination with the very well-insulated buildings. The introduction of LED lighting has led to a 30-40% reduction in heat input from the lighting and a corresponding reduction in cooling requirements. The cooling of the building takes place, on the one hand, through night cooling, where cold outside air is sucked in via a rear rock space and blown into the building. On the other hand, concrete core activation is used to cool the ceilings with the help of the stream water. The server room is cooled with sprinkler water, which warms up the sprinkler tank. This heat is then removed via a heat pump in order to use it for processes or as ambient heating. In order to minimise energy consumption as much as possible, the sockets are automatically switched off in the office buildings after a certain time – unless employees have reported to the system that they still need electricity in the office later on. The J. Schmalz GmbH pursues the “Green IT” approach by using energy-efficient IT technology on a broad scale. For reasons of climate protection, the family-owned company has been relying for decades on its own generation of energy from renewable energy sources. Available for the generation: 1.1 MW photovoltaic systems, 2.1 MW wind turbines, a 32 kW hydroelectric power plant and a wood chip heating system. The power required in excess of that which is generated and used by the company itself is sourced externally in a CO_2-neutral manner. In the context of energy and environmental management systems, J. Schmalz GmbH introduced a separate tool for the calculation of the life cycle assessment and the CO_2 footprint for the systematic consideration of the climate and environment-relevant measures. In addition, the renewable energy fed into the grid from the company’s own systems reduces CO_2 emissions to a larger amount than those caused by the company. In this respect, J. Schmalz GmbH has a negative CO_2 balance and thus a “CO_2 credit”, which is included in the CO_2 footprint of the products.

The in-house measures in the area of sustainability are also used for public exposure. This helps communication on the sustainability of the products, which can be more resource- and energy-saving in their utilisation phase and are characterised by their high recyclability.

Digital transformation

The digital transformation is being pursued by J. Schmalz GmbH in different directions. On the one hand, it concerns the **design of the products**, so they can be integrated into a digital industrial production environment with CPS. This basically leads to completely new requirements for the products: They must be able to capture data and provide it to the world of Industry 4.0. Exact customer requirements are based on the compatibility of the data supplied by Schmalz products so that they can be further processed in the customer’s systems. For instance, J. Schmalz GmbH produces vacuum generators equipped with smart and communication capabilities. These are able to collect and reprocess energy consumption data during operation. For example, a new generation of sensors that can be identified via Near Field Communication technology (NFC technology) can thus enable mobile devices to access the digital image of the devices. These so-called “smart field devices” are thus in principle “CPS at the level of the field devices”. They offer clear advantages, e.g. faster and cheaper maintenance. In addition, the family-owned company is committed to **improving data exchange in in-house production processes**. This involves combining the idea of lean production with the support of digital tools, e.g., for energy management and interaction with customers.

For this purpose, machine and process data are collected and processed via various systems. For instance, processing centres are equipped with software for condition monitoring, whereby any fault data can then be evaluated directly by the machine suppliers to optimise their maintenance work.

On most machines, the overall equipment effectiveness (OEE) is determined and failure data, operating hours and rejects are recorded. These and many other metrics, such as the status of orders and the degree of fulfilment per day are recorded digitally, displayed, communicated and further processed. The leading enterprise resource planning (ERP) system is very modular. It also covers the supply chain management (SCM), and Schmalz also uses the so-called “Vendor Managed Inventory”.

The **supplier and customer relationships** are also included in digitalisation. Customers can check current availability online. In addition, some vendors are always informed about the current material requirements via a webcam that constantly monitors a classic Kanban system. At J. Schmalz GmbH, a high proportion of jobs and orders to suppliers is now automatically triggered by only scanning barcodes on crates. In this context, customer requirements – especially those from key customers – are aligned to the compatibility of these ordering systems with their own systems. The management of customer and warehouse orders regarding delivery times is automatically updated and optimised every half hour. There is also the possibility to intervene manually, for example, machines that only partially process the material can continue to be used to reduce set-up times as well as resources.

The entire **storage strategy** of the operation is optimised via simulation. The aim is to achieve the highest possible “picking number” in the warehouse. This is possible because the Warehouse Management System (WMS) has continuous control over the pallet warehouse as well as the fully automated small parts warehouse. The latter is also automatically energetically load-optimised. Storage and retrieval systems are automatically prevented from accelerating at the same time. The energy recovered from braking movements is also used for lifting movements or fed into the grid. The new lathes in the company also have this system.

During the construction of a new production hall at J. Schmalz GmbH, the production in the assembly areas was switched from preferential series production to **single-part production (One Piece Flow)** in a successive three-year process. The goals were to make processes faster and more customer-oriented, to reduce inventory and to minimise rejects. An example of this is an order-controlled, individually configurable production line of a so-called area gripper.

Before the conversion, this gripper was manufactured in a standardised way and then stored. This led to high inventories, long storage and delivery times and waste of materials.

The gripper can now be manufactured in more than a million possible variants according to the specific requirements of the customer. The mould images of the foam parts are automatically transferred as CAD files to the cutting machine, which then cuts the specific foam mould overnight. This customised production was combined with the smart replenishment logistics system (Kanban system). Overall, this more flexible production and storage leads to an almost complete elimination of inventory, a sustainable increase in material efficiency and a significant reduction in process costs and delivery times for highly customised products in small batch sizes.

The family-run enterprise also developed the “**Pick-by-shutter**” **assembly workstation**, where numerous variants of a vacuum generator can be assembled more effectively from individual parts. The now partially automated workstation is equipped with small doors that open or close automatically depending on the product variant. This principle prevents incorrect component removal and thus reduces the reject rate.

J. Schmalz GmbH also uses **new manufacturing processes**, such as the 3D printing of plastic parts. This happens both in prototype construction and for some customer projects, where parts are produced in the 3D printing process for customer-specific solutions.

Overall, the family business estimates that the steps taken to date in digital transformation have increased material efficiency, production flexibility and product quality, and reduced lead times, inventories and manufacturing costs.

For J. Schmalz GmbH, the greatest challenges and obstacles to the digital transformation are the initial effort required to implement them and the original scepticism of the employees, as the success of these measures can never be foreseen. In some cases, the noise level has been proven to be the only drawback due to the presence of production machines in the assembly area during the conversion to **single-part production (one piece flow)**.

J. Schmalz GmbH sees opportunities offered by the digital transformation both in expanding market opportunities for its own products and in improving its competitiveness through more efficient production. The market is creating a need for new products and services in that the company's own products are located right where the data for digitalised production is generated.

The company from the Black Forest also sees a great opportunity in further improving internal processes, making them consistent and standardising them. In production itself, the aim is to fulfill customer requirements even better by offering custom products in the long term. It is important to strive for an optimal use of resources by using the available data from production.

Schmalz investigated exactly this data usage in a pilot project to determine who uses this data and how – a question of security and profitability.

Further potential in the company was identified in reconciling its own energy requirements with the fluctuating supply of the markets. Demand-side management (DSM) can be extended to e.g., avoid peak loads, for which the price is "punitive". Thus, when new peak loads occur at J. Schmalz GmbH, loads are already being automatically switched off. In order to drive an energy course in line with the electricity market prices, e.g., heat and electricity are generated at night – where possible – to consume them during the day. Participation in virtual power plants and the associated networking and transparency also offer potentials that the company still wants to exploit. Digitalisation will play a crucial role here.

Interactions between digital transformation and resource efficiency

As described, the digitalisation measures of J. Schmalz GmbH are aimed on the one hand at the functions of products for the customer, and on the other hand at increasing energy and material efficiency at the site, e.g., in production. Accordingly, effects on resource efficiency can also be expected from the customer: For instance, J. Schmalz GmbH produces vacuum generators equipped with smart and communication capabilities that collect data on energy use during operation and process it in such a way that it is globally available. Customers have completely new options for monitoring energy consumption and designing efficiency measures.

Within the investigated site, effects on resource efficiency can be placed in different areas:

- Better utilisation of the warehouse is achieved by optimising the storage strategy through simulation. Indirectly, this leads to a delay in the expansion of the warehouse to include new rack aisles. This saves both space and resources for construction.

- More recently, the company has increasingly used digital tools to monitor material usage. The integrated Kanban system enables a streamlined and efficient material flow. This makes it possible to track which part of the material used ends up in the product.

- The introduction of an energy management system, coupled with the collection and evaluation of resource-relevant data in production, has led to a significant increase in energy efficiency at the Glatten site.

Another step that Schmalz is taking is expanding its own life cycle assessment tool to calculate CO_2-relevant data in order to enable the acquisition of sustainability indicators in the design and to produce even more resource-efficient products.

These engineering synergies are generally not fully exploited in machine manufacture, according to company representatives. The systematisation of material efficiency is strongly related to the use of digital tools. Starting with the design, better comparability of product designs should be given on the basis of automatically collected sustainability metrics to enable variant optimisation. Systems that evaluate such metrics are still in their infancy. For example, the question arises as to what is more material-efficient or more efficient overall: Die-cast aluminium, plastic injection moulding or additive manufacturing? What has the lowest CO_2 impact?

Such sustainability indicators could also effectively accompany technology benchmarks. According to J. Schmalz GmbH, digital tools must be developed for this, and life cycle costs and the life cycle load of materials and energy must be given greater focus.

A4: Case study portrait MAINCOR Rohrsysteme GmbH & Co. KG

MAINCOR

Company

The SME Maincor Rohrsysteme GmbH & Co. KG (short: Maincor) with sites in Schweinfurt and Knetzgau (Bavaria) produces plastic pipe systems for a wide variety of applications. The company belongs to the plastics industry and is divided into the two business units Pipe Systems Building Services (heating & plumbing, electrical & ventilation) and Pipe Systems Industry (industrial applications). The product spectrum ranges from pipes for the automotive, manufacturing and white goods industries to heating, electrical, ventilation and sanitary systems to plastic surface refinement in the nanostructure sector. Maincor has a total of 210 employees at its two sites. In 2016, the company generated annual sales of 43 million euros and thus achieved an increase in sales of 6 million euros compared to 2015.

Resource efficiency

The company has extensive experience from implementing resource efficiency projects. In addition to the research project "Energy-efficient Extrusion" with the aim of creating more energy-efficient extrusion processes, one example is the introduction of an energy management system in accordance with DIN EN ISO 50001. When the system was introduced, energy flows were measured at various points in the company; the results were compared with the state of the art, and action measures were derived from them. By implementing the derived measures, process-specific savings of 30-35% of energy and costs, as well as quality improvement, were achieved. The economic potential in the area of energy efficiency lies in a reduction of specific energy consumption by 25% in the area of production. In the area of material efficiency, the company has introduced measures and programmes to reduce scrap and waste in the production of pipe systems. Any rejects and waste are recycled as much as possible. However, the company reports that there is currently no purchase market for high-grade plastic residuals. High accuracies can be achieved by using modern machinery, and thus production can be carried out within the manufacturing tolerance in a resource-saving manner. An example of this is a heating pipe. The applicable tolerance of ± 0.3 mm can be improved by the accuracy of the system to ± 0.05 mm, resulting in material and energy savings.

For the production and packaging waste resulting from the production of the plastic pipes, a recycling strategy has been defined, which provides for the reuse of these materials.

Digital transformation

Maincor's predominant data landscape currently consists of two systems: The ERP system for resource, supplies and material planning, and the WMS for stock management. At the machine level, different systems exist for the recording of operating data and quality characteristics. The introduction of an MES or a system for production planning and control is in the planning phase (PPS).

In particular, the horizontal networking of supply chains is, from the company's point of view, an important step in the direction of digital transformation. In addition to the targeted digitalisation of their own processes, the integration of the customer, e.g. through the possibility of a custom design of heating systems, is important to the company. Networking and the exchange of data with suppliers are also given high priority. Suppliers are currently granted access to the WMS, including up-to-date warehouse capacity and inventory, to improve delivery management. With regard to the digitalisation of their own production, there are already siloed solutions for the collection and evaluation of data, however, the data pool situation can still be described as heterogeneous. This is demonstrated by the fact that fault data and their causes are documented manually, but quality characteristics and machine operating data are recorded digitally. In addition, there are no system standards for data acquisition and analysis at the machine level, which is why existing data pools are still insufficiently evaluated.

In the course of digitalisation, customers should be enabled to customise systems and view their availabilities online, among other things. At present, systems are being developed together with the customer in a sharepoint solution. In addition, networking at the plant, process and production level should be further advanced so that systems and processes can be coordinated and resource efficiency can be increased. For this purpose, the basic requirements have already been met and first pilot implementation planned.

In contrast, in the process optimisation area, in 2015, a digital product memory in the form of a WMS including optical object identification using manual operating devices was implemented. The system stores object-relevant data based on chaotic storage and is to be adapted to the production of Maincor. A side effect of the measure is the increase in efficiency in the warehouse through accelerated storage and retrieval processes and the reduction of written documents. The implementation of the measure has hitherto been smooth and is consistently rated as positive. The optimisation of warehousing is rated particularly positively for the value chain of the company. Despite a reduction in staff, a 25% higher throughput was achieved at the same time. Measures are planned in the future for networking through additional sensors and also actuators in order to expand the product memory. Through homogeneous data integration and usage, this will enable not only the implementation of Condition Monitoring but also Predictive Analytics with Predictive Maintenance.

Interactions between digital transformation and resource efficiency

The interactions between digital transformation and resource efficiency are viewed positively by Maincor. While digitalisation often requires a one-time effort in the implementation of applications and data collection and evaluation efforts, this is offset by the increased availability of information. This will help to better plan and control energy efficiency and material efficiency measures. The introduction of a digital product memory has improved the efficiency of intralogistics processes, resulting not only in lower energy consumption but also lower warehousing space requirements.

A5: Case study portrait Sensitec GmbH

Company

The company Sensitec is an SME specialising in the development and production of sensors. The company was founded in 1999 and has belonged to the Körber Group since 2013, which acquired Sensitec in its entirety at the end of 2015. It has a total of 145 employees, of whom about 60 work in Mainz. The other location is in Lahnau near Wetzlar. The product portfolio mainly includes magneto-resistive sensors, which can measure quantities such as travel, angle, current and magnetic fields. About one-third of the produced goods are sold to the automotive industry, while the remaining two-thirds are supplied to other industries. Sensitec's sensors, in turn, enable the digitalisation of products and the production of other companies.

Resource efficiency

Since January 2015, the company has been producing exclusively with green electricity. In addition, the company has developed a new energy system that enables it to reduce its energy requirements by up to 20%. This is carried out, e.g., through the partial-automatic shutdown of individual machines or production areas, which are not needed for a certain period. This measure also leads to a significant reduction in material requirements, as certain equipment needs to be replaced less frequently.

Moreover, customers have significantly increased their awareness of resource efficiency in recent years, so changes of this nature not only serve economic purposes, but also the social image of the company. Due to a construction project, the plant at the Mainz site will soon be in the immediate vicinity of a residential area, so an environmentally friendly overall impression should prevent later conflicts with residents. Above all, by increasing resource efficiency, the company sees an opportunity to reduce costs and gain additional customers through environmentally friendly and modern production.

In addition, the company has switched to completely paper-free production over a period of less than two years. The measure for this conversion is called Sensitec "Data-On-a-Stick" (DOS), which is implemented by using data carriers that are permanently connected to the workpiece carrier for the duration of production and thus accompany the product at every step throughout the production.

Another measure is to strictly control the recycling cycle of various elements of the manufacturing process. For example, some materials are recycled in the in-house cycle, for others, such as gold, external companies are involved.

Digital transformation

The digital transformation at Sensitec is particularly important in the monitoring of process chains in production. The production facilities of both plants are cross-site networked and transmit machine and process data. This allows continuous monitoring of the data (condition monitoring) and can lead to early detection of trends, e.g. in the loss of quality of a critical equipment (predictive maintenance).

The data generated in production are recorded and processed by an MES. The MES is at the heart of production and is so important to Sensitec that it has developed a proprietary solution because the systems available on the market either do not provide the required functionality or exceed the functional and financial scope of SME production. Furthermore, measurement data is captured in quality assurance, with certain optical inspections still being performed by humans, since according to Sensitec, there is no optical sensor that outperforms the sensitivity of the human eye and the experience of its employees.

In 2011, the company conceptualised the measure of "Data-On-a-Stick" digital transformation (DOS). DOS represents a complete transition to a paperless manufacturing. Prior to their introduction, the produced wafers (silicon wafers that provide the foundation for microelectronic devices) moved through the production in workpiece carriers to which the entire documentation, such as product data, work plan and production data, were attached in paper form. In the case of production in a cleanroom, this not only leads to constant contamination, but also to high costs through the use of expensive cleanroom paper. Furthermore, it was not possible to locate a specific workpiece carrier, and in the case of a production error, the production data recorded on paper and archived had to be first digitalised manually in order to find the cause of the error. Since the conversion, paper is no longer used in production. The required data is now stored on a digital data carrier, which travels through production while firmly attached to the workpiece carrier. The data carrier logs on to the respective production station (currently still using USB, but planned in the future via wireless technology) and sends and receives the required production data. Another reason for the introduction of DOS was an increasing incidence of power outages due to plant-related construction, which was accompanied by a network outage each time. The network failure again led to a halt in production. Since the implementation of the Data-on-a-Stick measure, production can continue even in the event of data network failures. The introduction of a digital transformation measure was therefore made out of necessity. However, it has been able to accomplish the aforementioned advantages of paperless production, continuous condition monitoring, and localisation of a batch beyond pure necessity.

To date, the company has only drawn a positive conclusion from the structuring and digitalisation of its value chain. The networking of the data and the restructuring on the DOS system not only save the company money, but also time, unnecessary paths and stress for employees, e.g., through the considerably simplified troubleshooting due to the direct availability of data.

An important finding in the conversion of an existing system was that digitalisation is generally a sociotechnical task. Much of the success of DOS is attributed to the fact that the company’s employees were involved early in the transition, and the benefits of the transformation were made clear to individual employees. Without the acceptance of the employees, no technological innovation, no matter how advanced can be implemented.

A special feature of the company is that, for historical reasons, it posesses an exceptionally well-qualified IT department for an SME. This was another key success factor both in the transition to paperless production and in the development of the in-house MES.

Interactions between digital transformation and resource efficiency

Data collected by Sensitec is used to monitor processes in real-time. As a result, unused equipment is shut down and energy and resources can be saved. Furthermore, the data acquisition and evaluation allow continuous monitoring of the quality of critical equipment, so that interventions can be carried out before a threshold value is reached and a loss of quality of the product all the way to rejects can be avoided.

A6: Case study portrait Hermos AG

HERMOS

Company

Hermos AG, headquartered in Mistelgau (Bavaria), operates in the fields of automation and information processing and is a group of companies with twelve locations in Germany and four international locations in the USA, Poland, Malaysia and the United Arab Emirates. Hermos offers its customers products and services in the form of customised solutions for industry, energy, the environment and buildings. These include engineering, the manufacture of switchgear through the subsidiary Hermos Schaltanlagen GmbH, the development of software for automation and IT systems, and the provision of after-sales service. Hermos markets its own IT platforms FIS# and MATRIX for the implementation of SCADA, energy monitoring, system integration and MES. Product tracking solutions (Track & Trace) are based on self-developed RFID components and image processing. In total, Hermos AG has 200 employees, 110 of them at the Mistelgau location. In 2015, the company generated sales of 18 million euros at the company's Mistelgau location. Overall, Hermos AG posted annual sales of 25 million euros.

Resource efficiency

Together with the construction of a new hall for switchgear production, a modern energy centre was implemented at the Mistelgau location. In addition to the actual goal of self-supply of the plant, the constructed energy centre is used for technical and economic investigations of plant concepts with various energy converters, and storage and distribution systems. Using the FIS#energy software, a certified energy data management system, energy and media consumption can be recorded, displayed in graphs and subsequently evaluated. In addition to energy savings, the objectives of this measure are to increase profitability, uncover cost-saving potential and to reduce CO_2 emissions. In addition to saving energy, the IT solutions developed by Hermos save, above all, the "time" factor. As an example, the fully automated production of control cabinet cables in the desired length, with desired labelling and the provided cable lugs can be mentioned. The optimisation of production can be achieved by using the modular, scalable MATRIX application framework. With this IT software, complex, distributed production processes can be easily and efficiently managed. All these measures can save costs and make processes faster. Hermos sees the further positive effect of the digital transformation here especially on increasing competitiveness.

As part of energy efficiency improvements, various measures were taken at Hermos Schaltanlagen GmbH to reduce energy consumption. In terms of material efficiency, the fully automated production of the cable harness results in significantly less rejects and waste. Copper residues are recycled. Accumulated packaging material such as plastic and cardboard boxes are collected, separated and fed to the recycling cycle. In cooperation with component suppliers, control cabinets and individual parts at Hermos Schaltanlagen GmbH are no longer completely packaged, but delivered in crates. This considerably saved packaging material.

Digital transformation

Hermos has implemented comprehensive data integration as part of its digital transformation. This can be described by using the example of an order for a building automation system. When ordering, the customer data is transferred to the company. The Business Warehouse System (BWS) contains data on the products such as product parameters, time periods for standardised work steps, product prices, suppliers and availability. Parallel to the creation of the circuit diagrams and the software programming, all required components (e.g. control cabinet, sensors, actuators) are ordered from the respective suppliers. The required cables for the wiring of the control cabinets with the parameters type, colour, length, connection system and labelling are automatically transferred to the production from the product databases and the circuit diagrams. A production plant automatically insulates and cuts the cables according to plan and then marks them with the connection points. So the fitter will find all the information needed on the cables. The order is documented completely electronically until delivery.

This end-to-end data integration enables the company to provide highly detailed expenses and calculate project costs that are included into order negotiations with customers. A comprehensive data landscape was integrated for continuous data integration. The company uses ERP, CAE, CAD, PDA, MDE, WMS and PPS.

Data integration not only improved process transparency but also improved inventory management in the company itself. Hermos is also an enabler for digital transformation and offers automation solutions. Warehousing has been optimised for a manufacturer of semiconductor products. For example, detailed storage of intermediates, e.g., in the case of repetitive process steps, has made it possible to significantly increase the error detection rate within a process. As a result, the average processing time of a faulty product could be reduced by eliminating unnecessary process steps.

Interactions between digital transformation and resource efficiency

Hermos was able to achieve savings in energy and raw materials through continuous data integration. The company offers automation solutions and IT services in the building construction, industry and energy sectors, which generally lead to greater resource efficiency.

A7: Case study portrait Sanner GmbH

SANNER

Protecting Health.

Company

Headquartered in Bensheim, Hesse, Germany, Sanner is a global family-owned company that has been producing and developing plastic packaging and components for pharmaceutical, medical device, healthcare and nutritional supplements for over 100 years. The company generates sales of approx. 55 million euros (2014) with approximately 500 employees in Germany, China, Indonesia, Hungary and the USA. There are 220 employees at the Bensheim site, where around 30 million euros in sales are generated each year. This location is considered below.

Resource efficiency

To save costs, Sanner implements measures to increase resource efficiency in materials, energy and staff, with business representatives seeing the greatest potential in energy efficiency. Currently, the company uses an improvement management in the form of the 20-keys method as well as energy management according to DIN EN ISO 50001.

No concrete demands regarding resource efficiency are made to the company on the part of the customers. On the contrary, there are strict regulations that do not allow the use of recycled plastic or bioplastics, as the Sanner company manufactures for the pharmaceutical and medical technology industries. However, a few customers ask for wastewater volumes, energy consumption and a specification of the waste.

Energy costs are financially relevant for the company in the plant or process area (injection moulding plants), and measures are taken to reduce energy consumption. For example, when purchasing 14 new injection moulding machines, energy efficiency was taken into account. The company is also a member of the regional energy efficiency network “ETA-Plus”.

Production material is lost through rejects and waste in the processes, and measures are taken to reduce material requirements. Already in the development phase, attention is paid to a material-efficient design of the products and, e.g., geometrical changes are made to avoid rejects. A 3D printer has been in use in prototype construction since 2015. This eliminates the expensive and resource-intensive construction of injection moulds for the production of ever new prototypes to the satisfaction of customers. In production, investments are made in the optimisation of plants in order to reduce scrap and material demands.

In addition, the plants generate production and packaging waste, which is sorted by type, recycled by an external company and reused in companies outside the pharmaceutical industry. The recycled materials are not fed back into the company's own production due to the strict requirements of the industry. Sanner uses a standardised system to reduce the use of biocides: To do this, the biocides used are examined every two years, and it is checked whether non-toxic or less toxic substitutes can be used.

However, as an SME, Sanner GmbH finds it difficult in general to provide personnel and financial resources for resource efficiency projects.

Digital transformation

The digital transformation at Sanner GmbH is mainly represented in the form of a digital inspection plan to support staff, a building control system for condition monitoring, 3D printing in development and the use of cloud computing. In addition, an IT strategy is developed by the external IT consultant every two to three years. The topic of Industry 4.0, with its strategic focus on the topics of flexibility and productivity, has also now been included.

Software systems used

The company has a permanent process and machine data collection, whose data is evaluated in terms of overall equipment effectiveness, average operating time between failures for repaired units, rejects, start-up scrap and energy consumption. ERP, MES, WMS, PPS, CAD/CAM, BDE, MDE as well as a training software for managing the employee competences and degrees of training are used, whereby approx. 70% of the systems are mapped via SAP.

Digital inspection plan for staff support

In order to avoid the use of paper during the test as well as errors in the transfer of handwritten test values into digital systems, an optimisation of the test process was envisaged. In addition, the employees should be relieved by standardised inspection plans. Since 2002, the employees have been guided by a digital test plan in which the individual work steps are specified and must be confirmed by the employee. All test results are saved. Due to the implementation of this measure, test documents no longer need to be managed in production.

Introduction of a comprehensive building management system

Due to the high quality requirements of the products, constant production conditions are an important prerequisite for the company. In addition to ensuring process stability, energy savings should be implemented with the help of energy management; thus in 2013, Sanner decided to introduce a self-regulating building management system. With the help of the building management system, the previously used siloed solutions were to be replaced by a holistic system. In the implementation, however, there were major problems due to staff shortages, so that even today, continuous improvement of control technology is needed.

Introduction of a 3D printing process for prototype production

With the goal of quickly creating customer and exhibit samples and saving the cost of prototype tooling, a 3D printer for product development was purchased in 2015. The 3D printer is being used in prototype development and is helping to save resources and materials by eliminating prototype tooling. In addition, this measure saves a great deal of time in order acquisition and the product development process.

Cloud computing

Due to the high availability requirements for IT systems, it was preferred to outsource these services than invest in the company's own IT department. The service provider should offer more security and high availability as well as 24/7 support. In the case of Sanner, the hosting of the MES and ERP (SAP), as well as the database management, has been taken over since 2006 by an external service provider. All sites are connected via VPN. The service provider has two data centres and is both SAP-certified and audited. As a result of the measure, less specialist knowledge is needed at the site, and 24/7 service is available. This minimised downtime. In addition, the in-house server infrastructure could be downsized, thus reducing energy consumption. (Data centres can generally be run more efficiently than decentralised server systems.)[316]

Future planned measures

With regard to further digital transformation measures in the near future, Sanner is planning digital product memory, a driverless transport system with digital integration of machinery, mobile operating devices and new HMIs on machines with work schedules as well as the possibility of electronic know-how transfer and the expansion of condition monitoring. Augmented reality applications to support maintenance are also currently being planned.

The implementation of digitalisation measures is made especially difficult by the high demands of the pharmaceutical and medical technology industry for documentation. Software solutions, especially in the field of quality control and tracking, are not yet feasible, as software validation cannot be carried out. Uniform standards and evaluation criteria are missing for this purpose.

Conclusion on the measures

Sanner has carried out digitalisation measures, but up till now, there has been no specific search for ways to use digitalisation, rather, solutions to existing problems have been developed (in part) without linking them to Industry 4.0. However, this has changed since the latest version of the IT strategy. The company is now specifically looking for measures to achieve the strategic goals of flexibility and productivity. For this purpose, task forces are typically formed with a small number of employees who can test measures with a limited budget.

[316] **Zarnekow, R. and Kolbe L. M. (2013), p. 44.**

Interactions between digital transformation and resource efficiency

The interaction between resource efficiency and digitalisation is shown by Sanner GmbH in reducing waste. This will monitor the machine scrap and use the data collected to derive measures to minimise scrap.

A8: Case study portrait Festo AG & Co. KG

FESTO

Company

Festo AG & Co. KG, headquartered in Esslingen am Neckar, was founded in 1925 and is divided into the two business units Automation (automation technology) and Didactic (learning systems, training and consulting). With approximately 18,700 employees, the independent family-owned company generates sales of approx. € 2.64 billion worldwide and supplies pneumatic and electrical automation technology for 300,000 customers in 35 sectors. The technology factory in Scharnhausen considered in this study has approximately 1,200 active employees, and it primarily produces valves, valve terminals and electronics. The company's service portfolio ranges from catalogue products for pneumatic, servo-pneumatic and electrical automation technology to tailor-made customer solutions, industry-oriented qualification solutions and industry consulting.

Resource efficiency

Resource efficiency is of strategic relevance, and therefore, a topic especially in the areas of product development, production and building. The new construction of the Scharnhausen site, in which, among other things, more than 50 suggestions from employees on the topic of resource efficiency were implemented, was recently awarded the platinum certificate of the German Sustainable Building Council. The production system, Festo Value Production, also supports the environmentally friendly use of resources.

The opportunities for Festo to increase resource efficiency are reflected in cost, image and innovation advantages. It contributes to the image of a sustainably operating company in this way and can serve as a unique selling proposition for Festo products on the market, helping to secure its technological lead.

When dealing with resource efficiency, the range of possible starting points is striking. Experience in implementing measures shows: Even though corporate management and employees have recognised the relevance of the topic at an operational level, persuasion is often still required at the middle management level.

Festo is committed to energy management based on DIN EN ISO 50001. Although Festo is not an energy-intensive company and energy costs make up only a small part of the total costs, energy consumption is considered relevant. Customer requirements expressed in terms of energy efficiency refer to the products and technologies from Festo. In most cases, concrete products are requested that are themselves energy-efficient or increase the energy efficiency of plants. There is less interest on CO_2 balance data for individual products or applications.

The potential offered by increasing the company's energy efficiency is estimated at around 20% of its energy requirements. How much of that can be raised depends on how much funding is made available and what payback periods are given. Potentials are also seen in the area of material savings, and these are also addressed, for example, via product development, value management or environmental management. However, Festo considers material efficiency to be more difficult to address due to the complexity of the topic. Since Festo's products mainly use aluminium, which is easy to recycle and generally uses comparatively little material per product, there is no great call for action here.

Measures to reduce energy consumption are carried out at various levels of the company. For example, a work instruction has been developed that regulates the shutdown of machinery over the weekend to save energy. Employees are trained in the topic of energy efficiency in their own learning factory, e.g. on the influence of a compressed air leak. This is intended to raise awareness on the topic of energy.

In production, material is always lost through scrap and waste. At Festo, aluminium, steel and plastic are used in particular. Various structural measures have already been implemented to reduce the material requirements in the production, e.g., preferential use of cast parts instead of solid material to be machined.

Any production and packaging waste is recorded with the help of environmental controlling in accordance with DIN EN ISO 14001. The separation in the consideration depends on the legal requirements of the individual production sites, whereby a distinction is usually made between waste for disposal and elimination and thereby between dangerous and harmless substances. In production, waste is separated according to the recycling strategy and applied to the production and packaging waste. For example, chips are briquetted in a special facility. In this way, the cooling lubricant can be squeezed out and reused. In addition, the briquettes can be disposed of as non-contaminated waste.

Festo uses a service provider to carry out the identification of ecotoxic substances and emissions in production. When introducing new substances, a substitution test is carried out, and environmental management, the occupational doctor and the occupational safety must agree to the introduction.

Digital transformation

Festo's motivation to address digital transformation concerns the question of how production in Central Europe can remain competitive and how unique selling points and competitive advantages can be created. The goal is thus, on the one hand, to support Festo's own production areas, but also to help Festo's customers improve their productivity.

The digital transformation at Festo is reflected in numerous measures, whereby a distinction can be made between measures for products and for the company's own production. For example, an energy transparency system is currently being set up, with building and machine data being linked together to determine the total energy consumption as well as the energy consumption per produced product. In the future, the collected data will also be analysed with data-mining methods in order to, e.g., determine optimal load curves. In addition, Festo uses energy-transparent machines that record energy data for electricity and compressed air as well as relevant machine data.

Digitalisation is designed together with customers at Festo. This starts with creating a common understanding of digitalisation and leads from developing products in research projects to designing new business models. The customers primarily expect a concrete benefit and, e.g., place requirements on communication interfaces. They are also interested in how they can make the energy data of their plants transparent.

Software systems used

The key system is an ERP. In addition, an MES, operating data and machine data acquisition (BDE, MDE), a PPS and computer-aided design or manufacturing (CAD or CAM) are used. Supply Chain Management (SCM) and PLM are used in the form of organisational systems.

Digital product memory

Currently, a so-called product key is introduced, through which the customer can retrieve selected information. Within the company, this format is used to store product information and process data. This measure was motivated, among other things, by customer requirements for traceability.

Networking of sensors and actuators

Vertical integration is increasingly taking place from the sensor via the control to the management system. For example, this approach was implemented two years ago in the acquisition of a large automation system. Consequently, the cycle times could be reduced and productivity increased, but there is still a need for optimisation. Since the introduction of this measure, the degree of automation at the site has been increased by 30-40%. The vertical integration also improved the connection of the value chain with the suppliers or other Festo plants by significantly increasing the transparency of the product and process data. A need for action resulted from the qualification requirements of the employees.

Decentralised controls

For years, Festo's production has been showing a trend towards decentralised control systems that are distributed at stations and communicate with each other. They need no central control or only that which is significantly unburdened.

Assistance systems/staff support

Plants in production are partially equipped with QR codes which can be used to access the information about the machine, such as maintenance videos. For the evaluation of energy efficiency, regular energy efficiency tours are conducted in different organisational units. For this purpose, the staff is provided with a checklist on a tablet as support during the collection of the data. Other maintenance support systems are currently being tested.

Mobile HMIs/Augmented Reality

Tablets are used in maintenance and for organisational processes, like indicator recording or tours. In addition, smart watches are currently under review; the use of augmented reality glasses was tested to support remote maintenance, but has not yet been further implemented.

Modularity/Plug and Produce

Festo uses a modular assembly line in its own production. This consists of several cells, is a total of 30 metres long and has its own controller per module, so that it can be operated independently. Coupling several modules requires a control system for the line, which takes over the storage of process data in databases as well as the transmission of information to the system. Further research should reduce the changeover time (currently one day) and enable simulation of production processes and plug and produce.

Condition Monitoring/Predictive Maintenance

Festo has been using condition monitoring for filters, both in its own production and in prototypical product solutions since 2010. This allows the current state of the filter to be visualised via a display and thus enables optimal maintenance. As a result, downtimes are reduced and material and time are saved. The central exhaust air system of the company's production is also linked with the supplier so that the latter has the opportunity to connect and to check the condition of the filters. However, currently, Condition Monitoring and Predictive Maintenance are rarely explicit customer requirements for Festo. In this context, data security, which must be guaranteed at all times, also plays a major role.

Virtual training

In addition to various classic and innovative qualification services, such as a learning factory directly in the factory, Festo also has a "virtual academy" in which virtual trainings are offered. Every employee in the production department has to, e.g., complete the quality and environmental training when starting his or her job. For customers, Festo provides videos for commissioning and repairing products.

New manufacturing processes – 3D printing

Festo has been operating the so-called "Fast Factory" for about eight years, in which initial experience with generative manufacturing processes was gained. Today, two technologies (stereolithography and selective laser sintering) are used especially for the production of prototypes and small series. In prototype construction, in particular, the product development time, as well as the number of iteration loops, should be reduced, and customer feedback obtained earlier. Before the measure was introduced, prototypes were produced manually by mechanical processing. Even today, technology is constantly being developed by testing new materials and making new geometries feasible. Company representatives currently consider mass production using additive processes to be uneconomical.

Virtual product development

For about five years, calculations and simulations have been carried out in product development in order to minimise manufacturing costs and ultimately increase material efficiency. FEM programmes as well as thermal and flow simulations are used here. The aim of this measure is to achieve material savings (fewer prototypes for experimental purposes) and to test the use of cheaper materials. In addition, the trial times were shortened significantly. Here, too, the growing demand for qualified professionals presents a challenge for the company.

Conclusion on the measures

Festo already uses a variety of digitalisation measures, and others are in the planning and test phases. These measures are aimed at cost reduction on the one hand, but also at resource efficiency on the other. Successful measures are shared with Festo plants around the world through experience-sharing groups. One of the biggest challenges for Festo in connection with digitalisation measures is employee training.

Interactions between digital transformation and resource efficiency

Festo uses the collected data to increase resource efficiency, especially energy efficiency. In particular, energy and production data are recorded using appropriate software and used, among other things, for building energy management. For the automation technology industry, the business representatives see little resource efficiency potential compared to other industries, except in energy efficiency.

A9: Case study portrait SMB Schwede Maschinenbau GmbH

Company

The SME SMB Schwede Maschinenbau GmbH (SMB for short) produces strapping machines for the processing of plastic strapping at the Goldkronach site in Bavaria. Thanks to a modular product portfolio, customers from a wide variety of industries, but above all the graphics industry, corrugated board industry, pharmaceutical and food industry and logistics industry, can be addressed individually. The focus is always on the customer's perspective in order to deliver sustainable added value and be able to support them in all issues. The company employs 85 people and generated sales of 13 million euros in 2015.

Resource efficiency

As the product costs in the machine building sector are heavily influenced by material and personnel costs, measures to increase resource efficiency at SMB focus precisely on these areas.

In terms of material efficiency, the strategy developed has mainly addressed two pillars: material substitution and material-efficient construction. For example, the integration of alternative materials in the development of components or machine elements can constructively influence the later use of lighter or more sustainable materials. This reduces moving masses and minimises the electrical energy consumption of the strapping system during operation. The focus here is on customer benefit in terms of low operating costs. Even the production of components themselves is influenced by this measure. For example, parts that are otherwise made of solid materials or semi-finished products are tested for substitution options and alternative, more resource-efficient production.

To increase resource efficiency in final assembly, SMB developed a system linked to the machine parts list: Assembly time analysis (“MonZA”). In terms of digitalisation, this system is based on the method of predetermined times (Methods-Time Measurement – MTM) and is used for capacity and staff assignment planning. On the one hand, time for required work steps are provided to increase transparency, and on the other hand, an assembly instruction is provided. Thus, employees are deployed more efficiently and work organisation in assembly is optimised with regard to the use of resources.

For the purposes of post-costing in production, the acquisition of process data and its evaluation offers the opportunity to improve workflows. This will record any malfunctions and collect them in an 8D error message database. Workflows are provided for the rectification. And in addition to fault messages, change requests are also recorded.

Digital transformation

The data landscape of SMB Schwede Maschinenbau GmbH consists of an ERP system that includes the functions of various subsystems. This includes the functionalities of a supply chain management system (SCM system), a PLM system, a PPS and the functions of the operational data acquisition (BDE). Furthermore, Computer-Aided design and manufacturing (CAD/CAM) are used throughout. This is illustrated for the detailed visual representation of the products themselves through rendered models in the sense of a digital twin.

From the company’s point of view, digitalisation poses challenges and opportunities, especially with regard to the product portfolio. In addition to the customer’s requirement of high availability of machines, the focus is on the adaptation of the product portfolio. The latter is being promoted in the form of modularisation of mechanical assemblies, electronic assemblies and software packages, which is intended to ensure improved maintenance. Existing knowledge and gained insights into machines as well as associated subgroups are made available to customers on the specially developed “MySMB” portal. Here, all machines of a customer are listed and the following data is provided digitally: operating instructions, spare parts catalogues, wear parts lists, programme numbers of PLC and HMI, circuit diagram and CE documents. Furthermore, customers have access to an online shop with the entire scope of their own machines.

Internally, a help desk is used to support technical support. For a maintenance or service assignment, all life cycle data of the machine can be accessed by serial number. In addition to customer data, the current service level of the machine, including completed and pending service measures and their date, as well as the machine structure with exploded views are also provided. In addition, typical machine faults and rectification measures are suggested to service employees. After a completed service operation, a digital report is created, which is used as the basis for automatically creating a billing document in the ERP system and booking all expenses and materials.

Interactions between digital transformation and resource efficiency

Interactions between digitalisation and resource efficiency are viewed positively by SMB. Initial one-time expenditures of digitalisation applications in terms of data collection and evaluation are offset by an increase in efficiency of routine work through IT-supported systems. This means that work scopes that were previously covered by the documentation can be replaced by value-added activities. Furthermore, there are quality improvements and efficiency improvements in the service area. Through the coupling of the ERP system and helpdesks, the customer benefits are increased service speed, the creation of reports as well as an acceleration of the business processes within the company. Looking ahead, SMB hopes to further customer benefits through demand-oriented, preventive maintenance as digitalisation progresses. Here, the use of big data analysis seems promising.

A10: Case study portrait Wetropa Kunststoffverarbeitung GmbH & Co. KG

WETROPA GROUP

Company

The company Wetropa Kunststoffverarbeitung GmbH & Co. KG employs 85 of its 125 employees at its headquarters in Mörfelden, which is considered in this study. Other locations are in Feldkirchen and Baiersdorf. The company has been specialising in foam processing for 45 years and offers packaging and packaging solutions to both industry and retail. The products are highly customised to the customer's packaging requirements and can also be produced in very small quantities (1 unit). In 2015, Wetropa generated sales of approximately € 15 million.

Resource efficiency

Measures to increase resource efficiency at Wetropa are implemented in design, production and recycling. During construction, attention is always paid to optimum material utilisation in order to minimise waste. In production, assistant systems are used to minimise waste, which will be described in more detail later. In addition, all waste is separated, recycled by a supplier and partly repurchased from the said supplier. For the company this results in cost and space savings as well as an image improvement. There are also demands from customers to Wetropa regarding resource efficiency and environmental friendliness. The company regularly informs its customers about waste and recycling-related figures in the form of newsletters. Energy costs are particularly relevant at the plant level, so organisational measures are implemented for this, such as the shutdown of plants after the end of the shift to reduce power consumption.

The company representative sees high potential for resource efficiency in their own company as well as in the plastics industry.

Digital transformation

The digital transformation at Wetropa is mainly in the form of staff assistance systems, continuous data integration and in virtual product development in the form of the so-called Foam Creator, which can help customers to automatically design and order individual foam inserts.

Software systems used

The company has an ERP system that includes a WMS. In addition, an MES with PPS is used, and both machine and operating data are recorded (MDE, BDE), which are stored and managed in the MES. A CAD / CAM system is used in development or construction.

BDE terminals

For two years, Wetropa has been using so-called BDE terminals to improve the transparency in production management and the predictability of production. The BDE terminals were introduced simultaneously with the MES. Before, there was no data collection at the production level. The BDE terminals allow better monitoring of orders and process times. After the execution of an order, these are analysed and compared with the standard times to ensure that they are up-to-date as much as the offered price.. In addition, employees can use the terminals to access additional functions, such as vacation management. Problems in production can also be reported. In the implementation, the qualification requirement of the employees presented a particular challenge.

Projector for staff support

For about three and a half years, Wetropa has been using projectors for staff support on cutting machines for foam boards. The aim was to optimise material utilisation during cutting. The projector projects the machine-optimised cutting pattern onto the foam boards so that the staff can align them as accurately as possible. Prior to the introduction of the projectors, the alignment of the blanks was determined by the individual employees, which meant that the panel waste was dependent on the experience of the individual employees and varied widely. In addition to the waste of material resources, the fluctuating material requirements posed a problem for material procurement. When using this system, the optical distortion caused by the position of the projectors and the fluctuating plate thickness must be considered by the employees.

Continuous data integration

In addition to the ERP system, which has been in use since 2009, an MES was introduced about two years ago. The system is used in production planning to enter customer and order data. This measure aimed to optimise processes, improve traceability and increase delivery reliability.

Before the introduction of the MES, production planning was carried out manually, which was error-prone and associated with a high administrative effort. This effort has been greatly reduced, so today's production planning can be carried out with one employee instead of two.

Foam Creator

The company has been using the self-developed Foam Creator since April 2015 as part of virtual product development. Before implementing the measure, customer objects had to be recorded on site and modelled in a CAD programme. The foam insert could be manufactured after optimisation by the designer and obtaining customer feedback.

The aim of the introduction of the Foam Creator was to enable the customer to model his own inserts without any prior knowledge in the field of construction or foam processing. This was intended to save costs and time for both the customer and the company.

The Foam Creator can be used both as a web-based version on the computer or as an application on the smartphone. The customer takes photos of his objects, loads them into the Foam Creator and selects individual settings, such as the distance between the objects, colour and type of foam. The application then automatically creates a model of the foam insert and provides it to the customer for approval. After confirmation, the customer receives a delivery date; and in the latest version, an automatic offer. Internally, the orders are automatically confirmed and transferred directly to digital production planning.

From this measure, the new service company My Foam.net GmbH was founded, which makes the Foam Creator also available to competitors of Wetropa and provides the customers with the service in the form of a marketplace.

The technical limits of the system are currently in the optical range. There must be sufficient contrast between the object and the background during the image recording, and also a picture size of DIN A4 must not be exceeded since it leads to distortions by the camera lenses. Above all, the search for a qualified service provider for the development of the software posed problems with the implementation of the measure.

With the help of the Foam Creator, the development effort for simple foam inserts could be reduced to zero.

Future planned measures

In the future, Wetropa plans to expand its machine data acquisition system by acquiring new plants. Collected data should be made available to the manufacturer, among other things, in order to reduce downtimes and thus improve delivery reliability. In the future, a digital product memory will also be introduced with the help of QR codes.

Conclusion on the measures

Wetropa sees digitalisation as an opportunity to prevail against competitors from abroad who are constantly catching up with the quality of their products. The goals of the company are lean processes, a consistent quality and few complaints. Wetropa representatives also sees great potentials through digitalisation with regard to zero-error rate, e.g., in the form of digital inspection systems.

Interactions between digital transformation and resource efficiency

Wetropa recognises strong interactions between digitalisation and resource efficiency through the use of staff assistance systems and the Foam Creator. Digitalisation contributes to time, cost and resource savings by streamlining processes and, for example, in the case of the Foam Creator, eliminates shipping costs for objects or travel costs to the customer.

APPENDIX 2: RESOURCE SELF-ASSESSMENT TOOL (RESET)

In the Resource Self Assessment Tool or ReSET, six operational material resources are repeatedly displayed in six stages of data collection and analysis. The result is shown in Figure 25.

The process of repetition was deliberate, as was the enumeration of each level for each resource, despite obvious similarities. ReSET is a template for users. It aims to help SMEs assess their digitalisation in terms of resource efficiency and help generate ideas for digitalisation to increase resource efficiency. For this purpose, it is essential that the user consciously deals with each resource individually. In the following, three of the six resource levels are described in detail.

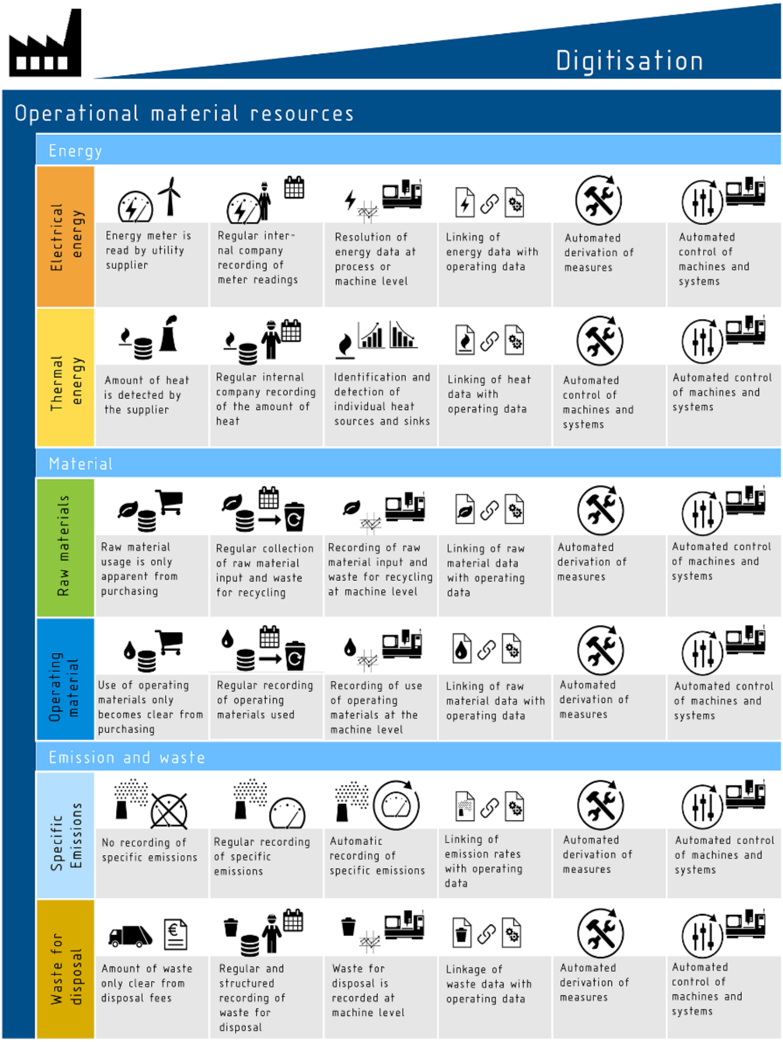

Figure 25: Detailed version of the resource self-assessment tool (ReSET)

Electrical energy

In the first development stage (Figure 26), the energy metres are read by the utility company at predetermined intervals, and the consumption is invoiced accordingly. The data on the electrical energy used in the payment period is available to the company management in the form of invoices. These can be used to make comparisons between payment periods and to create simple trend analyses. What is decisive, however, is that the chronological resolution is externally determined.

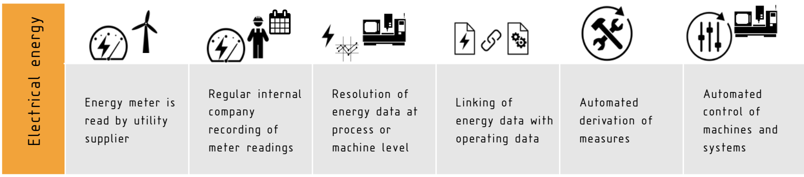

Figure 26: Development stages of the operational material resource “Electrical energy

In the second development stage, the metre readings are regularly recorded by the company itself. The intervals between the reading times can be determined, and the data stored in a suitable place. This allows the creation of annual consumption curves. Depending on the chosen interval, seasonal, monthly or weekly differences can be analysed and queried.

The third stage of development requires the use of additional energy metres at the hall, plant or machine level. This increases the locational resolution. Depending on the number of metres used and the selected reading interval, it is quite expedient in this stage to automate the collection and processing of the data as well as their analyses. Based on the analyses, energy-intensive processes and changes in energy usage can be identified. Furthermore, the newly gained information can be used to prioritise the investigation of energy efficiency potentials.

In the fourth development stage, the acquired energy data is linked to the corresponding process or machine data. Correlations and causalities are highlighted. The identification of energy-intensive processing steps becomes possible. Optimisation measures, such as the internal-machine smoothing as well as the load peak smoothing across machines, can be used precisely. In addition, a distinction can be made between value-adding and non-value-adding energy use, and further comprehensive optimisation potential can be revealed.

With the introduction of smart systems, the processes described above are automated in the fifth development stage. The system independently calculates optimisation potentials and issues them to an employee at a suitable level. Further optimisation measures are holistic optimisation approaches involving buildings, production, machines, technical building equipment, etc. The sixth stage of development consists of enabling and allowing the system to autonomously implement the automatically derived optimisation measures.

Raw materials and consumables

The description of the six stages of development is given below for raw materials and consumables (Figure 27 and Figure 28). For better readability, if no distinction is made, only raw materials are referred to, which can in this context, however, always be substituted by consumables. The separate listing in two levels in the tool, however, is essential because raw materials and consumables are to be considered separately in the context of production. Waste for recycling is also analysed in this section. The recovery can be done in-house, resulting in a return to the cycle as raw material, or it can leave the system boundary of the company via disposal of the waste. In contrast, waste for elimination must be distinguished, which is described in a separate level under ecosystem services.

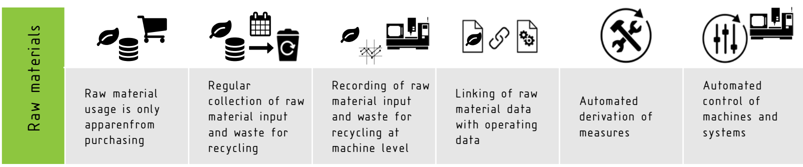

Figure 27: Development stages of the operational material resource "Raw materials"

In the first stage of development, data on the use of raw materials is not specifically recorded. The quantities used are only apparent from purchasing and must be extracted manually from the corresponding organisational unit of the company for resource efficiency analysis. Once this has been done, it is possible to visualise the chronological course of the use of the raw materials and to evaluate possible fluctuations. The number of data points, however, depends on the frequency of ordering the respective raw material.

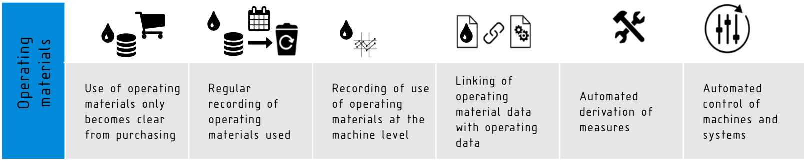

Figure 28: Development stages of the operational material resource "Consumables"

The next stage of development is a regular consideration of the use of raw materials at the company or plant level. The reusable waste is included in the analysis. As with the resources described above, deliberate periodic collection of resource usage data allows the query frequeny to be determined, whether daily, weekly or monthly, thereby increasing data quality and predictive value. In addition, an awareness of the use of resources is created, and the creation of reference states is made possible as a basis for efficiency enhancement considerations.

In the third stage of development, the data collection on used raw materials and generated waste for recycling is broken down at the machine level. The locational resolution is increased again. An automation of data acquisition and processing at a central location also allows an increase in chronological resolution. Production processes, machines or plants can be classified according to raw material use and prioritised with regard to the investigation of savings potentials. With correspondingly continuous analysis and visualisation, changes in usage during operation can also be identified. Increased use may indicate leaks or similar malfunctions, especially with consumables.

The fourth development stage involves linking the raw material data with the operating data. This allows the determination and evaluation of specific savings potentials. Raw material consumption and waste for recycling can be assigned directly to process steps and products. Greater understanding of the respective relationships enables far-reaching optimisation potentials to be realised.

In development stages five and six, smart systems automatically detect the correlations between processes and the use of raw materials, and independently derive measures or, if appropriately networked, adapt process parameters in order to autonomously implement the derived measures.

With the help of the resource self-assessment tool described in detail, SMEs have the opportunity to assess their own degree of digitalisation in terms of the six resources considered. The identification of the current stage of development is followed by the determination of the desired and company-specific strategy for achieving it. The process can be repeated several times for each resource.

VDI Zentrum Ressourceneffizienz GmbH (VDI ZRE)
Bertolt-Brecht-Platz 3
10117 Berlin
Tel. +49 30-2759506-0
Fax +49 30-2759506-30
zre-info@vdi.de
www.ressource-deutschland.de