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VDI ZRE publications: Study

Resource efficiency potential through digitally supported circular measures

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VDI ZRE Study: Resource efficiency potential through digitally supported circular measures

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LIST OF ABBREVIATIONS

BITC	Business in the Community
BMBF	German Federal Ministry of Education and Research
BMUV	German Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection
BMWK	German Federal Ministry for Economic Affairs and Climate Action
CEID	Circular Economy Initiative Germany
CO_2	Carbon dioxide
DPP	Digital product passport
EDI	Electronic Data Interchange
EEA	European Environment Agency
EM	Employees
EMF	Ellen McArthur Foundation
ERP	Enterprise resource planning
EU	European Union
IEDS	Incentives and Economics of Data Sharing
IoT	Internet of Things
IW	Institut der deutschen Wirtschaft (‘German Economic Institute’)

MCI	Material Circularity Indicator
OECD	Organisation for Economic Co-operation and Development
PaaS	Platform-as-a-Service
PDM	Product data management
R&D	Research and development
SaaS	Software-as-a-Service
SME	Small and medium-sized enterprises
VDI	Association of German Engineers
VDI ZRE	VDI Zentrum Ressourceneffizienz

FACT SHEET

Aim of the study

The transformation to a climate-neutral economy includes the transition from a linear economy to a circular economy, the aim of which is to utilise products, product parts, materials and raw materials for as long and as intensively as possible and to manage them in cycles. Digitalisation is an important trailblazer for this transformation, enabling the adaptation of production processes as well as product and service systems. For companies, the interplay of circular strategies and measures on the one hand and digital solutions on the other can offer potential savings. However, small and medium-sized enterprises (SMEs) in particular are not yet sufficiently digitalised. Against this background, this study analyses the relationships between digitally supported circular measures, the resources used to implement those measures, and how these measures contribute to achieving circularity. These correlations are presented in a practice-orientated way for SMEs in the form of guidelines for measuring the efficiency of circular measures.

Procedure and methodology of the study

This study explores the resource efficiency potential of digitally supported circular measures for SMEs in a structured manner in five work packages that build on each other. A mix of methods is used, including current research literature, practical examples from a representative company survey and expert interviews. In addition, a target group-specific guideline for industrial SMEs is developed, which includes a procedure and indicators for measuring the circularity efficiency of digitally supported circular measures.

Resource efficiency through circular measures

Circular strategies can relate to the entire product life cycle and are implemented through circular measures. From the wide range of circular strategies and measures in the literature, five circular strategies and eleven circular measures can be identified that are both digitally supported and particularly relevant for SMEs. Matching the circularity strategies against the digitally supported circular measures enables an initial assessment of the effectiveness of the measures and the interplay of measures and strategies, and provides information on the resource efficiency potential of individual measures.

The majority of SMEs surveyed in the manufacturing sector have either taken circular measures or are planning to do so. The proportion of companies with circular measures increases significantly with the company's success. They are currently still focusing mainly on energy saving and efficiency measures as well as process-related internal optimisation measures that lead to a reduction in resource consumption in line with the R-Strategy "Reduce". Fewer approaches are being pursued that directly address the product, be it through the use of new materials or expansion of the range to include product-service systems. There is also potential for improvement in the use of new and recycled raw materials. It would be helpful if more companies systematically recorded and strategically managed the circularity of their resources.

Digital technologies for circular measures

Companies use digital technologies, for example, to create transparency in their processes or to leverage identified efficiency potential. Against this backdrop, digital technologies can make a significant contribution to greater circularity in companies when using circular measures. The interplay of strategies and measures for improving circularity and digital solutions offers potential savings and efficiency gains that still need to be leveraged.

In practice, however, digital technologies for the implementation of circular measures have only played a subordinate role for SMEs to date. There are many reasons for this: For example, the assessment of the cost-benefit ratio of digitally supported circular measures varies greatly from company to company. There are also far-reaching obstacles to using digital technologies. Frequently mentioned factors include a lack of expertise, a lack of information and advice on costs, benefits and targets, a lack of complete solutions for comprehensive data collection and utilisation, the inability to retrofit existing systems and a lack of financial resources.

Determination of circularity efficiency

For SMEs, in addition to the resource efficiency potential that can be achieved through the use of digitally supported circular measures, the efficiency of the measure taken in relation to the implementation of a specific circularity strategy also plays a central role. To date, there are no indicators that can be used to determine circularity efficiency. The study therefore presents a set of indicators and a proposal for calculating the circularity efficiency of digitally supported circular measures. The guidelines are intended to enable SMEs in particular to find suitable indicators for evaluation and to be able to apply them in practice.

The results of the survey show that some companies do perceive positive effects from digitally supported measures with regard to the use of natural resources. At the same time, however, the proportion of companies that do not observe any effects is very high. Overall, the survey makes it clear that the majority of companies have great difficulty in determining the effects of the circular measures implemented.

Recommended actions

The first goal should be for more companies to realise circular strategies. To this end, adequate incentives must be created or strengthened by increasing demand from the public sector, as well as accompanying support measures such as knowledge transfer and networking opportunities. This includes scientific research into new types of circular products and/or services and rapid transfer into business practice.

The second goal should be to support companies in implementing digital solutions and to enable them to handle data and use it as a basis for circular measures. To this end, the necessary framework conditions - such as the digital infrastructure and the regulatory framework - must be created in order to minimise the risks of digitalisation and data exchange for companies.

The third goal should be to provide better information about the costs and benefits of digitally supported circular measures and to put the information provided into practice. For policymakers, this means that information services, guidance and standards for measurement should be established. Companies can utilise these offers and implement them internally. The prerequisite for this is that they manage the use of preliminary products, materials and raw materials in a structured and targeted manner and establish co-operations with other companies along the value chain. Science can contribute to the realisation of this goal by further developing circularity measurement and creating practical tools that can be used by companies in order to reduce the barriers to the introduction of circularity measurement.

EXECUTIVE SUMMARY

Aim of this study

The transformation to a climate-neutral economy includes the transition from a linear economy to a circular economy. The aim is to use products, product parts, materials and raw materials for as long and as intensively as possible, keeping them in cycles. Digitalisation is a key enabler, facilitating the adaptation of production processes as well as product and service systems. For companies, the interplay of circular strategies and measures on the one hand, and digital solutions on the other hand, can offer potential savings. However, small and medium-sized enterprises (SMEs) are often not sufficiently digitalised yet. Against this background, this study analyses the relationships between digitally supported circular measures, the resources used for this purpose, and the contribution of these measures to achieving circularity. These correlations are presented in a practice-oriented way for SMEs in the form of a guideline for measuring the efficiency of circular measures.

Approach and methodology of this study

This study systematically identifies resource efficiency potentials through digitally supported circular measures for SMEs in five interrelated modules. A mix of methods is applied, including current research literature, practical examples from a representative company survey and from expert interviews. Additionally, a target-group-specific guide for industrial SMEs is developed, which includes a procedure and indicators for measuring the circularity efficiency of digitally supported circular measures.

Resource efficiency through circular measures

Circular strategies cover the entire product life cycle and are implemented through circular measures. From the wide range of circular strategies and measures found in the literature, five circular strategies and eleven circular measures can be identified that are both digitally supported and particularly relevant for SMEs. Matching the circularity strategies with the digitally supported circular measures allows for an initial assessment of their effects and interrelation, providing insights into the resource efficiency potentials of individual measures.

Many of the surveyed SMEs in the manufacturing sector have either implemented circular measures or plan to do so. The proportion of companies with circular measures increases significantly with the company's success. They are currently still focusing mainly on energy saving and efficiency measures as well as process-related internal optimisation measures that lead to a reduction in resource consumption in line with the R-Strategy ‘Reduce’. There is also potential for improvement in the use of new and recycled raw materials. Fewer approaches directly address the product itself, such as the use of new materials or the expansion of the product range to include product-service systems.

Digital technologies for circular measures

Companies use digital technologies, for instance, to create transparency in their processes or to exploit identified efficiency potentials. In this context, digital technologies can make a significant contribution to increased circularity when implementing circular measures. The interplay of strategies and measures for improving circularity and digital solutions offers new potential for efficiency improvements.

In practice, however, digital technologies play only a minor role in the implementation of circular measures within SMEs. The reasons for this are diverse: the cost-benefit assessment of digitally supported circular measures varies greatly among companies. Additionally, the obstacles to their use are extensive. Barriers are often a lack of expertise, insufficient information and advisory services, the absence of comprehensive solutions for data collection and usage, the inability to retrofit existing equipment, and a lack of financial resources.

Determination of circularity efficiency

For SMEs, the efficiency of digitally supported circular measures in implementing a specific circularity strategy is just as crucial as the resource efficiency potentials these measures can achieve. Currently, there are no indicators available to determine circularity efficiency. Therefore, an indicator set and a method for calculating the circularity efficiency of digitally supported circular measures are presented. The guidelines are intended to enable SMEs to identify suitable indicators for evaluation and apply them in practice.

The results of the survey show that some companies do perceive positive effects from digitally supported measures with regard to the use of natural resources. At the same time, however, the proportion of companies that do not observe any effects is very high. Overall, the survey indicates that many companies find it challenging to determine the impact of implemented circular measures.

Recommendations

The first objective should be that more companies implement circular strategies. To this end, adequate incentives must be created by strengthening demand on the part of the public sector, as well as flanking support measures such as knowledge transfer and networking opportunities. This also includes scientific research into new types of circular products and/or services and a rapid transfer to business practice.

The second objective should be to support companies in implementing digital solutions and to enable them to handle data and use it as a basis for circular measures. To this end, the framework conditions - such as the digital infrastructure and the regulatory framework - must be appropriately designed and applied to minimise the existing risks of digitalisation and data exchange for companies.

The third objective should be to provide better information about the costs and benefits of digitally supported circular measures and to apply the information provided in practice. For policymakers, this means that information services, guidance and standards for measurement should be established. Companies can utilise these offers and implement them. One prerequisite is that they manage the use of preliminary products, materials and raw materials in a structured and targeted manner and enter co-operations with other companies along the value chain. The scientific community can contribute to the realisation of this goal by further developing circularity measurement and expanding practical tools that can be used by companies to reduce the barriers to the introduction of circularity measurement.

1 INITIAL SITUATION

Section 1.1 explains the background and motivation of the study. Section 1.2 briefly presents the main questions of the study.

1.1 Introduction and motivation

The transition from a linear economy to a circular economy that utilises products, product parts, materials and raw materials for as long as possible is an important building block on the path to climate neutrality. Circular business models that are strategically geared towards enabling, closing, creating or extending cycles are becoming relevant. These circularity strategies are implemented by taking concrete measures at companies, such as reuse, strategic resource management and the use of new technologies that promote circularity[1].

Digitalisation is an important trailblazer for the adaptation of production processes, product systems and service systems. It can therefore support the development of modified or even new circular business models, as it enables the intelligent use of innovations and access to data, for example through the use of digital product passports. The interplay of strategies and measures for improving circularity and digital solutions offers potential savings in terms of material and/or energy use.

Many companies, especially small and medium-sized enterprises (SMEs), face a number of challenges in this context, however, as they are not (yet) sufficiently digitalised. A large volume of data from operational value creation processes are not stored digitally and not (yet) managed efficiently[2, 3]. So far, companies have not sufficiently exploited the potential of available data, for example to optimise their processes or adapt their business model based on data. In addition, it is often nearly impossible for

[1] Cf. Lichtenthäler, S. and Neligan, A. (2023), p. 80.

[2] Cf. Büchel, J. and Engels, B. (2023b), p. 38.

[3] Cf. Neligan, A.; Schleicher, C.; Engels, B. and Kroke, T. (2023b), p. 4

SMEs in particular to assess whether a measure or investment in circularity is worthwhile due to technical, organisational, financial and personnel challenges.

The interdependencies between digitally supported circular measures, the resources used for them and the resource efficiency potential that can be realised are analysed in more detail in this study and prepared in a practice-orientated manner for SMEs in the form of guidelines for determining the efficiency of circular measures.

1.2 Research questions

To investigate the interplay of circular approaches and digital solutions for increasing resource efficiency, the study focuses on the following key questions:

- Status quo: What are the applications of circular measures? To what extent are they digitally supported?
- Implementation: What are the expenses associated with digitally supported circular measures? What are the relevant implementation challenges?
- Effects: What are the effects of digitally supported circular measures on resource efficiency?
- Measurement: To what extent is circularity measured at companies? How can the efficiency of circular measures be measured or determined and their benefits for companies evaluated?

2 PROCEDURE AND METHODOLOGY

This chapter contains the procedure and underlying methodology of the study. Section 2.1 begins by describing the objectives, process and methodology used in the individual work packages. Section 2.2 explains the structure of the study. Finally, Section 2.3 provides the definitions of key terms used in the context of resource efficiency, circular economy and digitalisation.

2.1 Aim and structure of the study

The aim of this study is to identify resource efficiency potential through digitally supported circular measures for SMEs in the German manufacturing sector. A combination of methods is used to answer these questions. Taking into account current research and literature, the topic is systematically being analysed with current, relevant facts and practical examples based on a representative company survey and expert interviews. In addition, guidelines prepared for industrial SMEs in a target group-orientated manner provide approaches for determining the circularity efficiency of digitally supported circular measures.

The study was conducted in five work packages:

(1) Desk research was initially used to evaluate the theoretical resource efficiency potential of digitally supported circular measures by analysing the current state of knowledge and open questions in this subject area from the literature.

(2) A company survey of SMEs in the manufacturing sector was subsequently conducted to determine the status quo of the distribution of digitally supported measures and the associated resource-saving potential. Empirical research was carried out to determine which digitally supported circular measures are used in industrial practice, the associated costs for SMEs and the resource efficiency potential that can be realised as a result.

(3) Practical guidelines for SMEs were then developed with the aim of making the efficiency of digitally supported measure visible for companies based on their circularity goals.

(4) The concluding expert interviews provide deeper insight into business practice and show examples of the successful implementation of digitally supported circular measures.

(5) The study is rounded off with recommendations for action for industry, politics and science. These recommendations are derived from the analyses of the drivers, obstacles and success factors for the implementation of digitally supported circular measures.

2.1.1 Desk research

Desk research is used to take stock of the current state of knowledge. A comprehensive search of the available scientific (specialist literature) and grey literature (expert opinions, studies and brochures) forms the basis of this. For this purpose, it was possible to build on the literature research already conducted in various preliminary studies by the IW. Comprehensive and frequently cited meta-literature studies were taken into account. This thematic research was expanded specifically with a view to the questions envisaged for the study. The focus was directed at publications from 2015 onwards. Search terms in German and English were as follows: Word combinations such as circular measures, circular strategies, circular business models, circular economy, resource efficiency (potential), digitalisation and digital technologies and also indicators for circularity efficiency.

The terms were not only searched for separately, but were also combined into search criteria to find relevant studies on digitalisation with a focus on the realisation of circularity. Relevant databases such as Researchgate, Econstor, econlit and OECD iLibrary were used for the specialist literature and a general Internet search for the grey literature.

The literature researched was structured and prepared in a results-orientated manner. The findings from the available literature and the existing data were incorporated into the project in the following ways:

- As a basis for the development of the mapping of circular measures and the derivation of suitable indicators for the efficiency assessment of circular measures
- For the development of the questionnaire for the planned company survey
- For the development of the guidelines for the planned expert interviews
- To identify possible recommendations for action for industry, politics and science

2.1.2 Company survey

Data basis

The empirical study is based on a company survey conducted by the German Economic Institute (IW) as part of the 46th wave of the IW Future Panel between 15 November 2023 and 19 January, 2024. The IW Future Panel is a recurring online company survey that collects data on current economically relevant change processes in addition to various structural data. The respondents are management, board members and heads of strategy departments at companies in the industrial and industry-related service sectors.

982 companies took part in this survey, of which 438 in total or 380 SMEs (up to 249 employees) from the manufacturing sector answered the questions about "digitally supported circular measures" (cf. Table 1). Due to relevance filters after the initial question, the case numbers for individual questions may deviate downwards. All results tables contain the unweighted case numbers for the respective question.

Table 1: Net sample of the survey – number of companies, unweighted[4]

	Employee (EM) size classes				
Industries	Up to 49 EM	50 to 249 EM	SMEs total	250 EM or more	Total
Chemical, pharmaceutical, rubber and plastics industries	42	18	60	5	65
Metal production and -processing and manufacture of metal products	58	46	104	13	117
Mechanical engineering, electrical industry, vehicle construction	84	48	132	21	153
Other lines of the manufacturing sector	61	23	84	19	103
Manufacturing sector total	**245**	**135**	**380**	**58**	**438**

[4] IW Future Panel, wave 46, 2023

Survey methodology

For this study, nine questions were asked exclusively to provide an overall picture of the status quo at manufacturing SMEs. They cover the following topics:

- Existence, degree of utilisation and degree of digitalisation of circular measures
- Degree of utilisation of digital technologies in circular measures
- Effects of the use of digital solutions in circular measures
- Determination quality of the effects of circular measures
- Evaluation of resource efficiency through the use of digital solutions in circular measures
- Barriers to the use of digital technologies for the implementation of circular measures

In addition, the IW Future Panel simultaneously surveys a large number of structural and success factors that can be used as typification variables. Cross variables are also used for typification according to employee size class, company success and degree of digitalisation. The following definitions are used as a basis:

- **Employee size classes**: For the definition of SMEs, the limit is set at 249 employees as per the EU definition. It can be seen that the results for SMEs with up to 49 employees are almost identical to the results for SMEs as a whole, as this size class represents the majority of companies and therefore significantly determines the average (see also weighting below).
- **Success classes**: A performance index with two components is used for the company's success – one component based on equally weighted information on the company's development in the recent past (development of turnover, employment & net return on turnover and the achievement of company targets) and another component that contains

the short-term future estimates (expectations regarding turnover, employment and investment development) equally weighted. The overall index includes the component on past company development with a weighting of 70 percent and the component on the assessment of future development with a weighting of 30 percent. On this basis, the companies are categorised into three success groups (low, medium and high)[5].

- **Degree of digitalisation**: The degree of digitalisation is determined on the basis of the questions on the contribution of the use of digital technologies for improving circularity and the use of digital technologies in circular measures. The more the digital technologies surveyed are used to a high degree, the higher the company's level of digitalisation. These questions were only asked of companies that are already implementing or planning to implement circular measures.

The sample for the survey was selected and extrapolated representatively as follows:

- **Sample**: The participating companies are based on a random sample stratified by the number of employees and sector, which was drawn from the beAddress company database. The sample contains proportionately more large companies than the population as a whole. This procedure allows a sufficiently high number of cases to be obtained for the analysis in this group as well.
- **Weighting**: To determine representative values for the population (industrial companies and industry-related services), the survey results were calculated using number-weighted averages (based on the number of companies using data from the German Federal Statistical Office's business register). Up to ten sectors and three employee size classes (1 to 49 employees, 50 to 249 employees and 250 or more employees) are taken into account. The results provide information on how the

[5] Cf. Fluchs, S.; Neligan, A.; Schleicher, C. and Schmitz, E. (2022), p. 20.

average company assesses an issue. In addition, a correction for "non-response bias" was made as part of the extrapolation. The term "non-response bias" refers to the potential distortion of extrapolation results that can arise if there are structural differences in the willingness to participate between different types of companies, for example according to company size, and these differences have an influence on the results of the survey.

2.1.3 Development of indicators and practical guidelines for SMEs

For the development of practice-orientated guidelines for SMEs, adequate indicators for measuring and evaluating efficiency increases through digitally supported circular measures were first identified. The practical guidelines are intended to enable companies to determine the effects of the measures they have taken on circularity strategies independently and in a targeted manner. The procedure for this was as follows:

(1) In the first step, existing methods and indicators for measuring circularity and/or resource efficiency from the literature were analysed and evaluated. The literature research is broadly based, as there have only been few indicators for measuring circularity efficiency to date. Based on the literature research and evaluation of the indicators developed and presented there, suitable indicators were derived with regard to the target group of SMEs in the manufacturing sector. These indicators need to take into account which data are available at SMEs or can be obtained with reasonable effort.

(2) In a second step, a comparison was made between the developed indicators and the circularity strategies by assigning the indicators to the respective strategies and thus to the associated measures.

(3) Finally, in the third step, the practical guidelines provide a systematic overview of the appropriate use of various indicators for measuring resource efficiency improvements at SMEs as well as a checklist of requirements for successful evaluation. The guidelines also provide a brief explanation of the indicators and which data must be available in order to calculate the indicators.

2.1.4 Expert interviews

The aim of the expert interviews was not only to gain practical business examples of the successful implementation of digitally supported circular measures, but also to discuss in-depth questions about the specific implementation and the associated opportunities and challenges at companies based on individual cases. These company representatives also trialled the SME guidelines afterwards and provided feedback. The profiles of the companies can be found in Appendix 2.

In the final question of the company survey, companies were asked about their basic willingness to participate in an in-depth expert interview. 77 SMEs in the manufacturing sector agreed to this question. From this pool, a selection of 15 companies with a suitable combination of sectors and sizes were contacted. A total of seven expert interviews were conducted in June 2024. They included companies from the textile, packaging and plastics industries as well as from the steel processing and toolmaking sectors. The companies surveyed employ between four and 140 people.

The expert interviews were conducted digitally as semi-structured interviews over Microsoft Teams and lasted around 45 to 60 minutes. Interview guidelines with key topics and sample questions were used as a basis. The aim of this approach was to create an open and natural atmosphere for dialogue. The results were recorded systematically and in a results-orientated manner.

2.2 Structure of the study

The structure of the study is based on the research questions defined in Section 1.2, utilising the results from the work packages described in Section 2.1. First, chapters 3 to 5 provide a compact description of the theory relevant to the respective issue and the derivations based on it. The results of the company survey are then presented separately. Individual results of the expert interviews are supplemented in appropriate places. This results in the following structure for the subsequent chapters:

- Chapter 3 shows how companies can increase resource efficiency through circular strategies and the associated measures.
- Chapter 4 examines the role of digital technologies in the implementation of circular strategies and measures.
- Chapter 5 goes into detail on how circularity efficiency is defined in this study and how it can be determined at companies.
- Chapter 6 provides recommendations for action for politics, business and science.

2.3 Definitions of terms

The key definitions of the terms used in the context of resource efficiency, circular economy and digitalisation are briefly described below.

2.3.1 Resources

This study refers to the definition of "natural" resources in the VDI 4800 Part 1 guidelines[6], which provides methodological foundations, principles and strategies for evaluating resource efficiency. They include renewable and non-renewable primary raw materials, energy resources as well as

[6] **Cf. VDI 4800 Blatt 1: 2016-02.**

land and environmental media (water, soil and air) as sinks for waste or emissions and ecosystem services[7].

To be able to link the societal objective of resource conservation with corporate options for action, this study draws on an extension of this definition from the VDI ZRE study entitled "Resource efficiency through Industry 4.0 – Potential for SMEs in the manufacturing sector". It divides the concept of resources into four different categories: natural, operational, tangible operational and intangible operational.[8] The intersection of both definitions is the subset of operational resources: material operational resources (namely, materials and energy)[9]. It can be seen that natural resources are influenced by certain operational resources, such as final energy consumption, materials and land/soil. This subset represents the material operating resources. In addition, emissions to air and water and the generation of waste also lead to the consumption of natural resources at an operational level, which places a strain on the carrying capacity of the environment[10].

2.3.2 Resource efficiency and resource efficiency potential

The main objective of resource efficiency in this study is to reduce the consumption of natural resources in the production of goods, in particular the use of raw materials and water, the utilisation of space and the reduction of environmental pollution in accordance with the VDI 4800 Part 1 guidelines[11]. It should be noted that, in operational practice, it is often the case that only the consumption of operational resources can be measured directly[12].

[7] Cf. VDI Zentrum Ressourceneffizienz GmbH (2023), p. 7.

[8] Cf. VDI Zentrum Ressourceneffizienz (2017), p. 21 et seqq.

[9] Cf. Schebeck, L. (2018), pp. 69.

[10] Cf. Schebeck, L. (2018), pp. 22.

[11] Cf. Schmidt, M.; Spieth, H.; Bauer, J. and Haubach, C. (2017), pp. 13.

[12] Cf. Schebeck, L. (2018), pp. 69.

So far, there is no standardised definition of resource efficiency. From an economic perspective, sets of indicators have been established at both the national and European levels to map progress in resource utilisation[13]. In the German Resource Efficiency Programme (ProgRess), raw material productivity is an important reference parameter which has been supplemented by total raw material productivity[14].

From an economic perspective, "efficiency" is understood as the production of a given output with minimal input (minimum principle) or the production of maximal output with a given input (maximum principle). The VDI 4800 Part 1[15] guidelines define resource efficiency as the ratio of a certain benefit or result to the (natural) resources required to achieve it[16]. The benefit or result can be the manufacture of a product, the execution of a process or a service such as the transport of goods or the provision of information via electronic media[17]. Key measures at the operational level for increasing resource efficiency are aimed at saving primary raw materials and energy resources, reducing environmental pollution (emissions, waste and waste water), increasing the security of supply and reducing manufacturing costs.

According to the VDI 4800 Part 1 guidelines, a circular measure must improve resource efficiency across the entire product life cycle in order to achieve resource conservation[18]. This means that, within a value creation chain or product life cycle, it is not sufficient to merely shift the expenditure locally, for example to suppliers. The VDI 4800 Part 1 guidelines specify which resource efficiency measures require a life cycle analysis[19]. Resource efficiency potential is not explicitly defined. Instead, the potential

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[13] **Cf. Biebeler, H. and Lang, T. (2014), pp. 7 et seqq.**

[14] **Cf. BMU (2020), p. 23.**

[15] **Cf. VDI 4800 Blatt 1: 2016-02.**

[16] **Cf. VDI Zentrum Ressourceneffizienz GmbH (2023), p. 9.**

[17] **Cf. VDI Zentrum Ressourceneffizienz GmbH (2017a), p. 24.**

[18] **Cf. VDI 4800 Blatt 1: 2016-02.**

[19] **Cf. Schmidt, M.; Spieth, H.; Bauer, J. and Haubach, C. (2017), pp. 14.**

here corresponds to a possible improvement in resource efficiency through a specific change resulting from the implementation of a measure from the VDI 4800 Part 1 guidelines[20].

In the following, the term “resource efficiency potential” refers to the potential of the ratios shown in Figure 1. It shows how resource efficiency can be improved using digital circular measures. The benefits achieved and the associated costs compared to a reference state are compared with each other for this purpose. The reference state is defined here as the conventional process that is changed by the digital technology. Datasets for the entire life cycle, such as life cycle assessment databases, are required for identification of the natural resources themselves. These datasets are used to calculate the resource efficiency potential by multiplying their factors by the consumption of natural resources[21].

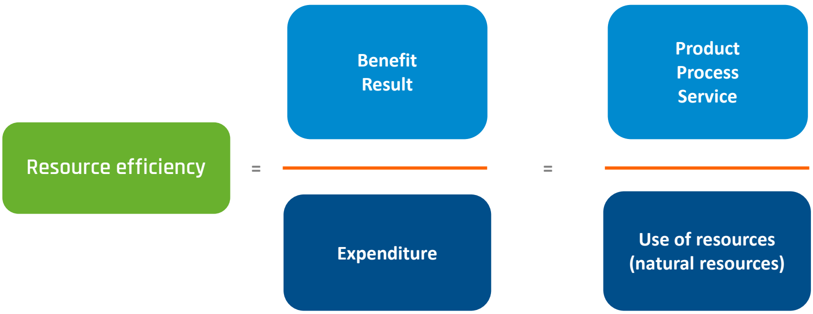

Figure 1: Definition of the term resource efficiency[22]

2.3.3 Circular economy and circular business models

The **basic principle of a circular economy** is to use products, materials and raw materials for as long as possible. This minimises the material and energy requirements as well as the waste and emissions of an economic

[20] Cf. VDI Zentrum Ressourceneffizienz GmbH (2017a), p. 62.

[21] Cf. VDI Zentrum Ressourceneffizienz GmbH (2017a), p. 62 et seq.

[22] VDI ZRE figure based on VDI 4800 Part 1: 2016-02. Reproduced with the permission of the Association of German Engineers.

system. The focus here lies on the entire value creation chain and the entire product life cycle. This includes the extraction of raw materials, product design, the manufacture of semi-finished and finished goods and products as well as the use and recycling of materials. Ideally, products are designed to have the longest possible service life, for reuse and for recycling. Decisions on the use of recyclable materials and raw materials (e.g. renewable raw materials and recycled materials) in the product to be designed are also made during the design phase. Existing product and service systems must be adapted for this, however. There is also room for new business models that fulfil these requirements[23].

The **concept of the circular economy** is currently the subject of intense debate in politics, business practice and science. Nevertheless, there is no standardised definition, which means that there are different views and no coherence, as shown by the overview study by Kirchherr et al. (2017) with their comparison of 114 definitions[24]. The circular economy is most frequently understood as being a combination of reduction, reuse and recycling, without emphasising that a systemic change is necessary[25]. In particular, the German term “Kreislaufwirtschaft”, which is commonly associated with circular economy, was only used in connection with a recycling or waste management system in the past. The concept of the circular economy analysed here is based on the comprehensive meaning of the term, which is also increasingly being used by the broader public today[26].

According to this use of the term, the goals of a circular economy are to optimise the use of resources, for example by reducing the use of resources and extending their useful life, and ultimately to return and reuse resources in a closed cycle. In this way, primary material can be conserved while at the same time avoiding negative effects on the environment. In

[23] Cf. Lichtenthäler, S. and Neligan, A. (2023), p. 79.

[24] Cf. Kirchherr, J.; Reike, D. and Hekkert, M. (2017), pp. 228 et seq.

[25] Cf. Kirchherr, J.; Reike, D. and Hekkert, M. (2017), pp. 221.

[26] Cf. Fluchs, S.; Neligan, A.; Schleicher, C. and Schmitz, E. (2022), p. 8

addition, material and energy inputs can be minimised through recycling-friendly product design and adapted production processes[27, 28].

Circular business models are business models that focus on preserving value for as long as possible and saving resources while maintaining competitiveness[29, 30]. Business models describe how companies organise their business. The focus lies on how companies embed their value proposition, value creation architecture and revenue model into their competition strategy. The general assumption is that companies set profit maximisation as their goal, which can be achieved by minimising costs and increasing turnover. Resources are regarded as an infinitely available input factor. This leads to a linear economy in which goods are disposed of after a single use and economic growth is linked to resource consumption[31].

Circular business models consist of various components and pursue circular strategies that slow down, extend and close resource cycles. In addition, a break is being made with linear production and business patterns, including, for example, the assumption of infinite resource availability[32,33]. Profit maximisation is no longer achieved solely by minimising costs and maximising turnover, but also by maximising the useful life of products and resources. This in turn means minimising the use of resources[34].

Circular strategies are implemented through circular measures. This reduces the input of resources into the organisation and maximises the preservation of value[35]. This is achieved at the appropriate point in the

[27] **Cf. Lichtenthäler, S. and Neligan, A. (2023), p. 79.**

[28] **Cf. Fluchs, S. and Schleicher, C. (2021), pp. 5 et seq.**

[29] **Cf. Geissdoerfer, M.; Savaget, P.; Bocken, N. M.P. and Hultink, E. J. (2017), pp. 763.**

[30] **Cf. Neligan, A.; Baumgartner, R. J.; Geissdoerfer, M. and Schöggl, J.-P. (2022), p. 1176 et seq.**

[31] **Cf. Lichtenthäler, S. and Neligan, A. (2023), p. 80.**

[32] **Cf. Fluchs, S.; Neligan, A.; Schleicher, C. and Schmitz, E. (2022), p. 10**

[33] **Cf. Lichtenthäler, S. and Neligan, A. (2023), p. 80.**

[34] **Cf. Fluchs, S.; Neligan, A.; Schleicher, C. and Schmitz, E. (2022), p. 9.**

[35] **Cf. Bocken, N. M. P.; Pauw, I. de; Bakker, C. and van der Grinten, B. (2016), P. 308 et seq.**

value creation chain through specific measures such as restructuring, innovation and the development of new business areas. Some of these measures may require a comprehensive restructuring and reorganisation of business processes, e.g. the changeover to a product service system, while others are easier to realise depending on the product, e.g. repair. Individual measures can support various strategies for promoting the circular economy. Many companies therefore build their business model from a combination of different measures[36]. The individual components of such a system are complex and interdependent. The effects of the circular measures therefore do not unfold in isolation, but rather interact and complement each other[37]. Section 3.1 goes into more detail on circular strategies and measures.

2.3.4 Digitalisation and digital technologies

The technical foundation of digitalisation is the conversion of data from the analogue world into digital data. This connection between the real and virtual worlds is at the heart of digitalisation, as it allows the real world to be captured, analysed and even influenced on or by a computer. [38]

Digitalisation also represents a megatrend[39]. A megatrend is a fundamental development with far-reaching consequences for the entire economy, which forms the basis for numerous other innovations and developments. For example, digitalisation represents the underlying megatrend for developments such as Industry 4.0, autonomous driving, smart contracts and the rise of digital platforms. Although it is therefore easy to describe the technical foundation and the core of digitalisation (see above), a uniform definition of the term digitalisation has not yet been established.

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[36] Cf. OECD (2019a), p. 25.
[37] Cf. Lichtenthäler, S. and Neligan, A. (2023), p. 81.
[38] Cf. Demary, V.; Engels, B.; Röhl, K.-H. and Rusche, C. (2016), p. 5.
[39] Cf. Naisbitt, J. (2015), p. 5.

The following definition according to the German Federal Ministry for Economic Affairs and Climate Action (formerly the German Federal Ministry for Economic Affairs and Energy) is used for operationalisation: "Digitalisation means the use of digital data and algorithmic systems as a production factor or as a component of new or improved processes and products. Characteristics include the virtualisation and networking of products and processes, the sharing of data and the platform-based organisation and management of value creation chains. The combination of these aspects results in new digital business models"[40]. This definition includes key aspects of digitalisation that can also be used to categorise technologies. These include Networking, virtualisation, data processing, processes, products and business models[41, 42].

In addition, this definition emphasises the importance of data by naming it first. Digital data are therefore at the beginning of all digital developments, as they are what makes a digital image of reality possible in the first place. For operationalisation purposes, the six categories resulting from the definition are used in this study for the analysis of digital technologies. In order to improve comprehensibility in the subsequent survey, the category "virtualisation" is being renamed "digital twins" and the category "digital processes" is specified by referring to "digital information systems". Specifically, the following categories and their definitions, which follow Stich et al. (2021), are used[43]:

(1) **Digital data collection**: all technologies that can be used to generate, store, process and analyse digital data. Examples include the use of sensors and Big Data applications, which can be used to derive information from large, unstructured data volumes.

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[40] **Stich, V.; Hicking, J.; Stroh, M.-F.; Abbas, M.; Kremer, S. and Henke, L. (2021), pp. 10**

[41] **Cf. Stich, V.; Hicking, J.; Stroh, M.-F.; Abbas, M.; Kremer, S. and Henke, L. (2021), pp. 9.**

[42] **Cf. Büchel, J.; Demary, V.; Goecke, H.; Mertens, A.; Rusche, C. and Wendt, J. M. (2021), pp. 5.**

[43] **Cf. Stich, V.; Hicking, J.; Stroh, M.-F.; Abbas, M.; Kremer, S. and Henke, L. (2021), pp. 14 et seqq.**

(2) **Digital networking**: all technologies that can be used to merge, exchange and forward data and information. Examples include Bluetooth and WLAN.

(3) **Digital twins**: all technologies that create or enable the creation of a digital image of reality based on digital data.

(4) **Digital processes, in the sense of operational information systems**: digital applications that are used in or enable operational processes. Utilisation of cloud computing, common standard applications (e.g. enterprise resource planning (ERP) or product data management (PDM) systems) are examples.

(5) **Digital products**: digital technologies that are used in a company's physical products or services and form at least part of this product and, for example, enable communication with the environment. Examples include apps, app stores and assistance systems.

(6) **Digital and data-driven business models**: Business models based on the centralised provision and use of digital information. Examples include the use of software or platform infrastructure as a service for customers (SaaS and PaaS).

This categorisation allows partial aspects of digitalisation and their significance for the circular economy and corresponding measures to be considered in more detail. These digital technologies are also becoming relevant for the planned digital product passport (DPP), which is seen as a key instrument for a circular economy. Just like with a "product memory", information about the product such as the manufacturer, material, properties and repair and disposal options are to be provided digitally in a dataset for all stakeholders in order to increase transparency across the entire product life cycle. The DPP must fulfil both content-related and technical requirements here.

2.3.5 Circularity efficiency

The term **circularity efficiency** is not yet used in the literature analysed. It plays a key role in evaluating the effectiveness of circular measures in relation to a circularity strategy being pursued, however. The term is therefore introduced in the context of the study. Similar to resource efficiency according to VDI 4800 Part 1[44], circularity efficiency is used to measure or determine the contribution of a digitally supported circular measure to achieving a circularity strategy relative to the effort required to implement this measure. Based on a comparison of the circularity efficiencies of different measures, companies can assess which measure makes a greater contribution to achieving the circularity strategy than others and prioritise their measures accordingly.

In practice, however, it is often difficult to measure the specific costs of implementing a digitally supported circular measure. On the one hand, there is a lack of standardised and reliable data for balancing the resource consumption of specific products (e.g. hardware components) or applications (e.g. operation of software). Existing data is often based on scientific studies that present aggregated average values in the results and may not be freely accessible or difficult to understand for SMEs, for example.

On the other hand, it is virtually impossible to specifically allocate resource consumption to individual measures in practice. IT infrastructures such as servers are rarely procured or operated for a single software application. Used applications such as ERP systems in turn support more than just one measure. Consequently, the corresponding energy consumption for the operation of hardware and software applications cannot be easily allocated to the individual use cases.

Furthermore, extensive conversions are often necessary to convert savings and different types of expenses to a comparable unit. For example, to calculate the efficiency of a measure, material savings achieved (e.g. x litres

[44] **Cf. VDI 4800 Blatt 1: 2016-02.**

of a chemical in production) and material costs for hardware components (e. g. x kg silicon) and energy consumption for the operation of software (e.g. x kWh) are converted to their respective equivalent GHG emissions or costs. The data required for such a conversion is also difficult for SMEs to access, as only a few commercial providers currently exist in this area.

In favour of practicality when considering circularity efficiency, resource expenditure is therefore only considered indirectly in this study and the associated guidelines. This is done using the indicators also developed in this study. They are described in detail in Section 5.1 and in the practical guidelines. For better understanding, it should only be mentioned here that these indicators record the effects that can be achieved through the implementation of a specific measure (e.g. saving energy).

The expenditure of resources is reflected in some of these indicators to the extent that they reduce or overcompensate for savings. Accordingly, the introduction of a software application as part of a circular measure can lead to more energy being consumed than is saved by the same measure. There are also indicators that measure specific expenses at the monetary level, such as initial and ongoing costs for the integration of digital technology

Due to the largely indirect consideration of these expenses, the study refers to a determination of circularity efficiency rather than a measurement.

3 RESOURCE EFFICIENCY THROUGH CIRCULAR MEASURES

Circular strategies can start at different points in the life cycle of products and are implemented using circular measures. Circular measures, such as the optimisation of manufacturing processes, resource-conserving product design and recycling, can help to increase resource efficiency. This chapter covers the relevance of circular measures. Section 3.1 uses findings from the relevant literature to define relevant circular strategies and measures for SMEs in the manufacturing sector and compares them with one another. Section 3.2 presents the results of the company survey conducted for this study with regard to the presence and degree of utilisation of various circular measures.

3.1 Circular measures at companies – Literature

Key messages

- Circular strategies are implemented through circular measures.
- Eleven circular measures are identified for this study which are digitally supported on the one hand and especially relevant for SMEs on the other.
- The identified circularity strategies are compared with the digitally supported circular measures to obtain information on the mode of action, interaction and resource efficiency potential of individual measures.

3.1.1 Circular strategies

The field of business administration defines a strategy in the context of corporate planning as a company's fundamental and long-term orientated action for achieving desired goals[45]. Circular strategies for implementing a circular economy can be categorised along the value creation chain and include closing, enabling, creating and extending cycles[46]. While the Ellen MacArthur Foundation (EMF, 2013) had already defined four circular strategies in 2013, they were further refined by Potting et al. (2017) for the purpose of mapping the entire product life cycle to the so-called 9R strategies (R0 Refuse, R1 Rethink, R2 Reduce, R3 Reuse, R4 Repair, R5 Refurbish, R6 Remanufacture, R7 Repurpose, R8 Recycle and R9 Recover)[47, 48]. Based on EMF (2013), Lichtenthäler/Neligan (2023) identify four circularity strategies, hereinafter referred to as IW strategies, which also consider the entire product life cycle: closing cycles, enabling cycles, creating new cycles and extending cycles[49].

These four strategies are supplemented in this study by the aspect of increasing resource efficiency. Lichtenthäler/Neligan (2023) include resource efficiency in their strategy "Enabling cycles" and make specific reference to ecodesign. Due to the importance of resource efficiency in production, this strategy must be separated from the enabling of cycles and considered separately in this study. The definitions of circularity strategies used in this study are as follows[50]:

- **Strategy 1 – Closing cycles (S1):** Closing the gap between the end of the life cycle of a product or product part and the input factor for its manufacture must create a cycle.

[45] Cf. Müller-Stewens, G. (2018).
[46] Cf. Lichtenthäler, S. and Neligan, A. (2023), p. 80.
[47] Cf. Ellen MacArthur Foundation (2013), p. 7.
[48] Cf. Potting, J.; Hekkert, M.; Worrell, E. and Hanemaaijer, A. (2017), pp. 14 et seqq.
[49] Cf. Lichtenthäler, S. and Neligan, A. (2023), p. 80.
[50] Cf. Lichtenthäler, S. and Neligan, A. (2023), p. 80.

- **Strategy 2a – Improved resource efficiency in the manufacturing process (S2a):** Increased resource efficiency in the manufacturing process must avoid waste and conserve natural resources.
- **Strategy 2b – Enabling cycles (S2b):** The aim of circularity must be taken into account as early as the planning, development and design stages of products.
- **Strategy 3 – Creating new cycles (S3):** New circularity options are created through material and production substitution. The waste product of a process can thus serve as input for a new process.
- **Strategy 4 – Extending cycles (S4):** Products and product parts must be used as intensively as possible to retain their value for as long as possible.

Table 2 provides an overview of the extent to which the existing literature considers the circularity strategies defined for this study. This is marked in blue. It also contains meta-studies in which extensive literature research has already been carried out. One example of this is the study by Bjørnbet et al. (2021)[51].

[51] **Cf. Bjørnbet, M. M.; Skaar, C.; Fet, A. M. and Schulte, K. Ø. (2021), pp. 9.**

Table 2: Coverage of the various circularity strategies defined in this study in the literature reviewed[52]

	Number of strategies	S1	S2a	S2b	S3	S3
acatech/CEID/ SYSTEMIQ (2020)	4	x	-	-	-	x
Björnbet et al. (2021).	4	x	x	-	-	x
Bocken et al. (2016).	3	x	x	x	x	x
econsense (2021)	4	x	x	x	-	x
EEA (2021)	5	x	x	x	x	x
EMF (2013)	4	x	-	-	x	x
Fluchs et al. (2022).	4	x	-	x	x	x
Geissdoerfer et al. (2020)	4	x	-	x	x	x
Kirchher et al. (2017)	10	x	x	x	x	x
Lichtenthäler/Neligan (2023)	4	x	-	x	x	x
Neligan et al. (2021).	3	x	x	x	-	x
OECD (2018)	3	x	x	x	-	x
OECD (2019)	5	x	-	x	-	x
Potting et al. (2017)	10	x	x	x	x	x
VDI 4800 Blatt 1	3	x	x	x	-	-
wbcsd/BCG (2018)	6	x	x	x	x	x

S1 – Closing cycles; **S2a** – Improving resource efficiency; **S2b** – Enabling cycles; **S3** – Creating cycles

3.1.2 Circular measures

Similar to the diversity of strategies, there is an equally wide range of literature on circular measures. Section 2.3 already provides a definition of the term. Table 3 provides an overview of the selection of literature identified above in which circular measures are explained. It illustrates that although the specific measures differ depending on the focus of the source, there is a great deal of overlap and a similar understanding.

[52] VDI ZRE figure.

Table 3: Literature covering circular measures

Study	Measures
acatech/CEID/SYSTEMIQ (2020)[53]	Maintenance, upgrades, detection of defects and replacement of defective parts, inspection, resale of a functioning product, restoration, functional recycling, downcycling, redesign, take-back systems, product service systems, waste management
Bocken et al. (2016)[54]	Design of durable goods, design for extended product life, design for a biological cycle, design for disassembly, repair and maintenance, remanufacturing, recycling, provision of services instead of ownership
econsense (2021)[55]	Circular resources, Product-as-a-Service, extension of product utilisation, shared use, resource recovery
EEA (2021)[56]	Reduction of resources and production waste, recycling, reduction of material consumption, design for a circular economy, reprocessing, reuse, repair, rethinking
Fluchs et al. (2022),[57] Neligan et al. (2021a)[58]	Resource-conserving product design, product-service systems, strategic resource management, optimisation of manufacturing processes, use of new technologies, use of new materials, energy efficiency, internal circularity, cross-company circularity
Geissdoerfer et al. (2020)	Recycling, reuse, recovery, remanufacturing, durable design, marketing, maintenance, repair, shared use, software solutions
OECD (2018)[59]	Product repair and remanufacturing, material recycling, robust and durable products through design, reuse and repair, increased material productivity, increased plant utilisation, modified consumer behaviour
OECD (2019)[1]	Recycling, reuse, maintenance and repair, reprocessing and recovery, production of raw materials from waste, sharing/leasing, replacement of production resources with bio-based/renewable/recovered materials, durable product design

[53] Cf. acatech; Circular Economy Initiative Deutschland and SYSTEMIQ (2021).

[54] Cf. Bocken, N. M. P.; Pauw, I. de; Bakker, C. and van der Grinten, B. (2016).

[55] Cf. econsense (2021).

[56] Cf. Gillabel, J.; Manshoven, S.; Grossi, F.; Fogh Mortensen, L. and Coscieme, L. (2021).

[57] Cf. Fluchs, S.; Neligan, A.; Schleicher, C. and Schmitz, E. (2022).

[58] Cf. Neligan, A.; Engels, B.; Schaefer, T.; Schleicher, C.; Fritsch, M.; Schmitz, E.; Wiegand, R. and Arnold, R.C.G. (2021a).

[59] Cf. OECD (2018).

VDI 4800 Part 1 guidelines[1]	Material substitution, use of secondary raw materials, use-orientated product design, extension of technical product service life, cascading use of products, reparability, recycling-orientated product design, predictive maintenance, modularisation of systems, avoidance of losses in production, recycling of production waste
wbcsd/BCG (2018)[1]	Recycling, reuse, waste-free production, resource-efficient production, sharing/leasing, responsible product use, collection and recycling of products, regenerative use of materials

In addition to the literature presented here, there are other, more extensive descriptions of circular measures within the framework of various regulations at the European Union level. This includes, for example, the EU Taxonomy Regulation for sustainable investments. In Article 13 (1) (a)-l)), this lists numerous economic activities that are conducive to the transition to a circular economy[60].

Some of the economic activities listed in the regulation are so specific that they can be counted as circular measures. Examples include economic activities that:

- improve the durability, reparability, retrofit capacity or reusability of products.
- extend the use of products through reuse, design for longevity, repurposing, disassembly, reprocessing, modernisation and repair and product sharing, among other things.
- prepare for the reuse and recycling of waste.
- avoid or reduce the volume of waste.

The EU Ecodesign Regulation formulates similar product group-specific requirements in Article 5(1) in order to ensure easier recycling, easy repair, longer product life and resource conservation throughout Europe right from the product planning stage[61, 62]. Each of these ecodesign requirements applies specifically to a certain product group, or common

[60] Cf. European Commission (2020).

[61] Cf. Neligan, A.; Lichtenthäler, S. and Schmitz, E. (2023a), pp. 8 et seq.

[62] Cf. Official Journal of the European Union (2024), p. 33.

requirements such as the provision of a common charger for several product groups (e.g. electronic devices) can also be defined horizontally, provided there are technical similarities.

The revised version of the VDI 4800 Part 1 guidelines[63] lists a total of 48 measures for greater resource efficiency and resource conservation in relation to products and production[64]. The measure "Production-related cycle management" (no. 32) explicitly mentions internal and external recycling with regard to production. Also based on an earlier version of this guideline and the literature available at the time, Neligan et al. (2021b) identify 80 specific measures from a product perspective and 61 measures at process level for greater resource efficiency and resource conservation[65].

3.1.3 Typification of relevant circular measures

With the aim of working out the role of digital solutions in supporting the circular economy and revealing the subsequent effects on resource efficiency, Table 4 shows eleven circular measures that are digitally supported on the one hand and especially relevant for SMEs on the other. This study is based on these eleven circular measures. The measures cover all strategies according to the IW strategies of Lichtenthäler/Neligan (2023) as well as Potting et al. (2017) and wbcsd/BCG (2018)[66,67,68] Potting et al. (2017) present a key strategic approach with their 9R framework. In addition, the product and process level categories according to Neligan et al. (2021a) and the essential aspects of the measures in Table 4, such as

63 Cf. VDI 4800 Blatt 1: 2016-02.

64 Cf. VDI Zentrum Ressourceneffizienz GmbH (2023), p. 21.

65 Cf. Neligan, A.; Engels, B.; Schaefer, T.; Schleicher, C.; Fritsch, M.; Schmitz, E.; Wiegand, R. and Arnold, R.C.G. (2021b), pp. 14 et seqq.

66 Cf. Fluchs, S.; Neligan, A.; Schleicher, C. and Schmitz, E. (2022), p. 14.

67 Cf. Potting, J.; Hekkert, M.; Worrell, E. and Hanemaaijer, A. (2017), pp. 5.

68 Cf. wbcsd/BCG (2017), p. 5.

appropriate product design, recycling, extended useful life and the use of secondary raw materials, are covered[69].

Table 4: Identified circular measures including allocation to the respective circularity strategies

	Circular strategies used	Lichten-thäler/ Neligan (2023)	Potting et al. (2017)	wbcsd/ BCG (2018)
Eleven operational measures for improving circularity		Four IW strategies	9R strategies	Six overarching strategies
Product level/Business models				
Use of new materials	S3	S3	R1 (Rethink) R2 (Reduce)	Buy, design, manufacture
Use of secondary raw materials	S1	S1	R8 (Recycling)	Buy, collect and recycle
Circular product design	S2b	S2	All 9R strategies	Design
Supplementary product services	S4	S4	R1 (Rethink)	Sell
Reuse and -reprocessing of products and/or product parts	S4	S4	R3 (Reuse), R4 (Repair), R5 (Refurbish), R6 (Remanu-facture), R7 (Repurpose)	Use, collect and recycle

[69] Cf. Neligan, A.; Engels, B.; Schaefer, T.; Schleicher, C.; Fritsch, M.; Schmitz, E.; Wiegand, R. and Arnold, R.C.G. (2021a), p. 34 et seqq.

Process level				
Measures for energy efficiency and -saving	S2a	S2	R2 (Reduce)	Manufacture
Optimisation of manufacturing processes to conserve resources and avoid waste (without energy efficiency and saving)	S2a	S2	R2 (Reduce)	Manufacture
Reuse and recycling of raw materials and other materials	S1, S4	S1, S4	R3 (Reuse), R4 (Repair), R5 (Refurbish), R6 (Remanufac-ture), R7 (Repurpose), R8 (Recycle)	Manufacture, use
Recycling of raw materials and other materials	S1, S3	S1, S3	R6 (Remanufac-ture), R7 (Repurpose), R8 (Recycle)	Collect and recycle
Strategic management of circular measures	S1 – S4	S1 – S4	All 9R strategies	All six overarching strategies
Information systems for circularity	S1 – S4	S1 – S4	All 9R strategies	All six overarching strategies

S1 – Closing cycles; **S2a** – Improved resource efficiency; **S2b or S2** (IW strategy) – Enabling cycles; **S3** – Creating new cycles; **S4** – Extending cycles

3.2 Circular measures – Company survey

Key messages

- The majority of SMEs surveyed in the manufacturing sector have either taken circular measures or are planning to do so. The proportion of companies with circular measures increases significantly with the company's success.
- The focus lies on energy saving and efficiency measures as well as process-related internal optimisation measures and less on approaches that directly address the product, such as expanding the range to include product service systems.
- There is also potential for improvement in the use of new and recycled raw materials.

3.2.1 The presence of circular measures

There are numerous opportunities for companies to take measures to improve the circularity of raw materials, other materials, products and/or product parts. As explained in Section 3.1, these measures in turn contribute to corporate strategies and have different objectives.

The majority of SMEs surveyed in the manufacturing sector have either taken circular measures or are at least planning to do so. A look at the employee size classes makes it clear that smaller companies are less likely to implement circular approaches than medium-sized companies.

Figure 2 shows that more than half of SMEs in the manufacturing sector are already implementing circular measures, while a further eleven percent are planning to do so. Among companies with 50 to 249 employees, almost two thirds of companies already have circular measures in place. More than four out of five large companies (250 employees or more) state that they are currently implementing or intend to implement circular measures in future.

The proportion of companies that are neither currently implementing such measures nor planning to do so in future is comparatively high in both SME employee size classes with at 24 percent (50 to 249 employees) and 31 percent (up to 49 employees), however. It is significantly lower for large companies (250 employees or more).

The following statements from the expert interviews provide an initial impression of how companies implement circularity. Statements in inverted commas are quotes, and those without inverted commas are summaries of key statements from the interviews.

> **Expert interview #3 (plastics industry):** “We recycle 100 percent of our rejects – they are added straight back into production.” What is sold is sold, however. The products are not returned.

> **Expert interview #6 (toolmaking):** Recycling in the sense of scrapping and returning to the steel production cycle is common practice in the industry.

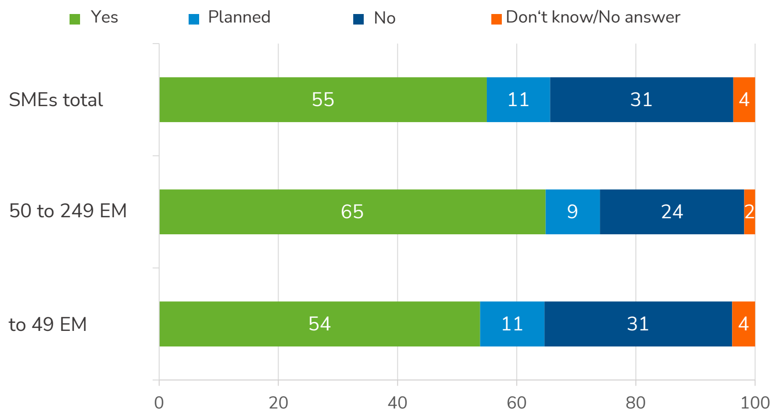

Figure 2: The presence of circular measures[70]

The relevance of circular measures becomes especially apparent when differentiating between their use within a company or across organisations, i.e. in co-operation with other companies/institutions (Cf. Figure 3). So far, however, these circular approaches have tended to be used within companies (43 percent) rather than across networks (18 percent). It can also be seen that the implementation of the measures in the network is increasingly being pursued by larger SMEs in the manufacturing sector.

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[70] **Percentage of SMEs in the manufacturing sector by size class**
Question: "Has your company taken measures to improve the circularity of raw materials, other materials, products and/or product parts?"
Own typification with the following multiple answer options: yes, within the company; yes, in co-operation with other companies or organisations; no, but this is planned; no, and this is not planned; don't know. Rounding differences are possible. – IW Future Panel, wave 46, 2023, N = 380

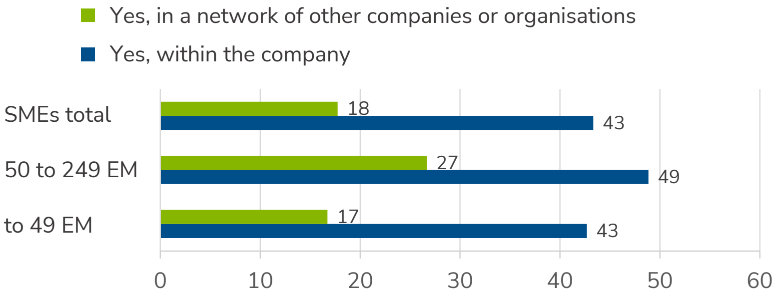

Figure 3: Application of circular measures[71]

Expert interview #2 (packaging industry): "We are only a small part of the supply chain. The potential for a circular economy exists. Not everyone involved in the supply chain has created the necessary conditions for implementation yet, however."

Expert interview #6 (toolmaking): "Cross-company co-operation would be helpful with regard to the circular economy in order to utilise the resources of each company, as margins are becoming ever smaller and price pressure is increasing all the time."

In terms of the company's success, a trend towards greater success can be recognised with more frequent implementation of circular measures (Cf. Figure 4).

[71] Percentage of SMEs in the manufacturing sector by size class
Question: "Has your company taken measures to improve the circularity of raw materials, other materials, products and/or product parts?" Multiple answers possible for: yes, within the company; yes, in co-operation with other companies or organisations; no, but this is planned; no, and this is not planned; don't know. Rounding differences are possible. – IW Future Panel, wave 46, 2023, N = 380

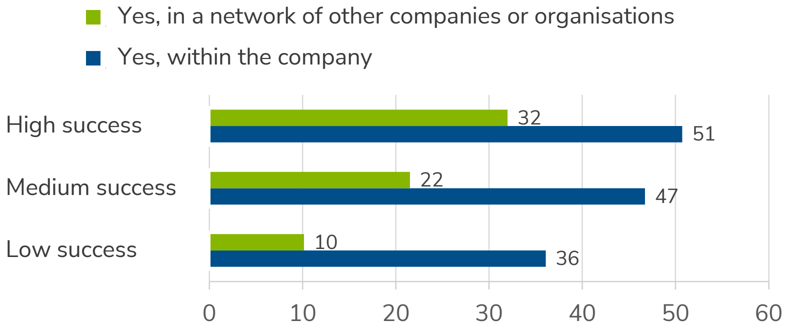

Figure 4: Application of circular measures according to company success[72]

While more than two thirds of highly successful companies take cycle-oriented measures, this proportion falls to 62 percent for companies with medium success and only 45 percent for companies with low success. This applies both within the company and within the network. Around a third of SMEs with a high level of success implement the measures in a network, and over half of the companies apply them internally.

These values are significantly lower for SMEs with low and medium success. It remains unclear at this point what the main drivers are for the use of circular measures at companies, however, and whether less successful companies underestimate the opportunities for the use of circular measures. These results indicate that the use of circular measures is seen as an opportunity to increase the company's success.

3.2.2 Utilisation of circular measures

Reducing resource consumption is not only an important goal for companies, but is also crucial for more efficient resource utilisation. So far,

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[72] **Percentage share of SMEs in the manufacturing sector by success class**
Question: "Has your company taken measures to improve the circularity of raw materials, other materials, products and/or product parts?" Multiple answers possible for: yes, within the company; yes, in co-operation with other companies or organisations; no, but this is planned; no, and this is not planned; don't know. Rounding differences are possible. – IW Future Panel, wave 46, 2023, N = 210

companies have mainly focused on energy-saving and energy-efficiency measures and traditional process optimisation as Figure 5 makes clear.

The majority (around 93 per cent) of the industrial SMEs surveyed stated that they utilise energy-saving measures, at least to a limited extent. An equally high proportion of companies (93 percent) optimise their manufacturing processes at least to a small extent with the aim of avoiding waste and conserving resources. At this point, it becomes clear that among the measures surveyed, particularly those whose purpose is not solely to conserve resources, but also contribute to other corporate goals, are utilised.

The examples of energy efficiency and waste avoidance show that overarching goals, such as monetary savings through lower energy and material consumption, can also be tracked via these measures. This fact could provide a possible explanation for the high degree of utilisation of these measures[73].

Of the measures surveyed, the recycling of raw materials/other materials is the one that most companies use to a high degree (28 percent). This shows that there are some companies that explicitly implement measures to promote circularity and conserve resources. The measures of reusing/recycling raw materials and other materials (82 percent), reusing/recycling products and/or product parts (80 percent) and circular product design (65 percent) also have a high degree of utilisation to a low to high extent.

[73] **Cf. Fluchs, S.; Neligan, A.; Schleicher, C. and Schmitz, E. (2022), p. 25 et seqq.**

Figure 5: Degree of utilisation of circular measures[74]

Overall, the survey shows that fewer approaches are being pursued that directly address the product, be it through the use of new materials or

[74] Percentage of SMEs in the manufacturing sector that implement circular measures. Question: “To what extent does your company utilise the following measures to improve the circularity of raw materials, other materials, products and/or product parts?” Possible answers: none yet; to a small extent; to a medium extent; to a large extent. Rounding differences are possible. – IW Future Panel, wave 46, 2023, N = 189 to 193

expansion of the range to include product-service systems. This means that many companies have not yet laid the foundations for a genuine circular economy[75].

Similarly, the approach of accompanying information systems for circularity is only implemented to a high degree by eight percent of SMEs and to a medium or low degree by a total of 38 percent. Potential explanations could lie in the different assessment of the costs in relation to the benefits of the individual measures, which is analysed in more detail in Section 4.2.3.

The current survey results support the statement on the degree of utilisation of various circular measures from earlier studies by Neligan et al. (2021a), Neligan/Schmitz (2017) and Biebeler (2014)[76,77,78]. There is further potential for conserving resources here, such as material and energy savings, which can be leveraged through digitalisation. A look at the measures planned by industrial SMEs in the survey also shows no trend reversal in favour of measures that directly address the product. This points to a corresponding need for action, as product-related, circular measures are very promising according to the current state of knowledge[79]. Companies that are planning circular measures are also considered, as it is assumed that a discussion has already taken place within the company in this regard. Among the measures implemented and planned, those for energy efficiency/saving are also the most widely used, while product-supplementing services and information systems for circularity are the least utilised.

[75] Cf. Neligan, A.; Engels, B.; Schaefer, T.; Schleicher, C.; Fritsch, M.; Schmitz, E.; Wiegand, R. and Arnold, R.C.G. (2021a), p. 35.

[76] Cf. Neligan, A.; Engels, B.; Schaefer, T.; Schleicher, C.; Fritsch, M.; Schmitz, E.; Wiegand, R. and Arnold, R.C.G. (2021a), p. 35 et seq.

[77] Cf. Neligan, A. (2018), pp. 103.

[78] Cf. Biebeler, H. (2014), pp. 35.

[79] Cf. Fluchs, S.; Neligan, A.; Schleicher, C. and Schmitz, E. (2022), p. 39.

In addition, the expert interviews show the main reasons for implementing circular measures:

> **Expert interview #3 (plastics industry):** The main reason for implementing energy efficiency/saving measures is the cost.
>
> **Expert interview #5 (steel processing):** Circular measures are used for intrinsic reasons, but also for economic reasons to reduce costs, sometimes also due to customer requirements that demand certificates and corresponding reporting. Another reason is the company's image.

4 DIGITAL TECHNOLOGIES FOR CIRCULAR MEASURES

Digital technologies can be used within a company, for example, to create process transparency and leverage identified efficiency potential. The main potential of digital technologies generally lies in cross-company networking and cross-company data exchange, however. Against this backdrop, this chapter looks at the nexus of digital technologies and circular measures.

Section 4.1 uses findings from the relevant literature to analyse the preconditions, extent of use and potential of digital technologies for the circular economy. Section 4.2 summarises and analyses the findings on digitalisation from the company survey conducted as part of this study. First, however, here are two quotes from the expert interviews that provide an initial impression of the importance of digitalisation for the circular economy from a practical business perspective:

> **Expert interview #1 (textile industry):** “Cross-company co-operation is important, even when calculating the carbon footprint, as each participant only covers smaller stages of the value creation chain. Collecting and sharing credible data is important. Digitalisation is helpful here.”

> **Expert interview #2 (packaging industry):** “Cross-company co-operation is crucial for the circular economy.”

The expert interviews also emphasised the need for a holistic approach to greater resource efficiency.

> **Expert interview #2 (packaging industry) provides insight into this:** “The combination of product, process and digitalisation is crucial for competitiveness and resource efficiency in general.”

4.1 Digital technologies – Literature

Key messages

- Digitalisation is an important enabler in the adaptation of production processes, product and service systems and the development of modified or even new circular business models in the direction of a circular economy.
- The interplay of strategies and measures for improving circularity and digital solutions offers potential savings and efficiency gains that still need to be leveraged.
- To realise the potential of digital technologies with regard to the circular economy, the technical requirements must be met and efficient data management and cross-company networking must be in place.

4.1.1 Digitalisation requirements

The requirements for leveraging digitalisation potential and thus also the use of digital technologies for the circular economy can be identified on the basis of the previously determined technology subdivision (Cf. Section 2). First of all, it must be stated that although the mere use of computers and the Internet is an indispensable precondition for digitalisation, digitalisation goes far beyond this precondition. For example, networking and data exchange generally take place across company boundaries[80]. The technical equipment of a company is a necessary, but not sufficient, condition for the appropriate use of digital technologies.

The following requirements apply to comprehensive digitalisation and are described in more detail below:

(1) Efficient data management

[80] **Cf. Demary, V.; Engels, B.; Röhl, K.-H. and Rusche, C. (2016), p. 16.**

(2) Cross-company networking

4.1.1.1 Efficient data management

Below are some examples of the experts' statements on the fundamental importance of data:

> **Expert interview #4 (plastics industry):** "The company is paperless. Data are collected (statistics are the be-all and end-all). The sale of articles and the consumption of raw materials etc. are documented and planning is based on these data (e.g. stock levels)."

> **Expert interview #5 (steel processing):** "The first step is to collect and analyse the data. The processes can then be optimised in this way."

Companies are generally capable of efficient data management if data storage, data management and data utilisation are advanced[81]. The aim of efficient data management is to utilise the collected and stored data in a diverse and targeted manner in order to generate added value. Examples of a wide range of uses include process automation and control, forecasting process developments and data-based (further) development of business models.

Specifically, digital data collection forms the basis for any further digital application, as this is the only way to digitally process information from the real world. The extent to which opportunities for the efficient use of data are utilised at German companies is clearly demonstrated by data economy readiness[82, 83]. This maturity model is part of the "Incentives and Economics of Data Sharing – IEDS" project, which was funded by the German Federal Ministry of Education and Research (BMBF) until 2024.

It evaluates whether companies can manage data efficiently. To this end, requirements are postulated according to an underlying model that must

[81] **Cf. Büchel, J. and Engels, B. (2022a), pp. 75.**

[82] **Cf. Büchel, J. and Engels, B. (2022a), pp. 75.**

[83] **Cf. Büchel, J. and Engels, B. (2022b), pp. 1.**

be fulfilled to ensure efficient data management. Companies are then questioned in a company survey in order to investigate the extent of data economy readiness in Germany.

It is clear from Figure 6 that larger companies are generally better able to manage data efficiently. While only 32 percent of small companies (up to and including 49 employees) were able to manage data efficiently according to the analysis carried out in 2023, the figure was 62 percent of medium-sized companies (50–249 employees) and 73 percent of large companies (more than 249 employees). Compared to 2021, data economy readiness has increased for all company size classes. The most significant increase of 22 percentage points was recorded by large companies. While the proportion of small and medium-sized companies has risen continuously since 2021, the highest figure of 77 percent was recorded for large companies in 2022.

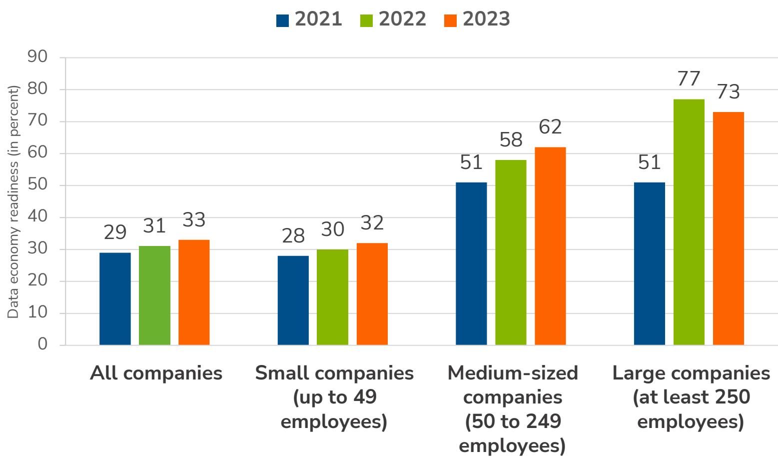

Figure 6: Data economy readiness by company size class [84]

Being categorised as data economy ready does not necessarily mean that a company is also using the potential of data and therefore digitalisation

[84] VDI ZRE figure based on Bakalis, D. and Büchel, J. (2024), p. 28.

for the circular economy. On the other hand, companies that are not considered data economy ready can utilise digital technologies, for example for circularity. Nevertheless, data economy readiness provides an indication of whether companies are at least in a position to make full use of digitalisation for themselves and the circular economy.

In addition, existing potential can be estimated from this. If only a minority of companies are able to utilise data efficiently, there is certainly still potential for expansion in this area. As a result, there should be untapped potential with regard to establishing a circular economy and thus increasing resource efficiency.

4.1.1.2 Cross-company networking

> **In expert interview #7 (steel processing), the following comments were made on the status of networking:** "Up to now, there has only been an extremely rudimentary exchange of data across company boundaries. Data are only exchanged automatically with one customer. This also has to do with size: Automated data exchange is only worthwhile for large companies with high volumes. Craft businesses, small businesses etc. send their individual orders by e-mail. Elaborate systems aren't worthwhile there."

The main benefit of digitalisation and the circular economy lies in networking across company boundaries. Ideally, from the perspective of the circular economy, communication takes place along the entire value creation network. The importance of cross-company data exchange is illustrated by an OECD analysis that focuses on the potential of digitalisation for resource efficiency and the circular economy[85]. In particular, the reduction of transaction costs and information asymmetries requires an exchange of data. This exchange is all the more efficient if it is automated. Neither data exchange nor digital networking are standard at companies in Germany, however. In their study of data sharing based on a survey of more than 1,000 industrial companies and industry-related service providers in

[85] **Cf. Barteková, E. and Börkey, P. (2022), p. 9.**

autumn 2023, Bakalis and Büchel (2024) come to the conclusion that 61 percent of companies do not receive any external data and 81 percent do not transfer any data to external partners[86].

The exchange of data with other companies, authorities, research institutes etc. is an indication of the extent to which companies are digitally networked. The degree of digital networking of companies in Germany was also analysed, however. For example, networking is an indicator of the digitalisation index commissioned by the German Federal Ministry for Economic Affairs and Climate Change[87, 88]. To determine the degree of networking, companies in Germany are asked to what extent individual processes are networked within the company and with customers, suppliers and other players in the value creation chain. While the proportion of externally networked companies in 2022 was nearly 19 percent among small companies, 26 percent of medium-sized companies and 33 percent of large companies were externally networked. The proportions have increased compared to 2020. Still, only a minority of all companies in Germany are externally networked (around 19 percent), [89].

4.1.2 Resource efficiency potential of digitally supported circular measures

The potential of digitalisation for the implementation of the circular economy is also seen in the expert interviews.

> **An example from expert interview #2 (packaging industry) concurs:** "Digitalisation provides a decisive lever for implementing the circular economy."

The resource efficiency potential of the circular measures supported by digital solutions is analysed qualitatively. Two existing studies in this

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[86] **Cf. Bakalis, D. and Büchel, J. (2024), p. 31.**

[87] **Cf. Büchel, J. and Engels, B. (2023b).**

[88] **Cf. Büchel, J.; Demary, V.; Goecke, H.; Mertens, A.; Rusche, C. and Wendt, J. M. (2021).**

[89] **Cf. Büchel, J. and Engels, B. (2023b), p. 54.**

subject area are used as a basis. In Neligan et al. (2021a), the importance of digitalisation for resource efficiency is examined on the basis of the direct influence of digital technologies on measures for increasing resource efficiency. This shows that the potential for saving resources in the German economy is by no means exhausted. Based on a company survey, the absolute resource-saving potential in the manufacturing sector is roughly estimated at more than ten billion Euros or a good one percent of gross industrial value creation. Digitalisation could be a key factor in leveraging this potential[90]. The importance of digital technologies for the establishment of a resource-efficient economy in the sense of a circular economy is addressed in the study by Barteková and Börkey (2022).

It should be noted that both studies show considerable differences with regard to the technologies analysed. The technologies listed are divided by Neligan et al. (2021a) into the clusters of data/analytics, artificial intelligence, IoT (Internet of Things)/robotics, virtualisation, green tech (the linking of digital technologies with environmental technologies[91]), standards as enablers, networks as enablers and hardware and interfaces as enablers[92]. Based on a company survey, the authors come to the conclusion that data analysis currently has the highest priority in terms of resource efficiency. The collection of data and the establishment of interfaces are important preconditions in this respect, however. Companies also use digital platforms, process monitoring and predictive maintenance to increase resource efficiency. Technologies are rarely used when it comes to further networking and collaboration or modelling and simulation[93].

[90] **Cf. Neligan, A.; Engels, B.; Schaefer, T.; Schleicher, C.; Fritsch, M.; Schmitz, E.; Wiegand, R. and Arnold, R.C.G. (2021a), p. 43.**

[91] **Cf. German Federal Ministry of Education and Research (2024).**

[92] **Cf. Neligan, A.; Engels, B.; Schaefer, T.; Schleicher, C.; Fritsch, M.; Schmitz, E.; Wiegand, R. and Arnold, R.C.G. (2021a), p. 79 et seq.**

[93] **Cf. Neligan, A.; Engels, B.; Schaefer, T.; Schleicher, C.; Fritsch, M.; Schmitz, E.; Wiegand, R. and Arnold, R.C.G. (2021a), p. 66.**

Barteková and Börkey (2022) focus on seven specific technologies: IoT, Big Data analytics, artificial intelligence, blockchain (a blockchain is a decentralised ledger that primarily records the ownership of assets of all participants in this network[94]), cloud computing, digital platforms and 3D printing[95]. The authors point out, however, that several of the technologies in question are generally used by companies at the same time and it is therefore hardly possible to specify the contribution of a single technology to the establishment of a resource-efficient economy[96]. A key aspect of this study is the implementation of policy measures. In addition, digital technologies are analysed in particular with regard to the extent to which market failures such as imperfect information, transaction costs and external effects can be reduced with regard to greater resource efficiency and the circular economy.

Both studies show a possible positive correlation between digital technologies and the successful implementation of a resource-efficient economy. If digital technologies are used to implement circular measures efficiently, this should also promote resource efficiency.

4.1.3 Deriving qualitative resource efficiency potential

Based on the preceding literature analysis, the following conclusions can be drawn in this chapter regarding the resource efficiency potential of digital technologies:

- **Resource efficiency potential through digital networking:** In the context of digital networking, it can be concluded based on the results of Neligan et al. (2021a) and Büchel/Engels (2023b) that there is still untapped resource efficiency potential[97,98]. Digital networking can

[94] Cf. Demary, M. and Demary, V. (2017), pp. 1.

[95] Cf. Barteková, E. and Börkey, P. (2022), p. 56 et seqq.

[96] Cf. Barteková, E. and Börkey, P. (2022), p. 17.

[97] Cf. Neligan, A.; Engels, B.; Schaefer, T.; Schleicher, C.; Fritsch, M.; Schmitz, E.; Wiegand, R. and Arnold, R.C.G. (2021a), p. 31.

[98] Cf. Büchel, J. and Engels, B. (2023b), p. 31.

contribute in particular to closing (S1), enabling (S2b) and creating (S3) cycles. There is also potential in the utilisation phase, i.e. the extension of cycles (S4).

- **Resource efficiency potential through the digital twin:** Digital twin technology also has high resource efficiency potential. To leverage the potential with the help of a circular economy, digital twins can be used for more efficient utilisation of resources in production in particular, e.g. through simulation (S2a), the consideration of circular capacity in design and/or material and production substitution (S2b).
- **Resource efficiency potential through process data collection:** The collection of process data can contribute to more resource-efficient production within the company, above all because more transparency can be created by analysing the data. By supporting processes along the value creation chain using digital technologies, existing efficiencies can also be leveraged there.
- **Resource efficiency potential through digital products and services:** Digital and partially digitalised products and services offer opportunities for implementing a circular economy and increasing resource efficiency, as digital components can be used to collect data and offer services that support or enable the transition to a circular economy. As the proportion of revenue generated by companies in Germany with purely digital products and services in 2022 was only twelve percent, there is significant potential to increase resource efficiency here[99].
- **Resource efficiency potential through digital business models:** Neligan et al. (2021a) show that it is difficult for companies to develop digital business models with the aim of increasing resource efficiency. Resource efficiency tends to manifest itself in smaller-scale concepts of entrepreneurial activity that are not necessarily directly linked to value creation. Only a few companies are highly digitalised when it comes to resource efficiency measures. As a result, there is a lack of holistic

[99] **Cf. Büchel, J. and Engels, B. (2023b), p. 56.**

consideration of digitalisation and resource efficiency and a failure to fully exploit the opportunities offered by digitalisation, which means that there is likely to be untapped resource efficiency potential[100]. This is also confirmed by Barteková and Börkey (2022) with regard to the circular economy[101]. In particular, sharing and platform business models can close (S1), enable (S2b) or extend (S4) cycles.

4.2 Digital technologies – Company survey

Key messages

- There is a positive correlation between the adoption of measures for improving circularity and the success of the companies surveyed.
- The majority of companies are aware of the need to collect sufficient data, so the prerequisites for the successful use of digital technologies in the context of a circular economy are in place.
- Digital technologies have only played a subordinate role in the implementation of circular measures in SME practice to date, however – many companies are not yet digitalised with regard to circular measures.
- For companies to remain competitive, the use of digital solutions for circular measures must be economically viable. The assessment of the cost-benefit ratio of digitally supported circular measures varies greatly from company to company – there are both companies that rate the benefits higher than the costs and vice versa, and at the same time there are some companies that consider the ratio to be balanced and those that cannot make an assessment.

[100] Cf. Neligan, A.; Engels, B.; Schaefer, T.; Schleicher, C.; Fritsch, M.; Schmitz, E.; Wiegand, R. and Arnold, R.C.G. (2021a), p. 7.

[101] Cf. Barteková, E. and Börkey, P. (2022), p. 19 et seqq.

- Companies that already use digital technologies for circular measures to a medium to high degree rate the cost-benefit ratio much more positively.
- Major obstacles to the use of digital technologies include the lack of expertise, the lack of information and consulting options, the lack of a complete solution for comprehensive data collection and utilisation, the inability to retrofit existing systems and the lack of financial resources.

4.2.1 The role of digital technologies in improving circularity

> **The role of digital technologies in improving circularity was discussed in expert interview #6 (toolmaking):** "Digitalisation offers numerous opportunities for supporting/implementing the circular economy. This is achieved through co-operation across company boundaries. Although the industry is rather conservative and there are hurdles to overcome, a shift in opinion towards digitalisation is foreseeable."

Digital technologies have so far only played a minor role in the implementation of circular measures at SMEs (cf. Figure 7). In this respect, 57 percent of the SMEs in the manufacturing sector that use circular measures are considered to be non-digitalised. This simply means that digital technologies are rarely used at companies for the direct implementation of circular measures, however. The degree of utilisation of digital technologies with regard to circular measures is low for 19 percent of SMEs and can be described as "medium" for 18 percent. Only six percent of SMEs already have a high level of digitalisation when it comes to using circular measures.

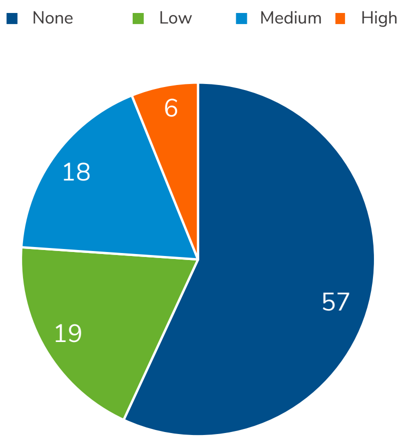

Figure 7: Distribution of SMEs according to the degree of digitalisation of the circular measures implemented[102]

Table 5 provides further insight into the use of digital technologies for supporting circular measures through data on SMEs that do not use digital technologies for circular measures. The presentation of the proportion of non-users also reveals whether resource efficiency potential can still be leveraged with the help of digital technologies. The higher the proportion of non-users, the more likely it is that the use of digital technologies could lead to greater resource efficiency. Looking at all SMEs, the only areas in which the majority of companies do not use digital technologies are the use of secondary raw materials (63 percent) and the reuse and reprocessing of products and/or product parts (50 percent). For all other measures, the proportion of companies that use digital technologies to at

[102] **Percentages of SMEs in the manufacturing sector that have already implemented circular measures.**

Own typification based on two questions: “To what extent do digital applications/technologies contribute to improving circularity at your organisation?” and “To what extent does your organisation use digital technologies for circular measures?” In each case with the possible answers: not at all; to a small extent; to a medium extent; to a large extent. Rounding differences are possible. – IW Future Panel, wave 46, 2023, N = 190

least a small extent predominates. This applies in particular to companies with up to 49 employees. In this size category, the proportion of non-users is also so high for the reuse (recycling) of raw materials and other materials at around 49 percent that only a very small majority use digital technologies, at least to a limited extent. Small companies are most likely to use digital technologies for product-related services (64 percent) and for energy efficiency and energy-saving measures (61 percent).

At companies with 50 to 249 employees, only a minority of all circular measures do not use digital technologies. The highest proportions of non-users are the reuse and recycling of raw materials and other materials (39 percent), the use of secondary raw materials and circular product design (35 percent each). Digital technologies are used most frequently for energy efficiency and energy saving in this size category. Only ten percent of the companies surveyed do not use digital technologies here. In the case of companies with 250 employees or more, which are not included in Figure 8 due to the focus on SMEs, only a minority are non-users of digital technologies with regard to the aforementioned circular measures. The number of responses in this size class is low, however, ranging from 21 responses (product-complementary service offerings) to 38 responses (optimisation of manufacturing processes), and must therefore be interpreted with caution. This applies to all statements on large companies in this chapter. All responding companies in this size class use digital technologies for product-related services. More than 92 percent use digital technologies for energy-efficiency and energy-saving measures. The highest proportions of non-users are found in the recycling of raw materials and other materials, circular product design and the use of secondary raw materials.

Table 5: SMEs that do not use digital technologies for the eleven circular measures analysed[103]

	SME total	Up to 49 EM	50 to 249 EM
Use of new materials	42	44	30
Use of secondary raw materials	63	67	35
Circular product design	40	41	35
Supplementary product services	34	36	23
Reuse/reprocessing of products and/or product parts	50	53	30
Energy-efficiency/-savings -measures	35	39	10
Optimisation of manufacturing processes for conserving resources/avoiding waste	42	46	17
Continued use/reuse of raw materials and other materials	43	44	39
Recycling of raw materials/other materials	47	49	30
Strategic management of circular measures	41	46	14
Information systems for circularity	37	42	16

4.2.2 Effects and evaluation options of digitally supported circular measures

Digitally supported circular measures can have various direct or indirect effects within the company and beyond.

[103] Proportions of the “not at all” category in percent of SMEs in the manufacturing sector with implemented circular measures by size class
Question: “To what extent does your company use digital technologies for circular measures?” Possible answers: not at all; to a small extent; to a medium extent; to a large extent.
Rounding differences are possible. – IW Future Panel, wave 46, 2023, N = 86 to 162

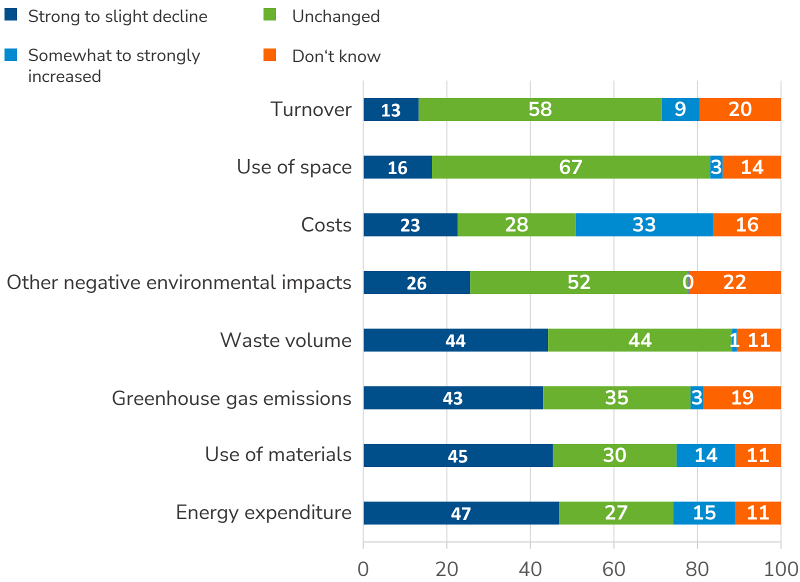

Figure 8: Effects of digital solutions in the case of circular measures[104]

Figure 8 indicates the assessments of SMEs that already use digital technologies to support circularity and have answered the question of what impact has been achieved at the company through the use of digital solutions in the case of circular measures. In particular, the use of natural resources such as space usage and greenhouse gas emissions was addressed. The companies were also asked about the impact on costs and turnover, however, which enables a statement to be made about the economic efficiency of using technology to support circular measures.

By analysing the difference between the proportions of SMEs that indicated a "strong to slight decrease" and those that indicated a "slight to

[104] Percentage of SMEs in the manufacturing sector with implemented circular measures

Question: "What effects has the use of digital solutions in the circular measures at your company had on …?" Possible answers: decreased significantly; decreased slightly; unchanged; increased slightly; increased significantly; don't know.

Other negative environmental impacts, e.g. pollution of air, water, soil. Rounding differences are possible. – IW Future Panel, wave 46, 2023, N = 124 strong increase", the following can be said about the extent of development of the responding companies:

- With a value of +40, the most significant effect can be seen in greenhouse gas emissions. This means that the proportion of companies that have identified a reduction is 40 percentage points higher than the proportion of companies that have identified more greenhouse gas emissions.
- In terms of energy consumption (+32 percentage points), material consumption (+31 percentage points), waste generation and other negative environmental impacts (e.g. air, water and soil pollution), each with +26 percentage points, also had predominantly positive effects.
- More SMEs have noticed cost increases due to the use of digital solutions. The proportion of companies where costs have risen is ten percentage points higher than the proportion of companies that have seen costs fall.
- The increased costs were only partially offset by higher turnover. The proportion of companies with higher turnover is four percentage points lower than the proportion of companies with falling turnover. Turnover fell slightly or strongly for 13 percent of SMEs. Only nine percent of SMEs that have already used digital technologies have seen a strong or slight increase.

The expert interviews provide insight into the entrepreneurial practice of SMEs.

> **This is stated in expert interview #5 (steel processing):** "Resource efficiency tends to be cost driven at the company. If the costs are too high, we react and then see whether we were able to improve the situation."

The statements made are relativised by the high proportion of companies that have not observed any effects or do not know whether there were any effects at all, however. In terms of the use of space, 81 percent of SMEs were unable to identify any effect or did not know whether there was an effect. There are similar uncertainties regarding turnover (78 percent stated "don't know" or "unchanged") and other negative environmental impacts (74 percent). The greatest clarity regarding the existence of effects was found for energy expenditure (38 percent stated "don't know" or "unchanged"), material expenditure (41 percent) and costs (44 percent). Consequently, an absolute majority of the companies surveyed assume the existence of an effect. Hence, the costs incurred and the consumption of energy and materials were the factors that could be estimated most reliably. For all other aspects, the majority of SMEs surveyed from the manufacturing sector were unable to identify any impact. This suggests that the effects of digital solutions linked to circular measures are still difficult to measure or determine and that there is therefore a knowledge gap.

There are only minor differences between the various SME size classes. Overall, the larger SMEs report more significant effects on energy expenditure when using digital solutions for circular measures. The proportion of companies that have noticed a reduction in energy consumption through the use of digital solutions is 58 percent among companies with 50 to 249 employees and only 45 percent among smaller companies. The proportion of companies with higher energy consumption is the same for both size classes (15 percent). The larger SMEs also note more significant impacts on greenhouse gas emissions. 51 percent reported falling emissions. The figure for smaller SMEs is 42 percent. In both size classes, companies hardly report any higher greenhouse gas emissions (three percent of small SMEs and one percent of larger SMEs).

A further difference can be identified with regard to turnover. Among companies with up to and including 49 employees, 15 percent reported a decrease and six percent an increase in turnover due to the use of digital technologies to support circular measures. Among companies with 50 to 249 employees, four percent reported falling turnover and 24 percent reported rising turnover. As a result, larger SMEs in the manufacturing sector benefit from digital technologies for circularity, while small companies tend to face declining turnover. As smaller companies are more frequently represented, the results in Figure 9 show that more companies are observing falling turnover. The cost trend is the same for both size classes. The proportion of companies with higher costs is around ten percentage points higher in both cases than the proportion of companies with falling costs.

4.2.3 Evaluation options for the effects of digitally supported circular measures

The high proportion of companies that did not know whether an effect of digital technologies used for circular measures exists already indicates difficulties in assessing the resulting effects. This is confirmed by the results of another question ("How well can your company determine the effects of the circular measures on the individual points?"). The majority of companies have great difficulty in determining the effects of the circular measures implemented.

Figure 9 presents the results of the survey by evaluation options for circular measures for SMEs. SMEs have the best options for assessing the use of materials: 51 percent of SMEs in the manufacturing sector are able to assess the changes in material use through circular measures fairly well to very well. For all other points, the majority of companies stated that they were unable to assess the effects very well or at all, or that they did not know the answer to the question.

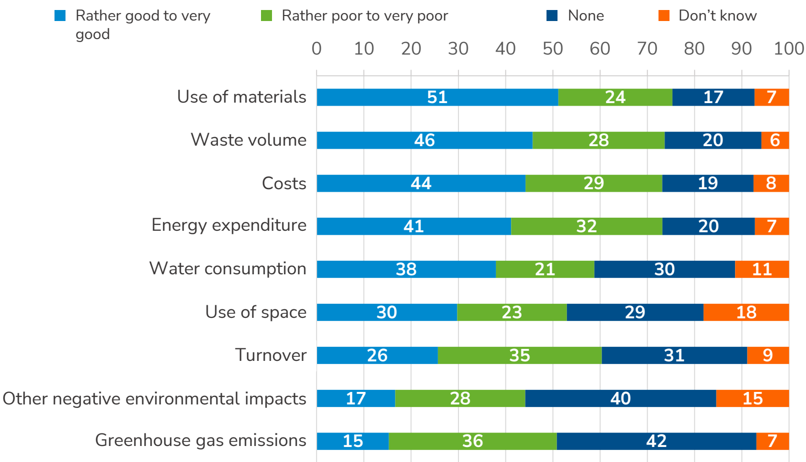

Figure 9: Quality of the evaluation options for the effects of circular measures[105]

The analysis by company size shows only minor differences in this respect. SMEs with 50 to 249 employees are better able to estimate their greenhouse gas emissions and energy consumption than smaller SMEs. In contrast, smaller SMEs are better able to estimate costs. For all other points, the differences between the SMEs are rather small. The biggest difference is in the assessment of the effects of circular measures on turnover, with a difference of four percentage points.

31 companies in the manufacturing sector with more than 249 employees also answered the question about the quality of the evaluation option. They can assess the circular effects much better than the SMEs surveyed. With the exception of turnover and other negative environmental impacts, the majority of respondents stated that they were able to assess the

[105] **Percentage of SMEs in the manufacturing sector with implemented circular measures Question: "How well can your company determine the effects of the circular measures on the individual points?" Possible answers: not at all; very poor; rather poor; rather good; very good; don't know. Rounding differences are possible. – IW Future Panel, wave 46, 2023, N = 161**

effects of all points rather well or very well. The best assessment is possible for material use and energy consumption (73 percent in each case).

4.2.4 Cost-benefit ratio

> **With regard to the cost-benefit ratio, expert interview #3 (plastics industry) summarised** that there is potential for further networking, but that the cost-benefit analysis has so far been negative.

When asked about the ratio between the costs and benefits of using digital solutions for circular measures, a mixed picture emerges (cf. Figure 10). Overall, a good two-fifths of SMEs rate the costs higher in comparison to the benefits, while only one-fifth rate the benefits higher in comparison to the costs and 16 percent consider this ratio to be balanced. Hardly any SMEs state that the benefits greatly outweigh the costs. At the same time, one in five companies state that they are unable to make an assessment. This is particularly the case for small SMEs with up to 49 employees.

For the sake of completeness, it is interesting to take a look at the large companies that are not included in Figure 10 due to the focus on SMEs. Among the 31 large companies with 250 or more employees surveyed, the benefits outweigh the costs more often than among SMEs. More than a third of large companies responded in this way.

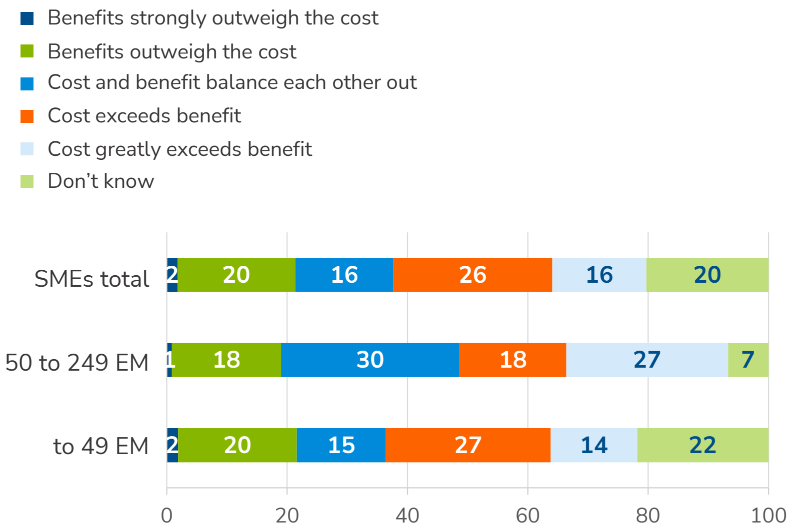

Figure 10: Assessment of the cost-benefit ratio when using digital solutions for circular measures[106]

A more balanced picture in terms of the cost-benefit ratio emerges when companies are classified according to their degree of digitalisation. Companies that already use digital technologies for circular measures to a medium to high degree rate the cost-benefit ratio much more positively (cf. Figure 11).

[106] Percentage of SMEs in the manufacturing sector with implemented circular measures by size class.
Question: "On balance, how would you rate the relationship between the costs and benefits of using digital solutions for circular measures?"
Possible answers: benefit strongly outweighs cost; benefit outweighs cost; cost and benefit are balanced; cost exceeds benefit; cost strongly exceeds benefit; don't know. Rounding differences are possible. – IW Future Panel, wave 46, 2023, N = 183

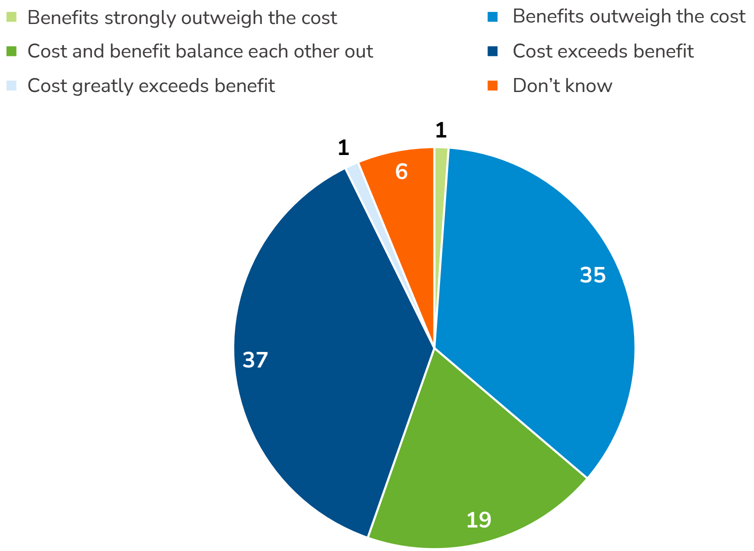

Figure 11: Digitalised SMEs: Assessment of the cost-benefit ratio[107]

Overall, more than a third of medium to highly digitalised companies rate the benefits as greater than the costs. A further third give the opposite assessment. The "don't know" rate of these companies (six percent) is low compared to all SMEs in the manufacturing sector (20 percent). This shows that companies that already use digital technologies and have gained experience are better able to assess the use of digitally supported circular measures. This, in turn, is a basic prerequisite for the successful implementation of these measures. In contrast, the costs outweigh the benefits for almost half of "not at all to slightly" digitalised companies; for one third of

[107] **Percentage of medium to highly digitalised SMEs in the manufacturing sector with implemented circular measures**

Question: "On balance, how would you rate the relationship between the costs and benefits of using digital solutions for circular measures?" Possible answers: benefit strongly outweighs cost; benefit outweighs cost; cost and benefit are balanced; cost exceeds benefit; cost strongly exceeds benefit; don't know. Rounding differences are possible. – IW Future Panel, wave 46, 2023, N = 61 medium to highly digitalised SMEs

these “not at all to slightly” digitalised companies, no assessment is possible.

Overall, the results show that many companies are still in the early stages of digitalisation. For them, the initial implementation or use of digital solutions for circular measures is initially correspondingly more expensive than for companies that have already digitalised. The survey results indicate that the ratio between costs and benefits can change when companies are digitalised. At this point, it becomes clear that companies need a certain degree of digitalisation in order to reap the corresponding benefits from the introduction of digitally supported circular measures. Nevertheless, many digitalised companies still face high expenditures.

4.2.5 Challenges in the use of digital technologies

The experts in the interviews made the following comments:

> **Expert interview #1 (textile industry): It was summarised** that the collection of data and their credibility are seen as the problem to be overcome. Digitalisation can help with subsequent transmission of the data, however.

> **Expert interview #2 (packaging industry): It depends on the mindset:** “Change begins with each individual. Everyone must leverage their own potential and create the conditions for co-operation with other partners.”

> **Expert interview #3 (plastics industry):** “The machines are not very digitalised, but they are expensive. It doesn’t pay to buy new ones or retrofit existing ones. There are also fears of problems with data protection, virus protection etc.”

> **Expert interview #5 (steel processing):** “There are few standards, but lots of ‘cooks’ who all have a solution. Everyone wants to offer as much as possible and push others out, but it has to be possible to have the best of everything. Politicians should encourage companies to help themselves and move forward.”

More successful companies tend to focus on circular measures as Lichtenthäler et al. (2023) have shown[108]. Digital technologies can also support the implementation of these measures. There are still some challenges for SMEs when using digital technologies as part of circular measures, however. Only a few SMEs consider the obstacles surveyed to be irrelevant (cf. Figure 12). At the same time, however, it is also clear that many SMEs are unable to judge whether the obstacles surveyed are relevant to them or not. The main obstacles for all SMEs in the manufacturing sector include:

- the lack of expertise or skilled labour (for 60 percent, this is a major or medium obstacle)
- the lack of a complete solution for comprehensive data collection and -use (59 percent see this as a medium or major obstacle)
- the lack of information and advice on costs, targets and benefits (55 percent)
- the inability to retrofit existing systems (50 percent)
- the lack of financial capacity (49 percent)

A lack of norms and standards, process-inhibiting internal procedures, a lack of trust in data security and an inadequate broadband structure are each seen as at least minor obstacles by around half of the companies. Only ten to 15 percent of companies rate these points as a medium or major obstacle, however.

[108] Cf. Lichtenthäler, S. and Neligan, A. (2023).

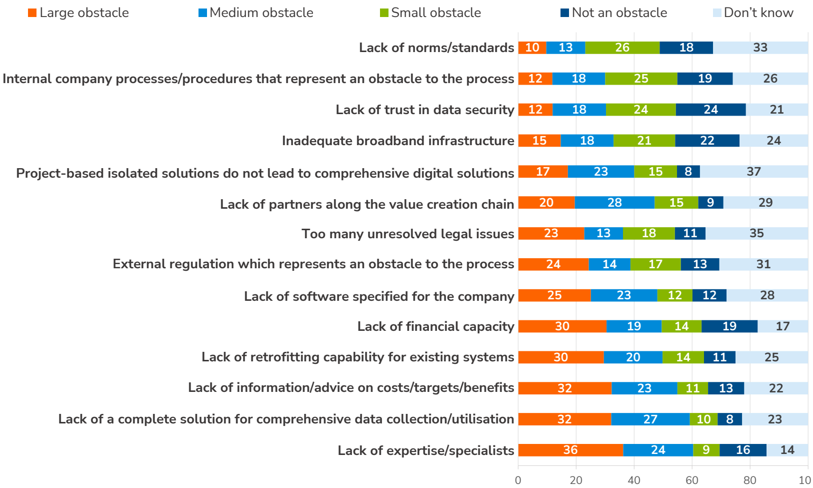

Figure 12: Relevance of existing obstacles for SMEs[109]

The company survey also shows that the perception of obstacles depends on the employee size class. Four-fifths of larger SMEs perceive the lack of partners along the value creation chain as at least a minor obstacle, while this only applies to three-fifths of small SMEs. Less decisive for larger SMEs are the inaccessible broadband infrastructure and trust in data security, at 55 percent and 49 percent, respectively. The latter is the only obstacle that receives a higher approval rate (55 percent) from small SMEs than from larger SMEs. Significant differences in perception can be seen in the assessment of whether project-related isolated solutions that do not lead to comprehensive digital solutions represent a significant challenge. While only 53 percent of small SMEs agree with this point, 73 percent of larger SMEs do. Even in the case of obstacles that have received a low

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[109] Percentage of SMEs in the manufacturing sector

Question: "What obstacles does your company experience when using digital technologies to implement circular measures?"

Possible answers: no obstacle; minor obstacle; medium obstacle; major obstacle; don't know. Rounding differences are possible. – IW Future Panel, wave 46, 2023, N = 280 to 289 level of agreement, the proportion of affected companies is usually over 50 percent.

Compared to SMEs, large companies with 250 or more employees (37 responses) are less likely to rate many of the challenges mentioned as a major obstacle. One exception is the answer “lack of norms and standards” – here, the proportion of twelve percent is comparable to the assessment by SMEs. This result indicates that, due to their higher level of digitalisation, large companies are already dealing with different topics than SMEs, which are often still in the early stages of digitalisation (cf. Section 4.2.2).

An interesting perspective on barriers to the use of digital technologies for circularity is provided by the distinction between companies that are not digitalised at all or digitalised to a low degree and those that are digitalised to a medium or high degree. It is clear that SMEs digitalised to a medium or high degree show an overall higher level of agreement with regard to the obstacles mentioned than the SMEs not digitalised at all or digitalised to a low degree. This applies to all obstacles with the exception of a lack of financial capacity. The most important obstacle for medium to highly digitalised companies is the lack of specialist knowledge or skilled workers, with 78 percent agreeing.

There is an unsurprising correlation between company success and the assessment of obstacles. This shows that successful companies generally see fewer obstacles to using digital technologies to implement circular measures than less successful companies. These different assessments of the obstacles are sometimes very clear. For example, 84 percent of companies with low success rate the lack of a complete solution for comprehensive data collection and use as an obstacle, while this only applies to 53 percent of successful companies. This trend applies to varying degrees to all of the obstacles surveyed, with the exception of the lack of partners along the value creation chain.

In 2024, the challenges are virtually unchanged compared to the survey by Neligan et al. (2021a) from 2020. In 2020, for example, the lack of financial capacity to set up fully digitalised systems and the ability to retrofit existing systems were already major obstacles. The problem also remains that there is a lack of complete solutions and that isolated solutions do not lead to comprehensive digitalisation. In addition, a lack of information and expert advice, a lack of expertise and uncertainty when assessing the cost-benefit ratio are major challenges. For example, there is still a lack of customised software for the company. Furthermore, the broadband infrastructure and data security, which are important for cross-company networking, are in need of improvement. Some companies also state that there is potential for improvement with regard to the existing legal framework, but also with regard to the lack of norms and standards[110].

[110] **Cf. Neligan, A.; Engels, B.; Schaefer, T.; Schleicher, C.; Fritsch, M.; Schmitz, E.; Wiegand, R. and Arnold, R.C.G. (2021a), p. 68.**

5 DETERMINATION OF CIRCULARITY EFFICIENCY BASED ON INDICATORS

In addition to the resource efficiency potential that can be realised through the use of digitally supported circular measures described in the previous chapter, the efficiency of the measure with regard to the implementation of a specific circularity strategy plays an important role. To date, there are no suitable indicators for measuring this circularity efficiency that SMEs can use to calculate the extent to which the measures implemented contribute to achieving their circularity goals. This chapter therefore covers ways of evaluating the circularity efficiency of digitally supported circular measures. Guidelines developed as part of this study are intended to support companies in finding suitable indicators for evaluation and applying them in practice.

Section 5.1 summarises and analyses the existing literature on the measurement of circularity. An assessment of the achievable resource efficiency potential resulting from the use of digital technologies as part of circularity strategies is then presented. Section 5.2 describes the development of the set of indicators for evaluating the circularity efficiency of digitally supported circular measures. Section 5.3 summarises and analyses the findings regarding the evaluation of digitally supported circular measures from the company survey and supplements them with examples from the expert interviews.

5.1 Circularity efficiency through digitally supported circular measures

Key messages

- The circularity efficiency of digitally supported circular measures can be determined with the help of indicators.
- There is a wide variety of literature in this area, but so far there is no practical measurement of circularity efficiency through digitally supported circular measures.

5.1.1 Indicators for determining circularity efficiency – Literature research

To determine circularity, indicators are used to quantify the degree of circularity. According to the literature, an indicator is the operational representation of a property of a system by a quantitative or qualitative variable[111]. A value is represented in relation to a reference value. Applied to circularity efficiency, an indicator measures the extent to which a digitally supported circular measure contributes to the achievement of a circularity strategy relative to the effort required to implement this measure (cf. chapter 2.3.5).

The literature research, mainly English-language scientific literature, primarily contains publications that present indicators for the measurement of circularity. The sources can be divided into primary sources and meta-studies (e.g. OECD, 2021; Kristensen et al., 2020)[112,113]. Both approaches are relevant for analysing existing indicators in this subject area, as the systematic literature reviews provide a good summary and structure of the indicators.

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[111] Cf. Waas, T.; Hugé, J.; Block, T.; Wright, T.; Benitez-Capistros, F. and Verbruggen, A. (2014), pp. 5520.

[112] Cf. OECD (2021).

[113] Cf. Kristensen, H. S. and Mosgaard, M. A. (2020).

Table 6 provides an overview of the literature analysed for the development of a company's own practical indicators. Among other things, the VDI 4800 Part 2[114] guidelines were taken into account. These include differentiating between primary and secondary raw materials when creating parts lists (listing of components) with the aim of obtaining raw material lists using material lists (including the energy used)[115].

Although there is a wealth of indicators for measuring resource efficiency or circularity, there is no standardised definition of resource efficiency on which these indicators are based. A resource efficiency concept was defined as part of this study (cf. Section 2.3.2), so that the literature can be evaluated in terms of the extent to which the term used there corresponds to the definition relevant to this work. In addition, not all indicators were developed to measure resource efficiency or the effect of specific measures on resource efficiency. Rather, they are intended to represent the degree of implementation of a circular economy in general.

The conclusion regarding the inconsistent definitions has already been reached by Huysman et al. (2015) in their project to systematise the indicators for assessing resource efficiency. The authors distinguish between level 1 and level 2 efficiency[116]. The former describes the relationship between the benefits and the measured flows of resources and emissions, and the latter the relationship between the (intended) effects or benefits and the environmental impacts.

Table 6: Overview of the analysed literature

[114] Cf. VDI 4800 Part 2: (2018-03).

[115] Cf. VDI (2018), pp. 7 et seq.

[116] Cf. Huysman, S.; Sala, S.; Mancini, L.; Ardente, F.; Alvarenga, R. A.F.; Meester, S. de; Mathieux, F. and Dewulf, J. (2015), P. 69.

Reference	Title
Huysman et al., 2015[117]	Toward a systematized framework for resource efficiency indicators
Potting et al., 2017[118]	Circular Economy: Measuring innovation in the product chain
VDI, 2017[119]	Ressourceneffizienz durch Industrie 4.0 – Potenziale für KMU des verarbeitenden Gewerbes [Resource efficiency through Industry 4.0 – Potential for SMEs in the manufacturing sector].
VDI, 2018[120]	VDI 4800 Part 2 guidelines
Lopez et al., 2019[121]	Business Model Innovation for Resource-efficiency, Circularity and Cleaner Production: What 143 Cases Tell Us
Kristensen et al., 2020[122]	A review of micro level indicators for a circular economy – moving away from the three dimensions of sustainability?
Rossi et al., 2020[123]	Circular economy indicators for organizations considering sustainability and business models: Plastic, textile and electro-electronics cases
OECD, 2021[124]	The OECD Inventory of Circular Economy indicators
Oliveira et al., 2021[125]	Nano and micro level circular economy indicators: Assisting decision-makers in circularity assessments
Brändström et al., 2022[126]	How circular is a value chain? Proposing a Material Efficiency Metric to evaluate business models
Goddin et al., 2019[127]	Circularity Indicators – An approach to measuring circularity

[117] Cf. Huysman, S.; Sala, S.; Mancini, L.; Ardente, F.; Alvarenga, R. A.F.; Meester, S. de; Mathieux, F. and Dewulf, J. (2015).

[118] Cf. Potting, J.; Hekkert, M.; Worrell, E. and Hanemaaijer, A. (2017).

[119] Cf. VDI Zentrum Ressourceneffizienz GmbH (2017a).

[120] Cf. VDI 4800 Part 2: 2018-03.

[121] Cf. Diaz Lopez, F. J.; Bastein, T. and Tukker, A. (2019).

[122] Cf. Kristensen, H. S. and Mosgaard, M. A. (2020).

[123] Cf. Rossi, E.; Bertassini, A. C.; Ferreira, C. d. S.; Neves do Amaral, Weber Antonio and Ometto, A. R. (2020).

[124] Cf. OECD (2021).

[125] Cf. Oliveira, C. T. de; Dantas, T. E. T. and Soares, S. R. (2021).

[126] Cf. Brändström, J. and Eriksson, O. (2022).

[127] Cf. Goddin, J.; Marshall, K.; Pereira, A.; Tuppen, C.; Herrmann, S.; Jones, S.; Krieger, T.; Lenges, C.; Coleman, B.; Pierce, C. J.; Iliefski-Janols, S.; Veenendaal, R.; Stoltz, P.; Ford, L.; Goodman, T.; Vetere, M.; Mistry, M.; Graichen, F.; Natarajan, A.; Cockburn, D.; Koski, O. and Sullens, W. (2019).

Huysman et al. (2015) explain some of the indicators that can be used to measure or determine the circularity efficiency of digitally supported circular measures. For example, they cite process efficiency, defined as the ratio between output and input flows, as an indicator[128]. Other examples include material intensity, defined as the material input per unit, and eco-efficiency, defined as monetary output versus environmental impact. These examples show that it is relevant to consider which data are available or can be obtained in SMEs in order to ensure practical suitability, however. In addition, a differentiation between primary and secondary raw materials is important for the present application[129].

There are also different levels of consideration with regard to measuring the degree of circularity and resource efficiency. Oliveira et al. (2021) explicitly address this fact and distinguish between four levels of circularity measurement indicators: the macro-, meso-, micro- and nano-circularity levels. The macro level refers to circular strategies in cities, federal states or regions. It includes the redesign of infrastructure systems such as clean energy and transport. The meso level comprises circular strategies such as for inter-company mergers, while the micro level relates to consumers and individual companies. The nano level includes circular strategies aimed at the circular capacity of products, components and materials. The indicators for SMEs developed as part of this study are based on the micro and nano levels[130].

The OECD study (2021) analyses 29 studies from 2018 to 2020 and provides the most comprehensive list of indicators for measuring the implementation of a circular economy. The authors identify a total of 474 indicators. Many of them are located at the macro or meso level, however. Examples of indicators that are relevant for this study include:

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[128] **Cf. Huysman, S.; Sala, S.; Mancini, L.; Ardente, F.; Alvarenga, R. A.F.; Meester, S. de; Mathieux, F. and Dewulf, J. (2015), P. 69.**

[129] **Cf. Oliveira, C. T. de; Dantas, T. E. T. and Soares, S. R. (2021), pp. 456.**

[130] **Cf. Oliveira, C. T. de; Dantas, T. E. T. and Soares, S. R. (2021), pp. 456.**

- Energy efficiency
- Utilisation of renewable energies
- CO_2 savings
- Recovery of materials through reuse and recycling
- Proportion of secondary raw materials in the materials used
- Amount of waste avoided
- Use of secondary materials and primary materials
- Material intensity
- Resource productivity[131]

In their article, Rossi et al. (2020) propose a list of indicators for measuring circularity and divide these into the dimensions “material”, “economic” and “social”[132]. Several indicators and sub-indicators are assigned to each dimension. Among other things, it is important to differentiate between the actual use of recycled materials (recycled content) and the possibility of recycling (recyclability), which is already established during product design. This distinction is also useful and relevant for measuring digitally supported circular measures. There are some indicators, such as “circular investment” and “job creation”, which are either not quantifiable in practice or are difficult to attribute to specific measures, however. In addition, qualitative and quantitative indicators are mixed.

Potting et al. (2017) assign concrete circularity strategies to the R strategies they have defined. They also draw up a list of diagnostic questions to determine the progress of the process and the effects on the transition to

[131] Cf. OECD (2021).

[132] Cf. Rossi, E.; Bertassini, A. C.; Ferreira, C. d. S.; Neves do Amaral, Weber Antonio and Ometto, A. R. (2020), pp. 8 et seq.

a circular economy[133]. Although these questions are not specific indicators, they help to structure and compare the completeness of an indicator.

The list of diagnostic questions below is a continuation of the questions developed by the EEA (2016)[134]:

- Is the absolute consumption of primary materials reduced?
- Does the design take reuse and recycling into account?
- Is the proportion of hazardous substances in products decreased?
- Are the products used more frequently or for longer periods of time?
- Do the materials retain their value, and are they recycled to a high standard?

The circular strategies defined by Potting et al. (2017) are related to specific use cases and therefore differ fundamentally from the product-independent circularity strategies used here. The strategies can be located along the value creation chain regardless of the type of product. The appropriate R strategies are assigned to each strategy. It is then determined to what extent and in which area they should be implemented[135].

Another approach is the development of the Material Circularity Indicator (MCI) by the Ellen McArthur Foundation. This is product-related and measures the extent to which the linear flow is minimised and the regenerative flow for its components is maximised. The indicator also takes into account how long and intensively the product is used in comparison to a similar average product in the industry.

The MCI is made up of three product features:

- the mass of primary raw materials used in production

[133] Cf. Potting, J.; Hekkert, M.; Worrell, E. and Hanemaaijer, A. (2017), pp. 22.
[134] Cf. EEA (2016).
[135] Cf. Potting, J.; Hekkert, M.; Worrell, E. and Hanemaaijer, A. (2017), pp. 23 et seqq.

- the mass of non-recyclable waste attributed to the product
- a utility factor that takes into account the duration and intensity of use of the product[136]

Overall, the calculation of the MCI is very complex. For this reason, the product characteristics can provide valuable input for the development of the company's own indicators, even though the calculation of the MCI is considered to be of little practical use for the SME guidelines. In addition, the product is the point of reference here, while the objective of this paper is the company level and the digitally supported circular measures taken there.

The VDI ZRE study (2017) on the resource efficiency potential of Industry 4.0 provides important information on the general creation of indicators. The focus of this study lies on the resource-conserving effects of the digital transformation, however. It does not include circular measures and strategies. The six defined effects of digital technologies include:

- Avoidance of waste
- Saving energy in the form of electricity
- Reduction of the defect rate and the associated waste
- Saving storage space
- Reduction in the use of materials
- Savings on (internal) transport

All these effects are relevant for the development of a company-specific set of indicators[137].

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[136] Cf. Goddin, J.; Marshall, K.; Pereira, A.; Tuppen, C.; Herrmann, S.; Jones, S.; Krieger, T.; Lenges, C.; Coleman, B.; Pierce, C. J.; Iliefski-Janols, S.; Veenendaal, R.; Stoltz, P.; Ford, L.; Goodman, T.; Vetere, M.; Mistry, M.; Graichen, F.; Natarajan, A.; Cockburn, D.; Koski, O. and Sullens, W. (2019), pp. 22 et seqq.

[137] Cf. VDI Zentrum Ressourceneffizienz GmbH (2017a), p. 127 et seqq.

The previous explanations show that the analysed literature is very heterogeneous in terms of its specific objectives and development of indicators. All studies differ in at least one criterion from the indicators developed in this study to determine the circularity efficiency of digitally supported circular measures and contain relevant approaches that can be taken into account for the development of a company's own indicators.

Figure 13 provides a clear visualisation of the evaluation of the literature with regard to the various characteristics.

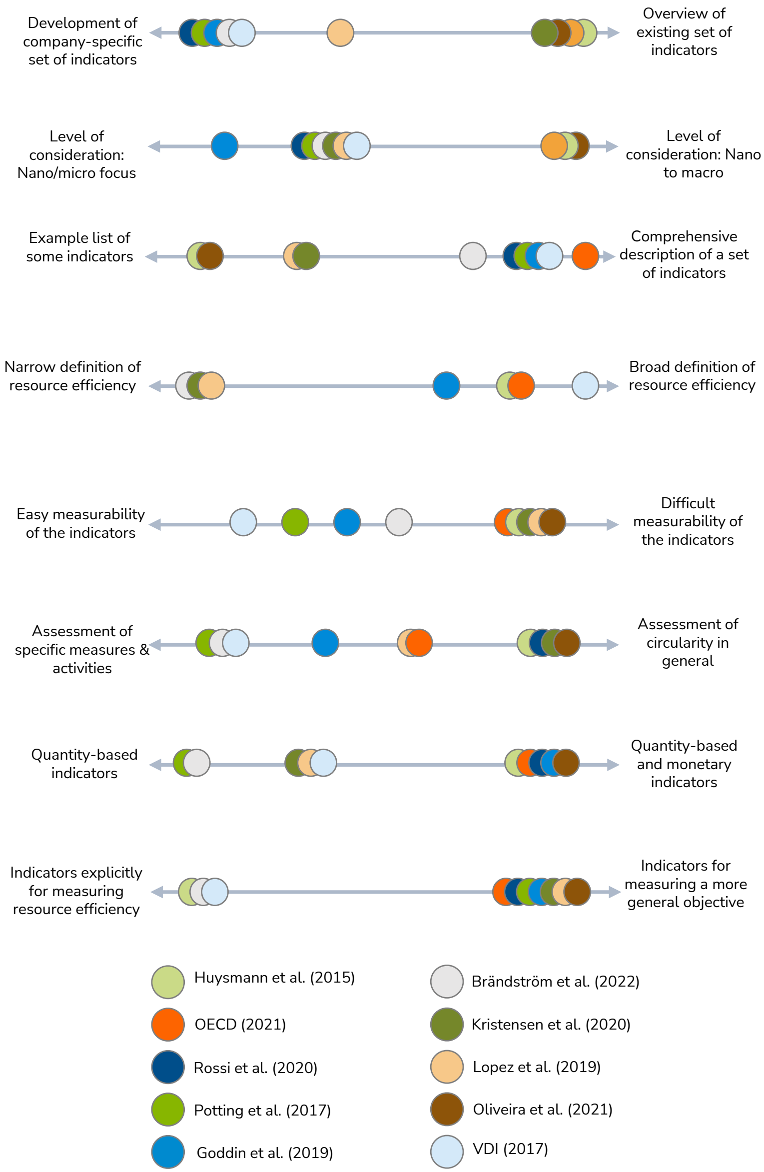

Figure 13: Comparison of indicators in the relevant literature[138]

Practical tools and guidelines

Some resource efficiency tools already exist. Examples include various cost calculators and the VDI ZRE resource checks. With a focus on resource efficiency through digitalisation, the SME guidelines prepared for the BMWK on this topic as well as two online tools and the VDI ZRE resource check on the topic of "digitalisation" and the "Readiness Check" of the Bavarian Resource Efficiency Centre (REZ), which also includes a section on digitalisation, should be mentioned[139, 140, 141]. None of these guidelines have a clear set of indicators, however.

There are also some practical guidelines that deal with the evaluation of circularity at companies, however. BITC (2022), CIRCLE Economy/BCG (2021) and CEIC (2023)[142, 143, 144] provide a good overview of the various circularity indicators and associated assessment tools. Specific indicators orientated towards circularity strategies are included in the WBCSD (2023) guidelines with the Circular Transitions Indicators, which are now available in their fourth version[145]. There is no reference to digitalisation here, however.

5.1.2 Comparison of digitally supported measures with circularity strategies

The resource efficiency potential of the various digital technologies varies depending on the strategy pursued. Overall, digitalisation can be used sensibly in all strategies. Analysing data is of fundamental importance for digital technologies and the digital representation of real-life situations.

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[138] VDI ZRE figure.
[139] Cf. VDI ZRE (without year).
[140] Cf. REZ Bayern (without year).
[141] Cf. IW Köln; IW Consult and WIK-Consult (2020), p. 48 et seqq.
[142] Cf. BITC (2022), p. 6
[143] Cf. CEIC (2023).
[144] Cf. Verstraeten-Jochemsen, J.; Oltmanns, J. and van Meeteren, O. (2021), pp. 13.
[145] Cf. wbcsd (2023).

Digital data collection therefore also plays a key role in terms of resource efficiency potential.

The guideline is simplified by merging the strategies “enabling cycles” (S2b) and “creating cycles” (S3). This has already been carried out in previous studies for the practical part in order to achieve better comprehensibility on the part of the companies[146]. Both strategies are similar in terms of the assigned measures and indicators, which is why merging them is a sensible simplification.

5.2 Development of a set of indicators for assessing the circularity efficiency of digitally supported measures

Key messages

- The indicators developed as part of this study can be used to determine the effects of digitally supported circular measures.
- The indicators offer SMEs the opportunity to decide which circular measures can be taken based on the circularity strategy pursued.
- The circularity efficiency can then be assessed using the indicators.

5.2.1 Requirements for indicators for determining circularity efficiency

Circularity efficiency, which is determined on the basis of the indicators, is intended to capture both the means and resources used and consumed by a company in the production of goods. The aim is to determine whether additional demand was generated by the digitally supported measures or whether resources could be conserved. For example, the use of digital technology can lead to the conservation of raw materials, while energy or water consumption increases. Increased energy consumption can lead to an increase in greenhouse gas emissions, which counteracts the

[146] Cf. Lichtenthäler, S. and Neligan, A. (2023).

conservation of raw materials. To obtain a meaningful overall measure of circularity efficiency, these effects must be taken into account and netted out.

As already mentioned (cf. Section 1), the measures taken at a company often have an impact along the entire value creation chain. These effects must also be considered with regard to the assessment of circularity efficiency, although some indicators can only be measured within company boundaries in order to avoid double counting. This applies, for example, to the conservation of primary raw materials or energy saving. Other indicators, such as the reuse/recycling/recovery rate, include a consideration of the value creation chain, as the reuse and recycling phase must be categorised after production and use. For an overall balance, it is important to consider the entire value creation chain, as circular measures must not merely lead to local shifts in expenditures, for example to suppliers and customers.

The developed indicators are mainly based on quantity-based data, but also include monetary aspects of circularity efficiency, particularly with regard to expenditure. Particularly with regard to feasibility in practice, quantity-based figures seem more realistic for SMEs compared to material savings. The latter are also based on additional information on prices, which may be time dependent and must be researched. A quantity-based approach seems to enable fundamental comparability between SMEs. It is also feasible to provide information on savings in monetary terms, for example, if this is desired by the SMEs, however. Monetary indicators are essential for establishing a measure of efficiency, which is why the development of new sources of revenue or new markets, for example, must also be taken into account.

In addition, there are overarching indicators with strategic components for assessing efficiency in the corporate context. This includes, for example, information systems for circularity and the strategic management of circular measures. In contrast to the quantity-based indicators, these indicators cannot be quantified, but only have a binary character. This means that the aspect covered or represented by the indicator is either present or not.

5.2.2 Matching of indicators with circular strategies and measures

The effects of circular measures, which were defined as part of the company survey, are important for structuring the indicators. These effects represent a structured overview with a broad understanding of resource efficiency.

Table 7 provides an overview of the indicators developed, including their allocation to the effects of circular measures. It is clear that all effects can be quantified using the indicators and are therefore included in the determination of circularity efficiency. While some effects of circular measures can be covered by just one indicator, the use of materials and costs in particular must be recorded much more comprehensively. Other environmental impacts, such as air, water and soil pollution, are difficult to visualise using indicators or are not very practical for SMEs and are therefore not easy to measure.

Despite their great relevance for resource efficiency, other environmental impacts should not be queried within the set of indicators. Instead, the guidelines should state that companies must also consider environmental impacts other than those mentioned and that they must be part of any strategy for greater resource efficiency.

Table 7: Allocation of indicators to the effects of circular measures[147]

	Effects of circular measures	Indicators
Monetary indicators	**Turnover**	• Development of new sources of revenue • Development of new markets or a larger market share
	Costs	• (Conserved) primary raw materials • (Saved) energy • (Reduced) CO_2 emissions • Reduced space requirement • (Reduced) water consumption • Use of secondary raw materials • Repair and upgrade expenses • Strategic management of circular measures in place • Information systems for circularity in place • Initial and ongoing costs for the integration of digital technology
Quantity-based indicators	**Use of materials**	• (Conserved) primary raw materials • Use of secondary raw materials • Proportion of products that take ecodesign into account • Reuse/recycling/recovery rate • Product life extension/intensification (resource life) • Repair and upgrade expenses (cost of materials)
	Energy expenditure	• (Saved) energy
	Water consumption	• (Reduced) water consumption
	Space requirement	• Reduced space requirement
	Waste volume	• (Avoided) waste • (Avoided) packaging waste
	Greenhouse gas emissions	• (Reduced) CO_2 emissions
	Other negative environmental impacts	(difficult to visualise using indicators; note in the guidelines)

The next step is to compare whether the indicators developed cover all circular measures. The requirement for the completeness of the indicators is that the effects of all measures – both on the product and business model levels and at the process level – can be measured or determined using the indicators. Table 8 shows that this requirement is met. There are

[147] VDI ZRE figure based on the literature reviewed (cf. Table 5).

three additional business indicators: opening up new sources of revenue, developing new markets or a larger market share as well as initial and ongoing costs for the integration of digital technology. To enable SMEs to use the guidelines to determine the resource efficiency of digitally supported circular measures in relation to the targeted circularity strategy, the strategies must finally be matched to the indicators.

The overview in Figure 14 offers SMEs the opportunity to decide which circular measures can be taken and which indicators are necessary for assessing the circularity efficiency of this strategy based on the circularity strategy pursued. Entry x describes a direct influence, and entry (x) an indirect influence of the indicator on a strategy.

As overarching measures, the strategic management of circular measures and information systems for circularity are not explicitly assigned to any strategy, but can rather be part of or the basis of any circularity strategy. For this reason, these measures appear under all strategies. Another special feature of these measures is that although the indicators query the existence of strategic management and information systems, they are not quantified.

When interpreting the allocation of indicators to the strategies, it is important to note that the strategy “resource efficiency in the manufacturing process” (S2a) focuses on the process and does not include any changes to the product. Product-related adjustments, such as ecodesign, are considered in the “enabling cycles” strategy. For this reason, indicators such as the possible conservation of primary raw materials are not assigned to strategy S2a.

The practical guidelines for SMEs in the manufacturing sector can be found in the appendix to this study. This also contains detailed descriptions of the indicators as well as help with their calculation.

Table 8: Allocation of the indicators to the circular measures[148]

	Circular measures	Indicators
Product level/Business models	Use of new materials	• (Conserved) primary raw materials • (Reduced) CO_2 emissions • Reduced space requirement • (Reduced) water consumption
	Use of secondary raw materials	• (Conserved) primary raw materials • (Reduced) CO_2 emissions • Use of secondary raw materials
	Circular product design	• (Reduced) CO_2 emissions • Proportion of ecodesign conformant products • (Avoided) waste • Product life extension/intensification (resource life)
	Supplementary product services	• (Reduced) CO_2 emissions • Product life extension/intensification (resource life)
	Reuse and -reprocessing of products/parts	• (Conserved) primary raw materials • (Reduced) CO_2 emissions • Reuse/recycling/recovery rate • Product life extension/intensification (resource life) • Repair and upgrade expenses
	Energy efficiency and energy savings measures	• (Saved) energy • (Reduced) CO_2 emissions
Process level	Optimisation of manufacturing processes for conserving resources/avoiding waste	• (Saved) energy • (Reduced) CO_2 emissions • Reduced space requirement • (Reduced) water consumption • (Avoided) waste/packaging waste
	Reuse and recycling of raw materials and other materials	• (Conserved) primary raw materials • (Reduced) CO_2 emissions • Reuse/recycling/recovery rate • Use of secondary raw materials • Repair and upgrade expenses
	Recycling of raw materials and other materials	• (Conserved) primary raw materials • (Reduced) CO_2 emissions • Reuse/recycling/recovery rate • Use of secondary raw materials
	Strategic management of circular measures	• Strategic management of circular measures in place
	Information systems for circularity	• Information systems for circularity in place
Superordinate		• Development of new sources of revenue • Development of new markets/greater market share • Initial and ongoing costs for the integration of digital technology

[148] VDI ZRE figure based on the literature reviewed (cf. Table 6).

		Closing cycles (S1)					Improved resource efficiency (S2a)				Enabling cycles (S2b)			Creating new cycles (S3)				Extending cycles (S4)				
	Indicators \ Measure	Use of secondary raw materials	Continued use and reuse of raw materials and other materials	Recycling of raw materials and other materials	Strategic management of cycle-orientated measures	Information systems for circularity	Energy efficiency and energy savings measures	Optimisation of manufacturing processes for conserving resources	Strategic management of cycle-orientated measures	Information systems for circularity	Cycle-conformant product design	Strategic management of cycle-orientated measures	Information systems for circularity	Use of new (innovative) materials	Recycling of raw materials and other materials	Strategic management of cycle-orientated measures	Information systems for circularity	Supplementary product services	Reuse & reprocessing of products/parts	Continued use and reuse of raw materials and other materials	Strategic management of cycle-orientated measures	Information systems for circularity
Quantity-based	Conserved primary raw materials	x	x	x							(x)			x	x				x	x		
	Conserved energy	(x)	(x)	(x)			x	x							(x)				(x)	(x)		
	Reduced CO_2 emissions	(x)	(x)	(x)			x	x							(x)				(x)	(x)		
	Reduced space requirement							x						x								
	Reduced water consumption							x						x								
	Reuse/recycling/recovery rate	(x)	x	x							(x)			(x)	x			(x)	x	x		
	Proportion of products that take ecodesign into account										x			(x)								
	Avoided waste	(x)	(x)	(x)				x			x				(x)			(x)	(x)	(x)		
	Avoided packaging waste							x										(x)				
	Product service life extension/ intensification (benefit factor)										x							x	x			
	Use of secondary raw materials	x	x	x											x					x		
	Repair & upgrade expenses (cost of materials)		x																x	x		
Superordinate	Strategic management of cycle-orientated measures in place				x				x			x				x					x	
	Information systems for circularity available					x				x			x				x					x
	Development of new sources of income	x	x	x			x	x			x			x	x			x	x	x		
	Development of new markets or a larger market share	x	x	x			x	x			x			x	x			x	x	x		
	Initial and ongoing costs for the integration of digital technology	x	x	x			x	x			x			x	x			x	x	x		

Figure 14: Overview of indicators, circular strategies and measures (VDI ZRE figure)

5.3 Evaluation of circular measures – Results from the company survey

Key messages

- Many companies perceive a positive impact of digitally supported circular measures on the utilisation of natural resources.
- Nevertheless, the proportion of companies that have not noticed any effects is very high.
- The majority of companies are unable to determine the effects of the circular measures implemented.
- For this reason, it is necessary to quantify these measures.
- This is precisely where the developed SME guidelines come in, which can be used to evaluate the digitally supported circular measures used in terms of their efficiency in achieving circularity.

The majority of companies have great difficulty in determining the effects of the circular measures they have implemented. Figure 15 presents the results of the survey on the assessment options for circular measures.

SMEs have the best options for assessing the use of materials: 51 percent of SMEs in the manufacturing sector are able to assess the changes in material use through circular measures fairly well to very well. At 46 percent for waste generation and 44 percent for costs, a high proportion of companies are able to assess the effects rather well to very well. SMEs in the manufacturing sector have the worst assessment options when it comes to greenhouse gas emissions. 78 percent state that they are not able to assess the effects on greenhouse gas emissions of implemented circular measures at all, or that they assess them rather poorly to very poorly.

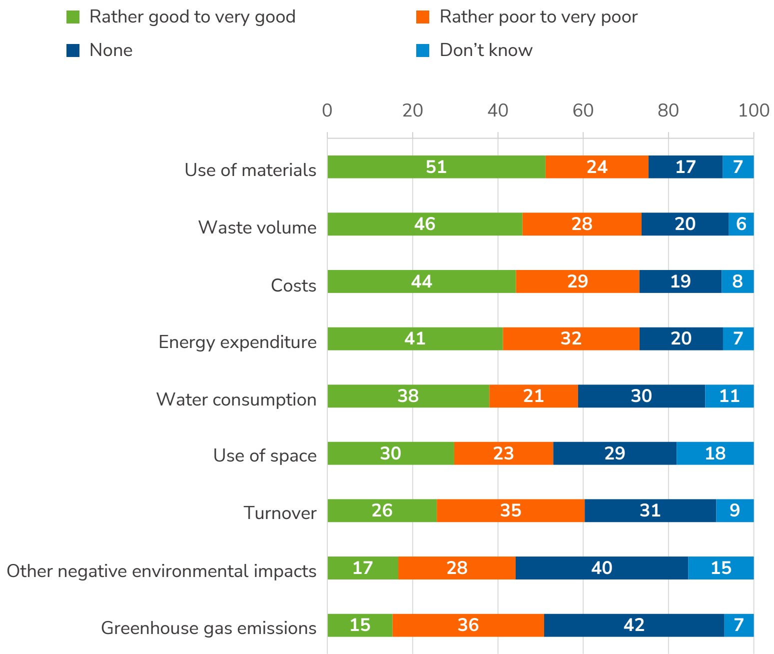

Figure 15: Quality of the evaluation options for the effects of circular measures[149]

The analysis by company size among SMEs shows only minor differences in this respect. SMEs with 50 to 249 employees are better able to estimate their greenhouse gas emissions and energy consumption than smaller SMEs. In contrast, smaller SMEs are better able to estimate costs. For all other points, the differences between company sizes are rather small. The biggest difference is in turnover, with a difference of four percentage points. 26 percent of small SMEs and 22 percent of larger SMEs state that they can assess the effects rather well or very well.

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[149] **Percentage of SMEs in the manufacturing sector with implemented circular measures Question: "How well can your company determine the effects of the circular measures on the individual points?" Possible answers: not at all; very poorly; rather poorly; rather well; very well; don't know. Rounding differences are possible. – IW Future Panel, wave 46, 2023, N = 161**

Companies with more than 249 employees can assess the effects of circular measures much better than the SMEs surveyed. With the exception of turnover and other negative environmental impacts, the majority of respondents greater than 50 percent stated that they were able to assess the effects of all points rather well or very well. The best estimate is possible in terms of material usage and energy consumption. In each case, 73 percent of companies state that they are able to assess the effects here rather well or very well.

The expert interviews support the picture already revealed by the company survey. Even those SMEs that are active in the areas of digitalisation and the circular economy largely do not measure their resource efficiency as such. Some of the companies surveyed do measure is energy, water, oil and gas consumption, but not changes. None of the companies surveyed in the interviews used indicators to measure resource efficiency.

> **Expert interview #1 (textile industry):** "If data on used products are available, this data could be used for circularity. Energy is required for data processing, however. The resources saved through the circular economy must be compared with the energy required."

> **Expert interview #2 (packaging industry):** "Everything plays into everything else. This means that it is not clear what proportion can be attributed to digitalisation, as changes have also been made to the processes and the product."

Reasons given for not measuring resource efficiency include a lack of time or excessive bureaucratic hurdles. The experts interviewed also emphasised that it is particularly difficult to collect key figures when they go beyond company boundaries. There is often a lack of interfaces and corresponding contacts with suppliers and customers.

> **Expert interview #4 (plastics industry):** "The waste bin is our indicator of efficiency and raw material management."

6 RECOMMENDED ACTIONS

The study provides starting points for how SMEs in the manufacturing sector can increase resource efficiency at the company and evaluate circularity efficiency by making greater use of digitally supported circular measures. The survey of the status quo as part of a representative company survey and the in-depth interviews with experts provide relevant information on the current status of digitally supported circular measures and the existing assessment options for the resulting resource efficiency potential.

Based on the need for action identified in the study, three fields of action are formulated in this chapter and specific recommendations for action are derived for policymakers, industry and science.

- Field of action 1: Strengthening circular measures
- Field of action 2: Strengthening the use of digital technologies for circular measures
- Field of action 3: Improving the measurability and assessability of circularity efficiency

After a brief summary of the need for action for each field of action, the following subsections describe three specific recommendations for action for the target groups of politics, industry and science (cf. Figure 16). Despite the customisation of the recommendations for action to the individual target groups, they do overlap to some extent. This shows the need for a common mindset and approach among the stakeholders involved and emphasises the relevance of such measures.

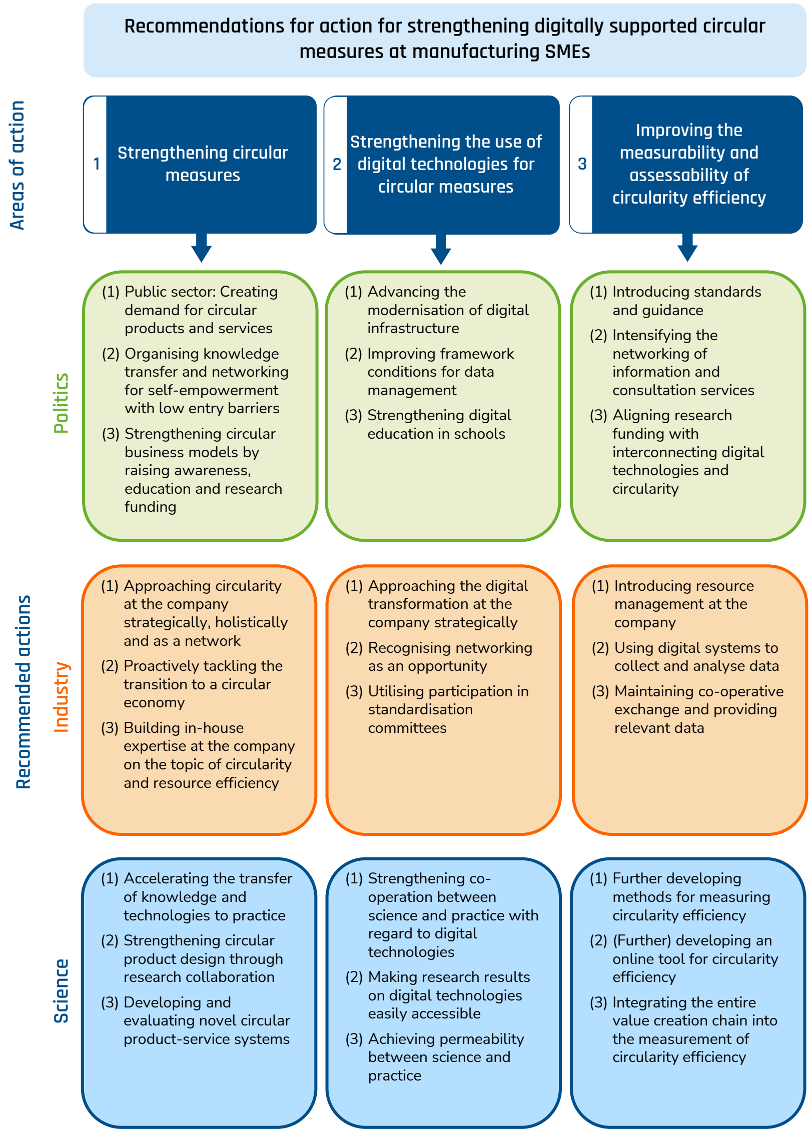

Figure 16: Overview of the recommendations for action for strengthening digitally supported measures at manufacturing SMEs[150]

[150] VDI ZRE figure.

Field of action 1: Strengthening circular measures

Need for action: Although the majority of SMEs in the manufacturing sector have either taken circular measures or are planning to do so, the focus to date has been on process-related internal optimisation measures. Intercompany measures in co-operation with other value creation partners have so far only been taken by larger SMEs. Circular measures that directly address the product are used less frequently. There is great potential here to enable and improve the circularity of products and/or materials. There is still potential for improvement in the use of new and recycled raw materials as well. It would be helpful if more companies systematically recorded and strategically managed the circularity of their resources. The digital exchange of information could leverage further resource efficiency potential here.

Goal: To leverage existing resource efficiency potential, it is important to raise awareness of circular strategies at companies so that suitable circular measures can be implemented for the company's processes. Part of this objective is to create adequate incentives for companies for focusing on circular production processes and products and making them part of their corporate strategy. This can be achieved by strengthening demand, but also through accompanying support measures. This includes scientific research into new types of circular products and/or services and rapid transfer into business practice.

Politics

(1) Public sector: Creating demand for circular products and services

In its role as a major consumer of products and services, the public sector should act as a role model and pioneer and create incentives for companies to make their business models more circular through their processes, products and services. To this end, when awarding public contracts, tenders can be formulated in favour of products and services that are manufactured or produced using circular principles (e.g. in accordance with the 10

R strategies). Politically, the aim should be to favour circular business models in the context of public tenders. This means that the public sector will be able to purchase used, refurbished or recycled products or utilise Product-as-a-Service offers.

(2) Organising knowledge transfer and networking for self-empowerment with low entry barriers

For more SMEs in the manufacturing sector to implement circular strategies, the associated circular measures and the necessary investments beyond process-related internal optimisation measures, companies need to better understand the requirements for circularity both at the process level (internal and external) and, above all, at the product level and become familiar with the possibilities of digitalisation. This can be achieved at companies in various ways: through examples of best practice, customised further training, advice and information services as well as self-checks for companies. As there are already a number of offers, they should ideally be bundled and interlinked even better via a central website. Existing competence centres in the field of resource efficiency, such as the VDI ZRE, but also in the field of digitalisation, such as Mittelstand-Digital, provide a good basis for using and expanding relevant networks for companies. The European Circular Economy Knowledge Hub[151], which is currently being set up at the European level, could possibly provide further funding, advice and information services. It is important that the relevant stakeholders at the national level are involved in this European project when this centre is put into practice.

(3) Strengthening circular business models by raising awareness, education and research funding

Existing market structures need to be rethought for circular products, processes and business models. The majority of SMEs in the manufacturing

[151] Cf. https://circulareconomy.europa.eu/platform/en/knowledge-hub

sector are not yet at this stage, however, as disruptive circular measures are rarely implemented.

The first step here is to **sensitise** companies to the topic by, among other things, highlighting the advantages of circular business models more strongly in public communication and prominently presenting examples of best practice. For this purpose, proprietary interaction formats, such as the Sustainable Digital Community and the Resource Efficiency Network (NeRess) of the BMUV, as well as events organised by external multipliers, such as efficiency agencies of the German federal states or professional associations, can be actively used to address them.

The second step is to further raise awareness of circularity and resource efficiency at SMEs in the manufacturing sector by specifically promoting corresponding **training programmes**. Existing qualification and further training programmes can be expanded more intensively to include circular economy topics. Co-operation with innovative start-ups can also be useful for this, as they are more strongly integrated into dynamic value creation networks. It would make sense to **support** such early adopters as part of existing start-up funding programmes.

In addition, curricula in schools and training programmes and at universities must be expanded in the direction of circularity and teachers must be trained accordingly so that future professionals are empowered to implement a circular business model. To this end, relevant networks, such as the BilRess network, should be strengthened through specific support.

Industry

(1) A strategic, holistic and networked approach to circularity at the company

At present, companies often lack information and advice on costs, targets and benefits. Circular flows of raw materials, other materials, products and product parts can be realised in different ways at companies. Initially, circular measures which only trigger a low-threshold intervention in the business model can be implemented. It is also possible for several companies to co-operate with each other in order to pursue a holistic circular strategy. In a circular economy, cross-company networking in the value creation chain becomes central. Co-operation and intensive dialogue between the various players along the product value creation chain and beyond are essential for this. The basic prerequisite for such steps is that circularity and resource efficiency become central target variables for measuring corporate success and that possible interactions with other strategic target variables are evaluated holistically, however. To this end, companies must develop appropriate circular strategies in order to establish suitable circular measures within the company or to develop joint solutions with other companies and set up interfaces.

For better networking, it is advisable to participate in relevant networks and existing platforms. Here, for example, the VDI ZRE with its network formats (e.g. NeRess, BilRess, Industrieclub) and its co-operation with multipliers provide a central contact point on the national level. Furthermore, efficiency agencies, chambers of industry and commerce and regional business development organisations, among others, provide a wide range of assistance at the state and regional level.

(2) Proactively tackling the transition to a circular economy

With circular products and production processes, companies can position themselves as pioneers on the market. SMEs in the manufacturing sector should first examine whether a modified or new business model with circular measures is forward looking for their product range. Existing advisory services such as the BMBF-funded SME-innovative pilot system offer options for initial advice and funding opportunities, including on the topic of resource efficiency and the circular economy specifically. The corporate strategy game “Make it circular” from acatech and WWF Germany is a low-threshold offer that provides the opportunity to align one’s own business model more closely with the circular economy through workshops.

To find out about best practice examples, help can be provided by comprehensive collections of good practice examples and the VDI ZRE innovation radar, among other things. Co-operation with innovative start-ups can also be a way to develop new ideas. The CIRCULAR REPUBLIC innovation network, as part of UnternehmerTUM, not only offers access to a suitable start-up ecosystem, but also supports networking and drives circular innovation. Ultimately, digitalisation also provides further opportunities to develop data-driven, usage- and results-orientated service business models such as rental/sharing concepts and payment for use instead of the purchase of a product (pay-per-use).

(3) Building in-house expertise at the company on the topic of circularity and resource efficiency

SMEs in the manufacturing sector must identify those areas in their processes or products where they see the greatest potential for savings. By analysing the status quo of product and business processes, for example through a life cycle assessment, companies must put themselves in a position to decide which circular goals and measures are relevant for them. The digital linking of data at different stages of the product life cycle can also improve the knowledge and transparency of operational processes and thus identify potential savings.

The implementation of circular measures is a cross-sectional task and requires very different skills at different points of the company. To ensure that the necessary expertise is not lacking, the company must build and expand their specialist knowledge and understanding of the key principles of resource efficiency and circularity. Awareness of these issues can be raised within the company through appropriate further training. In addition, companies need specialists with expertise in possible circular solutions and associated technologies.

Science

(1) Accelerating the transfer of knowledge and technologies into practice

Innovation is a key element in the transition to a circular economy, enabling new and modified products, services, processes and business models to emerge and prevail over existing ones. In such an innovation system, actors and networks, institutions as well as knowledge and technology are core elements. Universities and non-university research institutions have an important task in realising this transfer of knowledge and technologies. To this end, they should first identify the needs and challenges of the companies in their region in order to develop suitable transfer programmes for circular measures. In addition to the possibility of research co-operation, the start-up centres and co-operation with companies in the field of study and teaching are also helpful for transfer. In the context of start-up funding for universities and research institutes, the focus can be placed on circular measures.

(2) Strengthening circular product design through research collaboration

There is still room for improvement with regard to the circular capacity of products. The product design can have a major leverage effect in this context, as the later product properties are significantly defined in this phase, including, for example, how well the product can be repaired and dismantled. There is also still great potential for improvement in the use of recycled materials and renewable raw materials at the companies. For comprehensive circularity, concepts such as reuse, reprocessing and recycling must be taken into account in materials research. This requires fundamental material and process innovations, for example in the development of high-quality secondary raw materials as well as durable and repairable materials. These research endeavours can take place through research collaboration with companies. It is also important to bring these innovations to market quickly.

(3) Developing and testing novel circular product-service systems

New forms of products and services and new combinations can form the basis for the development of circular business models. Such product-service systems have been the subject of scientific research for some time and can be product-, usage- or result-orientated, depending on customer requirements.

In order for innovative circular business models in the form of product-service systems to be utilised more frequently, existing concepts must be continuously adapted to technological and social changes. In particular, service models must be systematically researched and trialled in practice to ensure longer product use, for example. through reuse, repair or product return. Research collaboration between companies and universities or non-university research institutions could be an effective format here. On the one hand, the aim is to analyse the opportunities and risks of such circular business models in greater depth, but also to better evaluate the acceptance and benefits for potential customers. To this end, analyses of market potential and possible target groups need to be examined more intensively.

6.1 Field of action 2: Strengthening the use of digital technologies for circular measures

Need for action: Digital technologies have the potential to adapt production processes as well as product and service systems and increase resource efficiency. Digitalisation is not yet significant for the implementation of circular measures at most companies, however. At the same time, the majority of companies lack the skills for the fundamental handling of data, which is a prerequisite for many digitally supported circular measures. Most companies are well aware of the need to handle data in the context of a circular economy, but they are held back by a lack of knowledge and expertise, a lack of complete solutions for handling data and a lack of information or advice.

Goal: Against this backdrop, supporting companies in the implementation of digital solutions plays an important role. The aim should be to enable companies to handle data and use them as a basis for circular measures. This target vision also includes ensuring that the framework conditions such as the digital infrastructure and the regulatory framework are appropriately designed and applied in order to minimise the existing risks of digitalisation and data exchange for companies.

Politics

(1) Advancing the modernisation of digital infrastructure

The German broadband network has recently been significantly improved, the number of underserved areas has been reduced, especially in rural areas, and the available speed has been improved. Technological progress and the increased implementation of digitally supported circular measures lead to more intensive utilisation of the existing digital infrastructure (e.g. through higher data throughput) and at the same time place new demands on them (e.g. higher bandwidths and lower latency times for real-time applications). The digital infrastructure must therefore be consistently expanded and further developed as the backbone of digitalisation. Politically, the aim should be to financially incentivise the nationwide expansion of fibre optics, 5G and later 6G where there is no market solution. In addition, bureaucratic hurdles to grid expansion in particular need to be further reduced.

(2) Improving framework conditions for data management

In order for more companies to manage data and thereby lay the foundation for the use of digitally supported circular measures, policymakers should improve the framework conditions for this. The main obstacles here are knowledge of the legal situation and the practical implementation of data exchange, for example.

A suitable policy measure for overcoming this is the provision of information, especially for SMEs, on the legal framework for data management, which SMEs are often unaware of and whose application is therefore perceived as a hurdle. Best practice examples in handling data can also help to overcome this hurdle. Appropriate policy measures could also include checklists for dealing with new EU laws, such as the AI Act[152] and the Data Act[153], in order to facilitate compliance and increase legal certainty, especially for SMEs. Data exchange could be incentivised directly by providing general and sector-specific model contracts and model general terms and conditions for data use and data transfer as well as general and sector-specific contract generators, as they significantly reduce the workload and thus a lessen a major hurdle for companies.

(3) Strengthening digital education in schools

A major bottleneck in the implementation of digitally supported circular measures is the lack of availability of skilled labour. Based on demographic trends, it is foreseeable that this problem will become even more acute. An important medium- to long-term political measure is therefore to strengthen digital education in schools.

On the one hand, this means an increase in the concrete use of technology, for example in the form of digital teaching units or the use of tablets in lessons. This requires all schools to have Internet access, suitable software and hardware as well as knowledge of how to use it among teaching staff. On the other hand, it is also crucial to teach content-related skills in relation to digital technologies in the classroom, e.g. through a comprehensive, possibly compulsory computer science curriculum of several years. Digital skills such as data protection and privacy should also be taught in other subjects in order to optimally prepare the specialists of tomorrow for the future, however.

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[152] **Cf. European Commission (2024a).**

[153] **Cf. European Commission (2024b).**

Industry

(1) Strategically approaching digital transformation at the company

The digital transformation should be perceived by companies as a strategic issue that is highly complex and therefore requires a structured approach. Individual digital pilot projects can be a first step, but in the medium term a coordinated and holistic approach is required in the various areas of the company and at different levels. In this way, a synergetic linking of circular measures with digital technology is possible so that the cost-benefit calculation can actually favour the benefits. This requires a commitment from top management and a change process that involves employees. Employee support is essential when implementing digital projects at the company.

(2) Recognising networking as an opportunity

Digitalisation is relevant for all companies, but their status quo in this respect is very different. This offers a great opportunity because companies are connected to each other within the framework of value creation networks or even beyond. Experiences can be exchanged, failures and successes shared and people can learn from each other. This is all the more important as digital transformation can be associated with major risks due to a lack of standards and complete solutions, which can be reduced by exchanging information with other (affected) companies.

(3) Utilising participation in standardisation committees

The lack of industry-wide digital standards poses a challenge for SMEs, as it increases the risk of companies investing in digital technologies and/or measures that subsequently turn out to be unsuitable. Companies’ fears of possible lock-in effects, high subsequent adjustment costs and similar negative consequences can lead to a reduced willingness to invest. By participating in standardisation committees, however, companies have the opportunity to contribute to the setting of new standards themselves and to help shape them according to their own requirements. It is important that German companies, including SMEs, play an active role here so that their interests and requirements are taken into account in international standards.

Science

(1) Strengthening co-operation between science and practice with regard to digital technologies

One of the strengths of the German research landscape is the co-operation between universities, research institutions and companies. Such collaboration should be further expanded, particularly in the areas of digital technologies such as data management, the cloud, artificial intelligence and quantum computing. In particular, SMEs should be increasingly involved in research collaboration in order to gain low-threshold access to relevant technologies and to be able to participate in their further development. Although numerous collaborations have already taken place in the past, it is now important to also involve companies without a history of university co-operation and to actively promote such opportunities.

(2) Making research results on digital technologies easily accessible

For companies that do not co-operate directly with a research institution, the research results are often not directly accessible. One reason for this is the publication of research results in scientific journals, which are often not freely accessible. On the other hand, the publications are tailored to an academic audience, so the presentation of the results is not practice-orientated. Here, science should endeavour to prepare and provide relevant research results on digital technologies in a differentiated manner in order to simplify access to this knowledge for various target groups. What is essential here is the accessibility of target groups in the corporate landscape that have not yet been tapped for such knowledge.

(3) Achieving permeability between science and practice

The problem of a lack of expertise or skilled labour at companies for digitally supported circular measures can also be tackled through greater permeability between science and practice. The transition of experts from research institutions to companies offers the opportunity to put the latest knowledge on digital technologies into practice and alleviate bottlenecks. There are also advantages to switching from practice to science. This can increase the practical relevance of research, which in turn could benefit both companies and research institutions. In essence, it is therefore helpful for research organisations to place greater emphasis on practical experience in their personnel policy.

6.2 Field of action 3: Improving the measurability and assessability of circularity efficiency

Need for action: Some companies recognise the positive effects of digitally supported circular measures on resource efficiency at their company. Nevertheless, there is a high percentage of SMEs that have not noticed any changes through the use of digitally supported circular measures. Overall, the company survey makes it clear that the majority of companies are unable to assess the impact of the digitally supported circular measures they have implemented. It is therefore of central importance for SMEs that there are options and tools for measuring circularity efficiency.

Goal: The overarching goal of the recommendations for action presented in this chapter must therefore be to provide better information about the costs in terms of natural resources, capital and personnel and the benefits of digitally supported circular measures and to implement the information provided. For policymakers, this means that information services, guidance and standards for measurement should be established. Companies can utilise these offers and implement them within the company. The prerequisite for this is that they manage resources in a structured and targeted manner and enter into co-operation with other companies along the value creation chain. Science can contribute to the realisation of this goal by further developing circularity measurement and creating practical tools that can be used by companies in order to reduce the barriers to the introduction of circularity measurement.

Politics

(1) Introducing standards and guidance

To better assess the efficiency of circular measures, policymakers should push for the development and introduction of uniform standards and guidance. In concrete terms, this means that methods for measuring circularity are clearly named and defined. As a first step, policymakers should work together with experts from science and industry to develop practical and realistically implementable criteria that companies can use as a basis and guide for their own assessments. These criteria can then be transferred into uniform standards that also define process models.

Companies that already measure their degree of circularity and use their own assessment approaches should be enabled to adapt these to the standards for measuring circularity efficiency in order to minimise the hurdles here. These uniform standards enable better comparability between companies and sectors and create transparency.

(2) Intensifying the networking of information and consultation services

Policymakers should intensify the networking of consultation services in the fields of resource efficiency and Industry 4.0 with services relating to assessment methods. By expanding and promoting such offers, companies, especially small and medium-sized enterprises, can be better informed about the benefits of digitally supported circular measures and supported in the selection of suitable measures and their implementation. There are information and consultation services for SMEs in the fields of Industry 4.0 and resource efficiency at the federal and state level. Examples include the centres in the Mittelstand-Digital Network and the VDI

ZRE with their various tools as well as information and qualification programmes.

These and other existing advisory services must be more closely linked and expanded to include services on evaluation methods so that a synergetic approach is possible, however. The aim should be to provide comprehensive, but very specific, information and consultation that is sufficiently practical to support companies in the implementation and optimisation of digitally supported circular measures.

(3) Aligning research funding towards a combination of digital technologies and circularity

Complementary to the recommendations in field of action 2, policymakers should focus research funding on linking digital technologies and measures for resource conservation and circularity in order to promote the development of a data basis for the assessment of circularity efficiency.

Research funding is already addressing the topics of Industry 4.0 and resource efficiency with various projects. However, these two subject areas should also be more closely interlinked in the area of research. For example, specific questions on realising the potential of using digital technologies for circular measures should be addressed. One example of such a funding programme is the BMUV's "Digital applications for increasing resource efficiency in circular production processes (DigiRess)" programme.

Industry

(1) Introducing resource management at the company

Companies should introduce comprehensive resource management systems in order to identify potential savings through the use of digitally supported circular measures. To date, there are a very large number of SMEs that do not measure their resource utilisation or do so only partially. Resource management of this kind requires an analysis of the status quo and then makes it possible to systematically record and analyse the consumption of raw materials and supplies. This is important, for example, in order to be able to map and estimate the overall effects of the application of digitally supported circular measures and the interaction of different measures as a whole and to plan the use of said measures in a targeted and effective manner.

By identifying inefficiencies and sources of waste, targeted measures can be developed to reduce resource consumption and increase efficiency. In addition to increasing and measuring circularity efficiency, resource management can help to reduce costs and thus improve the cost-benefit ratio of digitally supported circular measures for companies.

(2) Using digital systems to collect and analyse data

To continuously monitor and optimise resource consumption, companies should implement systems for data collection and analysis. This includes systems for data exchange within the company as well as systems for enabling data exchange across the entire value creation chain.

In-house systems include digital applications that are used in or enable operational processes as part of circularity. The exchange of data across company boundaries is of particular importance. The aim is to optimise processes, for example, and to facilitate recycling by providing relevant data on the materials used. These information systems are important in that they increase the effectiveness and efficiency of individual measures through appropriate coordination and monitoring.

(3) Maintaining co-operative exchange and providing relevant data

Industrial companies should provide important data and information within the framework of the existing regulatory requirements and support a co-operative exchange with other companies. The prerequisite for this is ensuring data protection. This exchange of data and information can improve the measurability and evaluability of circular measures and also promote business model innovation so that they are more focussed on resource efficiency and the implementation of circularity through digitally supported circular measures.

The introduction of digital product passports with standardised information will be an important instrument for greater transparency in the value creation chain. The product and process-related data to be provided in these passports form an important basis for evaluating the circularity efficiency of measures taken. Companies must also fulfil the corresponding technical requirements within the company, however.

Science

(1) Further developing methods for measuring circularity efficiency

On the one hand, science should further develop the existing methods for measuring circularity in order to, for example, create a standardised set of indicators that can be applied both generally for companies and specifically for SMEs. The results should then be used in standardisation committees in order to set important framework conditions together with industry and politics.

Secondly, the method developed as part of this study to determine the circularity efficiency of digitally supported circular measures should also be further developed to enable an objective assessment. The procedure presented here provides for the assessment of a specific measure by means of a subjective evaluation, as there are currently insufficient data available to allow an objective assessment. In particular, there is currently a lack of data on comparable measures within a sector. To increase comparability, including between companies, an objective assessment is therefore recommended.

As this study has also shown, existing assessment approaches must be further developed and existing databases expanded in order to measure the costs of digitally supported measures and to enable a quantitative assessment of circularity efficiency. Only this approach offers companies the option of understanding the effectiveness of individual measures. As a result, they can make well-founded decisions to optimise their circular measures and strategies.

(2) (Further) developing an online tool for circularity efficiency

In addition to a standardised methodology, easy-to-use tools are also needed for simplifying the measurement of circularity efficiency. They should enable companies to easily enter their data on resource utilisation and measures taken and to obtain meaningful evaluations. In this way, a further hurdle to implementation in practice can be removed. Thanks to an intuitive user interface and automated analyses, even smaller companies without extensive resources should be able to measure and optimise their circularity.

(3) Integrating the entire value creation chain into the measurement of circularity efficiency

To measure circularity efficiency, it is necessary to develop measurement models that integrate the entire value creation chain into the analysis. This requires the development of comprehensive models that take into account all stages of the production and supply process, from raw material extraction to manufacturing and recycling. The measurement models can, for example, use the digital product passport to extract data from different phases of the product life cycle. Only complete integration along the entire value creation chain enables a holistic assessment of circularity and the identification of global optimisation potential.

BIBLIOGRAPHY

acatech, Circular Economy Initiative Germany and SYSTEMIQ (2021): Circular Business Models: Overcoming Barriers, Unleashing Potentials.

Bakalis, D. and Büchel, J. (2024): Data utilisation and data sharing: Between potential and reality in German companies. In: IW-Trends, 51 (2), p. 25 - 43.

Barteková, E. and Börkey, P. (2022). Digitalisation for the transition to a resource efficient and circular economy, OECD Environment Working Papers**.**

Biebeler, H. (2014). Steigerung der Materialeffizienz in Unternehmen – Bedingungen, Aktivitäten, Hemmnisse und ihre Überwindung, Köln, IW Analyse, 98. (Biebeler, H. (2014): Increasing material efficiency at companies – Conditions, activities, obstacles and overcoming them, Cologne, IW Analysis, 98.)

Biebeler, H. and Lang, T. (2014): Resource efficiency indicators - presentation and evaluation. Study for the Federal Ministry for Economic Affairs and Energy [accessed on: 08.08.2024], available at: https://www.iwkoeln.de/studien/ressourceneffizienzindikatoren.html

BITC (2022): How Circular? - Measuring and Reporting Circular Economy in Business [accessed on: 08.08.2024], available at: https://www.bitc.org.uk/wp-content/uploads/2022/06/bitc-environmentreport-measuringreportingcirculareconomy-june2022.pdf

Bjørnbet, M. M.; Skaar, C.; Fet, A. M. and Schulte, K. Ø. (2021). Circular economy in manufacturing companies: A review of case study literature. In: Journal of Cleaner Production, 294. ISSN 09596526. doi:10.1016/j.jclepro.2021.126268

BMJ (2013): Verordnung über Systeme zur Verbesserung der Energieeffizienz im Zusammenhang mit der Entlastung von der Energie- und der Stromsteuer in Sonderfällen – SpaEfV. (BMJ (2013):Ordinance on systems for the improvement of energy efficiency in conjunction with relief from energy and electricity taxes in special cases – SpaEfV.)

BMU (2020): Deutsches Ressourceneffizienzprogramm II, Programm zur nachhaltigen Nutzung und zum Schutz der natürlichen Ressourcen (German Resource Efficiency Programme II, Programme for the Sustainable Use and Protection of Natural Resources). Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety).

Bocken, N. M. P.; Pauw, I. de; Bakker, C. and van der Grinten, B. (2016): Product design and business model strategies for a circular economy. In: Journal of Industrial and Production Engineering, 33 (5), pp. 308 - 320. ISSN 2168-1015. doi:10.1080/21681015.2016.1172124

Brändström, J. and Eriksson, O. (2022). How circular is a value chain? Proposing a Material Efficiency Metric to evaluate business models. In: Journal of Cleaner Production, 342, p. 130973. ISSN 09596526. doi:10.1016/j.jclepro.2022.130973

Büchel, J. and Engels, B. (2022a): Data management of companies in Germany. In: IW-Trends, 49 (1), p. 73 – 90.

Büchel, J. and Engels, B. (2022b): Many companies are not ready for the data economy, Cologne, IW-Kurzbericht, 96.

Büchel, J. and Engels, B. (2023b): Digitisation index 2022. Stagnation in times of multiple crises. Gutachten im Rahmen des Projekts „Entwicklung und Messung der Digitalisierung der Wirtschaft am Standort Deutschland“ im Auftrag des Bundesministeriums für Wirtschaft und Klimaschutz (BMWK), Köln. Expert opinion as part of the project “Development and measurement of the digitalisation if the economy in Germany” on behalf of the Federal Ministry of Economics and Climate Protection (BMWK), Cologne.

Büchel, J.; Demary, V.; Goecke, H.; Mertens, A.; Rusche, C. and Wendt, J. M. (2021). Digitalisation of the economy in Germany. Digitalisation Index 2020. Expert opinion as part of the project "Development and measurement of the digitalisation of the economy in Germany" on behalf of the Federal Ministry for Economic Affairs and Energy, Cologne.

German Federal Ministry of Education and Research (2024): Digital GreenTech - Environmental technology meets digitalisation [accessed on: 10.09.2024], available at: https://www.fona.de/de/massnahmen/foerder-massnahmen/DigitalGreenTech.php

CEIC (2023): Corporate circular target-setting guidance [accessed on: 08.08.2024], available at: https://pacecircular.org/sites/default/files/2023-02/FV_CEIC_Target%20activation%20guides_17.02.23.pdf

Demary, M. and Demary, V. (2017): The Promise of Blockchain, Cologne, IW-Kurzbericht, 1 [accessed on: 11.09.2024], available at: https://www.iwkoeln.de/studien/markus-demary-vera-demary-the-promise-of-blockchain-317239.html

Demary, V.; Engels, B.; Röhl, K.-H. and Rusche, C. (2016): Digitalisierung und Mittelstand – Eine Metastudie.(Digitalisation and SMEs - A meta-study. In: Demary IW-Analyse, (109).

Diaz Lopez, F. J.; Bastein, T. and Tukker, A. (2019): Business Model Innovation for Resource-efficiency, Circularity and Cleaner Production: What 143 Cases Tell Us. In: Ecological Economics, 155 (C), pp. 20 - 35 [accessed on: 08.08.2024], available at: https://ideas.repec.org/a/eee/ecolec/v155y2019icp20-35.html

econsense (2021): Germany's Transition to a Circular Economy - How to Unlock the Potential of Cross-Industry Collaboration [accessed on: 08.08.2024], available at: https://econsense.de/wp-content/uploads/2021/06/econsense_ACN_WI_Circular-EconomyStudy.pdf

EEA (2016): Circular economy in Europe – Developing the knowledge base, Publications Office of the European Union, Luxembourg, EEA report. No. 2/2016, ISBN 9789292137199.

Ellen MacArthur Foundation (2013): Towards the circular economy Vol. 1: an economic and business rationale for an accelerated transition [online] [accessed on: 08.08.2024], available at: https://www.ellenmacarthurfoundation.org/towards-the-circular-economy-vol-1-an-economic-and-business-rationale-for-an

European Commission (2020): Verordnung (EU) 2019/2088 über die Einrichtung eines Rahmens zur Erleichterung nachhaltiger Investitionen und zur Änderung der Verordnung (EU) 2019/2088. (European Commission (2020): Ordinance (EU) 2020/852 on the establishment of a framework for facilitating sustainable investment and for modification of Ordinance (EU) 2019/2088.)

European Commission (2024a). AI Act [online] [accessed on: 10.09.2024], available at: https://digital-strategy.ec.europa.eu/en/policies/regulatory-framework-ai

European Commission (2024b): Das Datengesetz tritt in Kraft: Was das für Sie bedeutet (The Data Act comes into force: What that means for you [online] [accessed on: 10.09.2024], available at: https://commission.europa.eu/news/data-act-enters-force-what-it-means-you-2024-01-11_en

Fluchs, S. and Schleicher, C. (2021). Abfallhierarchie – Die Stufen der Kreislaufwirtschaft – Teil 2 der Fact Sheet-Reihe Kreislaufwirtschaft für das Forschungsprojekt SCI4climate.NRW, Köln. (Fluchs, S. and Schleicher, C. The waste hierarchy – The stages of the circular economy – Part 2: The circular economy fact sheet series for the research project SCI4climate.NRW, Cologne.)

Fluchs, S.; Neligan, A.; Schleicher, C. and Schmitz, E. (2022). Zirkuläre Geschäftsmodelle – Wie zirkulär sind Unternehmen?, Köln, IW-Report, 27/2022. (Circular business models - How circular are companies?, Cologne)

Geissdoerfer, M.; Savaget, P.; Bocken, N. M. P. and Hultink, E. J. (2017): The Circular Economy - A new sustainability paradigm? In: Journal of Cleaner Production, 143, pp. 757 – 768. ISSN 09596526. doi:10.1016/j.jclepro.2016.12.048

Gillabel, J.; Manshoven, S.; Grossi, F.; Fogh Mortensen, L. and Cosciemе, L. (2021). Business Models in a Circular Economy.

Goddin, J.; Marshall, K.; Pereira, A.; Tuppen, C.; Herrmann, S.; Jones, S.; Krieger, T.; Lenges, C.; Coleman, B.; Pierce, C. J.; Iliefski-Janols, S.; Veenendaal, R.; Stoltz, P.; Ford, L.; Goodman, T.; Vetere, M.; Mistry, M.; Graichen, F.; Natarajan, A.; Cockburn, D.; Koski, O. and Sullens, W. (2019): Circularity Indicators: An Approach to Measuring Circularity, Methodology. Ellen MacArthur Foundation.

Huysman, S.; Sala, S.; Mancini, L.; Ardente, F.; Alvarenga, R. A. F.; Meester, S. de; Mathieux, F. and Dewulf, J. (2015): Toward a systematized framework for resource efficiency indicators. In: Resources, Conservation and Recycling, 95, pp. 68 – 76. ISSN 09213449. doi:10.1016/j.resconrec.2014.10.014

IW Köln; IW Consult and WIK-Consult (2020): More resource efficiency through digitalisation - recommendations for action for small and medium-sized enterprises.

Kirchherr, J.; Reike, D. and Hekkert, M. (2017): Conceptualizing the circular economy: An analysis of 114 definitions. In: Resources, Conservation and Recycling, 127, pp. 221–232. ISSN 09213449. doi:10.1016/j.resconrec.2017.09.005

Kristensen, H. S. and Mosgaard, M. A. (2020): A review of micro level indicators for a circular economy – moving away from the three dimensions of sustainability? In: Journal of Cleaner Production, 243, p. 118531. ISSN 09596526. doi:10.1016/j.jclepro.2019.118531

Kyrer, A. (2001): Business lexicon. 4 Edition, Oldenbourg Wissenschaftsverlag, Berlin, Boston, ISBN 9783486807608, available at: https://www.degruyter.com/isbn/9783486807608

Lichtenthäler, S. and Neligan, A. (2023). How Circular Are Businesses in Germany? In: Intereconomics, 58 (2), pp. 79 – 86. Intereconomics. doi:10.2478/ie-2023-0017

McCarthy, A., R. Dellink and R. Bibas (2018): The Macroeconomics of the Circular Economy Transition: A Critical Review of Modelling Approaches", OECD Environment Working Papers, No. 130, OECD Publishing, Paris [online] [accessed on: 08.08.2024], available at: http://dx.doi.org/10.1787/af983f9a-en"

Müller-Stewens, G. (2018): Definition: Strategy [online], 2018 [accessed on: 23.01.2024], available at: https://wirtschaftslexikon.gabler.de/definition/strategy43591

Naisbitt, J. (2015): "Der Horizont reicht meist nur bis zum nächsten Wahltag." – Interview mit John Naisbitt ("The horizon usually only extends to election day"). In: From Politics and Contemporary History, 65 (31-32), pp. 3 – 6.

Neligan, A. (2018): Digitalisation as Enabler Towards a Sustainable Circular Economy in Germany. In: Intereconomics, 53 (2).

Neligan, A.; Baumgartner, R. J.; Geissdoerfer, M. and Schöggl, J.-P. (2022). Circular disruption: Digitalisation as a driver of circular economy business models. In: Business Strategy and the Environment, **32** (3), pp. 1175 – 1188. ISSN 0964-4733. doi:10.1002/bse.3100

Neligan, A.; Engels, B.; Schaefer, T.; Schleicher, C.; Fritsch, M.; Schmitz, E.; Wiegand, R. and Arnold, R.C.G. (2021a): Digitalisation as an enabler for resource efficiency in companies (main report) - study commissioned by the Federal Ministry for Economic Affairs and Energy, Cologne.

Neligan, A.; Engels, B.; Schaefer, T.; Schleicher, C.; Fritsch, M.; Schmitz, E.; Wiegand, R. and Arnold, R.C.G. (2021b): Digitalisation as an enabler for resource efficiency in companies (Appendix) - Study commissioned by the Federal Ministry for Economic Affairs and Energy - Annex, Cologne.

Neligan, A.; Lichtenthäler, S. and Schmitz, E. (2023a): Products and services for a circular economy - results from the IW Future Panel, IW-Report, 16/2023.

Neligan, A.; Schleicher, C.; Engels, B. and Kroke, T. (2023b): Digitaler Produktpass – Enabler der Circular Economy – Relevanz und Umsetzbarkeit durch Unternehmen, Berlin, Köln, IW-Report, 47. (The digital product passport – Enabler of the circular economy – Relevance and implementation capacity by companies)

OECD (2019a): Business Models for the Circular Economy: Opportunities and Challenges for Policy, Paris [online][accessed on: 08.08.2024], available at:https://doi.org/10.1787/g2g9dd62-en

OECD (2021): The OECD Inventory of Circular Economy indicators, Paris [accessed on: 08.08.2024], available at: https://www.oecd.org/cfe/cities/InventoryCircularEconomyIndicators.pdf

Official Journal of the European Union (2024): Regulation (EU) 2024/1781 of the European Parliament and of the Council of 13 June 2024 establishing a framework for the setting of ecodesign requirements for sustainable products, amending Directive (EU) 2020/1828 and Regulation (EU) 2023/1542 and repealing Directive 2009/125/EU [accessed on: 08.08.2024], available at: https://eur-lex.europa.eu/legal-content/DE/TXT/PDF/?uri=OJ:L_202401781

Oliveira, C. T. de; Dantas, T. E. T. and Soares, S. R. (2021). Nano and micro level circular economy indicators: Assisting decision-makers in circularity assessments. In: Sustainable Production and Consumption, **26**, p. 455 – 468. ISSN 23525509. doi:10.1016/j.spc.2020.11.024

Potting, J.; Hekkert, M.; Worrell, E. and Hanemaaijer, A. (2017): Circular Economy: Measuring Innovation in the Product Chain, The Hague [accessed on: 08.08.2024], available at: https://cemc.org.uk/wp-content/uploads/2023/04/InventoryCircularEconomyIndicators.pdf

REZ Bayern (without year): Readiness check: Resourceneffizienz (Resource efficiency) [online] [accessed on: 28.05.2024], available at: https://www.umweltpakt.bayern.de/werkzeuge/readinesscheck/ (Readiness check: Resource efficiency)

Rossi, E.; Bertassini, A. C.; Ferreira, C. d. S.; Neves do Amaral, Weber Antonio and Ometto, A. R. (2020): Circular economy indicators for organizations considering sustainability and business models: Plastic, textile and electro-electronics cases. In: Journal of Cleaner Production, 247, pp. 119137. ISSN 09596526. doi:10.1016/j.jclepro.2019.119137

Schebeck, L. (2018): Resource efficiency through 4.0 - potential for small and medium-sized enterprises (SMEs) in the manufacturing industry. In: Thomé-Kozmiensky, K.J. and Goldmann, D., eds. Recycling und Rohstoffe, TK-Verl., Neuruppin. ISBN 3944310403.

Schmidt, M.; Spieth, H.; Bauer, J. and Haubach, C. (2017): 100 Betriebe für Ressourceneffizienz - Band 1 - Praxisbeispiele aus der produzierenden Wirtschaft, Springer, Berlin, Heidelberg. (100 businesses for Resource efficiency - Vol. 1 - Practical examples from the manufacturing economy) 1, ISBN 978-3-662-53366-6.

Stich, V.; Hicking, J.; Stroh, M.-F.; Abbas, M.; Kremer, S. and Henke, L. (2021): Digitalisation of the economy in Germany - Technology and Trend Radar 2021. Study as part of the project "Development and measurement of digitalisation. BMWi [accessed on: 08.08.2024], available at: https://www.iso.org/committee/54998.html?t=KomURwik-WDLiuB1P1c7SjLM-LEAgXOA7emZHKGWyn8f3KQUTU3m287NxnpA3DIuxm&view=documents#section-isodocuments-top

VDI 4800 Part 1: 2016-02: Verein Deutscher Ingenieure e. V., Ressourceneffizienz – Methodische Grundlagen, Prinzipien und Strategien, Beuth Verlag GmbH, Berlin (Resource efficiency - Methodological Foundations, Principles and Strategies).

VDI 4800 Part 2: 2018-03: Verein Deutscher Ingenieure e. V., Ressourceneffizienz - Bewertung des Rohstoffaufwands, Beuth Verlag GmbH, Berlin (Raw material demand assessment).

VDI Zentrum Ressourceneffizienz GmbH (2017): Ressourceneffizienz durch Industrie 4.0 - Potenziale für KMU des verarbeitenden Gewerbes (Resource efficiency through Industry 4.0 – Potential for SMEs in the manufacturing sector) [accessed on: 08.08.2024], available at: https://www.ressource-deutschland.de/fileadmin/user_upload/1_Themen/h_Publikationen/Studien/Studie_Ressourceneffizienz_durch_Industrie_4.0.pdf

VDI ZRE (o. year): Ressourcencheck Digitalisierung (Resource check digitalisation) [online] [accessed on: 28.05.2024], available at: https://www.ressource-deutschland.de/werkzeuge/analyse-werkzeuge/ressourcenchecks/digitalisierung/

Verstraeten-Jochemsen, J.; Oltmanns, J. and van Meeteren, O. (2021): Circular Metrics for Business - Introduction to the CIRCelligence indicators framework.

Waas, T.; Hugé, J.; Block, T.; Wright, T.; Benitez-Capistros, F. and Verbruggen, A. (2014): Sustainability Assessment and Indicators: Tools in a Decision-Making Strategy for Sustainable Development. In: Sustainability, **6** (9), pp. 5512–5534. ISSN 2071-1050. doi:10.3390/su6095512

wbcsd/BCG (2018): The new big circle - Achieving growth and business model innovation through circular economy implementation [accessed on: 08.08.2024], available at: https://www.wbcsd.org/resources/the-new-big-circle/

wbcsd (2023): Circular Transition Indicators V4.0 - Metrics for business, by business [accessed on: 08.08.2024], available at: https://www.wbcsd.org/resources/circular-transition-indicators-v4/

APPENDIX

PRACTICAL GUIDELINES FOR SMES IN THE MANUFACTURING SECTOR

PRACTICAL GUIDELINES FOR SMES IN THE MANUFACTURING SECTOR

What are the benefits of digitalisation and circular measures in the company?

Resource efficiency, the circular economy and digitalisation are more than just buzzwords. The transition from a linear economy to a circular economy that utilises products and resources for as long as possible is a relevant building block on the path to climate neutrality. This requires breaking with linear production and/or business models. Digitalisation is an important enabler for the adaptation of production processes, product systems and service systems. These guidelines are intended to help SMEs in the manufacturing sector to make the effects of digitally supported circular measures tangible and thus contribute to their efficient use – only if companies can determine the effects can they determine the usefulness of measures.

Determining the effects is particularly necessary because around one in five companies are currently unable to assess the cost-benefit ratio when implementing circular measures (cf. Figure I). These guidelines therefore aim to provide SMEs with a clear guide to the first steps in determining the success of the measures taken.

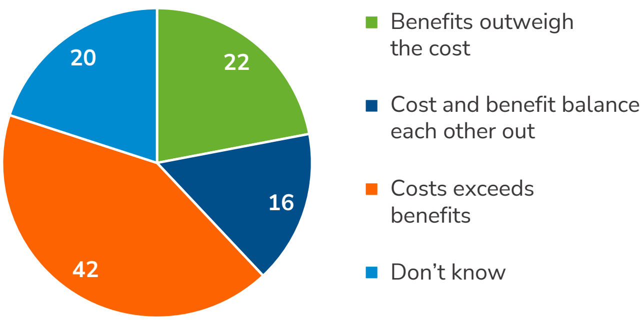

Figure I: Assessment of the cost-benefit ratio when using circular measures[154]

[154] Percentages of SMEs in the manufacturing sector with implemented circular measures – IW Future Panel, wave 46, 2023, N = 18

1 INTRODUCTION

What does circularity mean at the company?

The circularity of raw materials, other materials, products and product parts can reduce costs within the company and help to protect the environment and climate. With circularity, raw materials, other materials, products and product parts are **utilised as efficiently as possible, for as long as possible or multiple times**. Circularity can start at different points in the value creation chain and can be implemented in different ways.

There are numerous ways for companies to improve the circularity of raw materials, other materials, products and/or product parts within their own organisation. The implementation of specific **measures** contributes to circular **corporate strategies** which in turn are crucial for the design of circular business models (cf. Figure II). This transformation process towards circular business models is highly individual for companies. The strategies, and ultimately the measures, can vary depending on the size of the company, their field of activity and sector or their position in the value creation network. Measures taken within a company often have an impact along the value creation chain of a product and thus extend beyond the boundaries of the company.

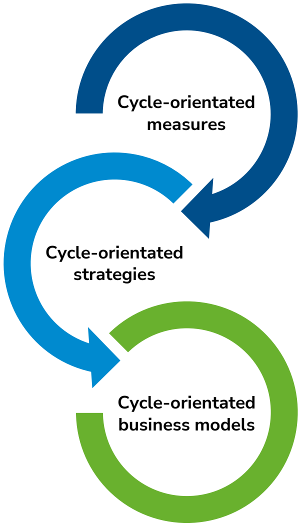

Figure II: Circular measures, strategies and business models[155]

What can circular strategies look like at a company?

In order to establish circular economy approaches at the company, it is necessary to integrate circular goals into the corporate strategy. According to an empirical study conducted by the German Economic Institute (IW) in 2023, the majority of companies in the manufacturing sector have already introduced or are planning to introduce circular measures[156]. There are various ways to strengthen the circularity of raw materials, other materials, products and product parts which are reflected in four different strategies (cf. Figure III).

It should be emphasised that the "improved resource efficiency in the manufacturing process" strategy focuses on the process and does not include any changes to the product itself. Product-related adjustments, such as modular design, are considered in the "enabling/creating cycles" strategy.

[155] VDI ZRE figure.

[156] Cf. Lichtenthäler, S. and Neligan, A. (2023).

Closing cycles	• A cycle is created by closing the gap between the end of the life cycle of a product or product part and the input factor for its manufacture. • **Example:** At the end of their service life in a vehicle, electric vehicle batteries are processed for stationary reuse.
Improved resource efficiency in the manufacturing process	• Waste is avoided and natural resources are conserved by increasing resource efficiency in the manufacturing process. • **Example:** Planned avoidance of waste through better utilisation of the material.
Enabling/ Creating cycles	• Circularity is already taken into account during planning, development and design of the products. Material substitution and new production processes enable new circularity options. • **Example:** Modular design of smartphones and range of spare parts for enabling repairs.
Extending cycles	• Products and parts are utilised as intensively as possible in order to retain their value for as long as possible. • **Example:** Sharing approach for companies – costs can be reduced by sharing expensive machines with one another

Figure III: Strategies that contribute to circularity at the company[157]

Which circular measures can be implemented?

These guidelines present a total of eleven circular measures that are both digitally supported and particularly relevant for SMEs. A distinction is made between two groups of measures here:

- Measures that focus on the product or business model
- Measures that work at the process level

Figure IV provides an overview of these eleven circular measures. As a guide, it shows the extent to which these measures were already being implemented at manufacturing SMEs at the time the study was conducted. It is clear that just under half of the measures are implemented by more

[157] VDI ZRE figure.

than 50 percent of the companies, with those measures that function at the process level being applied more frequently. It should be noted that the use of information systems can also be a measure at the business model level, depending on the purpose and application.

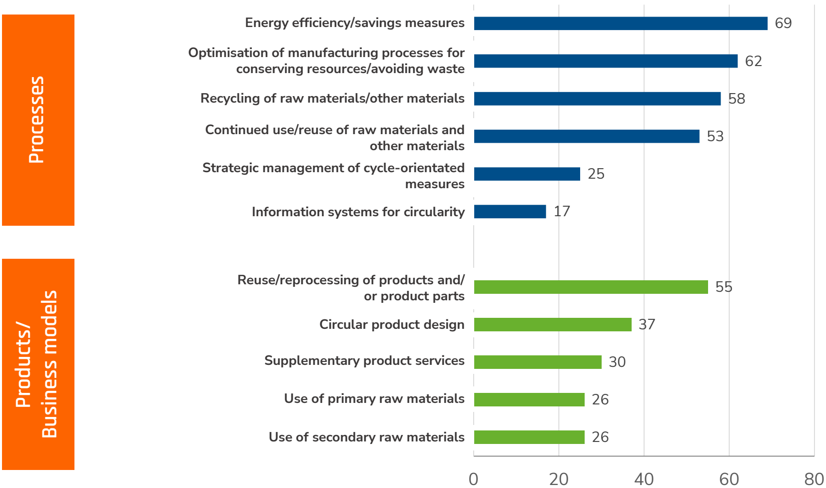

Figure IV: Percentage of SMEs in the manufacturing sector that implement circular measures to a medium extent, at a minimum[158]

How can digital technologies support the implementation of circular measures at companies?

Digital technologies, especially for implementing strategies and measures to improve circularity, offer potential for saving and conserving resources and represent an important lever for the transition to a circular economy. For example, the collection of data can create transparency within the company, revealing potential for optimisation. In addition, the exchange of data across company boundaries, e.g. on the materials used and their treatment, makes recycling of the product easier. The circular measures

[158] IW Future Panel, wave 46, 2023, N = 189 to 193

listed in these guidelines are either based on or at least benefit from digital support, which is why digital technologies play an important role. The guidelines distinguish between the following groups of digital technologies (cf. Figure V).

Digital data collection	•Basis for generating, storing, processing and analysing digital data. •**Examples**: Use of appropriate sensors, big data applications
Digital networking	•Enables the consolidation, exchange and forwarding of data and information via suitable interfaces. •**Examples:** Bluetooth or Wi-Fi
Digital twins	•The creation of a digital image of reality based on digital data. •**Example:** Utilisation of the digital image of a machine for monitoring its condition (condition monitoring) or for simulating changes in production parameters (e.g. feed speed and rotational speed) .
Digital processes in the sense of operational information systems	•Application in or facilitation of operational processes. •**Examples:** Utilisation of cloud computing, common standard applications (e.g. enterprise resource planning and product data management systems)
Digital products	•Use in physical products or services. They make up at least part of the products and enable, for example, communication with the environment. •**Examples:** Apps, app stores and assistance systems
Digital and data-driven business models	•Enabling of data- and platform-based business models. •**Examples:** Utilisation of software and platform infrastructure as a service for the customer (SaaS and PaaS).

Figure V: Categorisation of digital technologies, including practical examples[159]

[159] VDI ZRE figure.

From the perspective of the circular economy, the full potential of digital technologies can only be realised through the collection and use of data. Figure VI shows that 80 percent of SMEs in the manufacturing sector already use digital data collection technologies, at least to a limited extent. The majority of companies are therefore aware of the need to collect sufficient data. Technologies from the digital twin category are used at only 36 percent of companies to support circularity.

80 percent of SMEs in the manufacturing sector use **digital data collection** at least to a limited extent.

36 percent of SMEs in the manufacturing sector use **digital twins** at least to a limited extent.

Figure VI: Digital tools currently being used for circular measures[160]

Whether and which digitalisation measures are worthwhile for companies in the context of circularity must be considered on an individual basis. To this end, it is necessary that the measures can be evaluated in terms of their contribution to achieving a specific circularity strategy.

1.1 Determination of circularity efficiency based on the set of indicators

This chapter presents the set of indicators developed for determining the circularity efficiency of digitally supported circular measures. In accordance with the explanations in Section 2.3.5, circularity efficiency determines the contribution of a digitally supported circular measure to

[160] **IW Future Panel, wave 46, 2023, N = 132**

achieving a circularity strategy relative to the effort required to implement this measure. Based on a comparison of the circularity efficiencies of different digitally supported circular measures, SMEs can thereby assess which measure contributes better to the pursuit of a chosen circularity strategy and prioritise their measures accordingly.

Circularity efficiency is determined using a set of indicators, which – including the calculation of the individual indicators – is presented in the following sections. These indicators improve transparency with regard to the use of resources at the company and make the effects of digitally supported circular measures visible and tangible. The set of indicators developed supports a well-founded evaluation of the measures and enables companies to tailor them to their circularity strategies. Furthermore, the indicators can be used for cost-benefit analyses in order to gain empirical values for subsequent measures. Accordingly, the indicators represent the contribution of a measure compared to the reference state. Companies must then subjectively assess the extent of the change compared to the reference state.

As already mentioned, the measures taken at a company often have an impact along the entire value creation chain. These effects must also be considered with regard to the assessment of circularity efficiency, although some indicators can only be determined within company boundaries in order to avoid double counting. This applies, for example, to the conservation of primary raw materials or energy saving. Other indicators, such as the reuse/recycling/recovery rate, on the other hand, include a consideration of the value creation chain, as the reuse and recycling phase must be examined after production and use. For an overall balance, it is therefore important to consider the entire value creation chain, as digitally supported circular measures must not merely lead to local shifts in expenditures, for example to suppliers and customers.

Within the indicator set, there are “quantity-based” and “overarching” indicators. Quantity-based indicators are non-binary, i.e. they can assume different values on a defined scale. Reductions in raw materials and greenhouse gas emissions can be expressed in tonnes or percentages, for example. The value of cost changes is also non-binary. For example, raw material and energy costs saved can be stated in Euros or as a percentage. In contrast to the quantity-based indicators, the overarching indicators are predominantly binary. This means that they can only assume the values 0 or 1 as an expression of whether a property is present (value 1) or not (value 0). The indicator "initial and ongoing costs for the integration of digital technology" is an exception here, as the costs can generally be easily quantified.

Other environmental impacts

Other environmental impacts, such as air, water and soil pollution, are not included in the scope of these guidelines. It should be noted at this point, however, that other environmental impacts also exist and must be taken into account that are not covered by the indicators used. The reduction of these other environmental impacts should therefore also be part of the strategy for greater resource efficiency at the company.

Signs of the indicators

The indicators developed as part of the study aim to determine the resource conservation realised through the implementation of a digitally supported circular measure. As most of these indicators are calculated on the basis of a comparison with a reference state prior to the implementation of the measure, they can have either a positive or a negative sign. A positive sign means that conservation has been achieved. A negative sign, i.e. negative conservation, means that resource consumption has increased. The calculation of the indicators therefore also includes the costs of implementing the measures. As explained in Section 2.3.5, total expenditure is considered indirectly in the study in order to make the assessment of circularity efficiency practicable.

With regard to circularity efficiency, a reduction in the absolute use of resources should always be aimed for, i.e. a positive sign for the indicators. However, it can also happen that resource consumption increases as a result of a measure being taken because, for example, the energy savings in the production process are overcompensated by the consumption of additional IT infrastructure.

It may also be the case that the consumption of a particular resource has to be increased in order to reduce the overall use of resources or to achieve other circularity targets. In the case of primary raw materials, for example, it may make sense to increase the quantity of primary raw materials used by substituting materials in order to extend the shelf life, and therefore the service life, of the product. The indicator would then have a negative sign. A negative sign does not automatically mean that a measure has failed. It may well be the case that a measure requires more resources expenditure within the company, but achieves savings across all stages of the value creation chain.

1.1.1 Quantity-based indicators

Monetary measurement of the indicators

For a monetary measurement of the quantity-based indicators, estimates of cost changes can be used for most indicators and reported in monetary terms as follows, for example: costs saved due to reduced primary raw material consumption or costs saved due to reduced energy consumption.

The indicators are analysed in detail below and their calculation is discussed.

1.1.1.1 Conserved primary raw materials

Meaning of the indicator

This indicator records the quantity of primary raw materials used that changes as a result of the implementation of the circular measure. Primary raw materials are unprocessed raw materials such as wood and ores. If intermediate products or already processed materials are purchased instead of these raw materials, however, the raw material savings must be estimated on the basis of the total material savings or enquired about from the supplier.

Classification in the circular strategies and measures

The indicator of the quantity of primary raw materials saved can be used to determine the circularity efficiency through the following circular measures (cf. Figure VII):

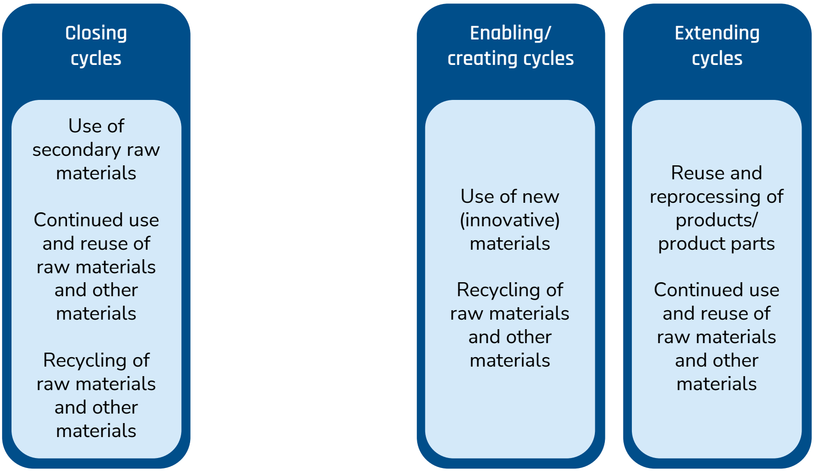

Figure VII: Classification of the "saved primary raw materials" indicator in circular strategies and measures[161]

[161] VDI ZRE figure.

Calculation

Figure VIII shows the calculation of the indicator. The quantity is specified, e.g. in kilogrammes (kg), tonnes (t) or cubic metres (m^3).

Figure VIII: **Calculation of the “saved primary raw materials” indicator**[162]

1.1.1.2 Conserved energy

Meaning of the indicator

This indicator records the amount of energy used that changes as a result of the implementation of the circular measure. In the manufacturing industry, energy is mainly used in electrical (e.g. operation of machines and systems) and thermal form (e. g. heating ovens and buildings).

Classification in the circular strategies and measures

The indicator of the quantity of energy saved can be used to determine the circularity efficiency through the following circular measures (cf. Figure IX):

[162] VDI ZRE figure.

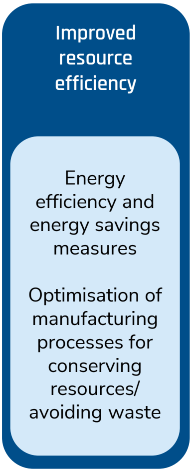

Figure IX: Classification of the “saved energy” indicator in circular strategies and measures[163]

Calculation

Figure X shows the calculation of the indicator. The quantity is specified depending on the form of energy considered, e.g. in kilowatt hours (kWh) or joules (J).

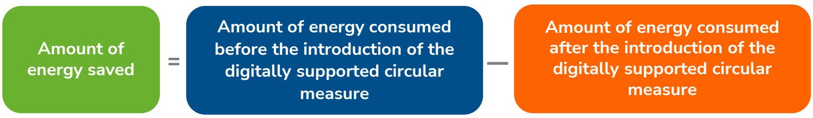

Figure X: Calculation of the “saved energy” indicator[164]

[163] VDI ZRE figure.

[164] VDI ZRE figure.

1.1.1.3 Reduced CO_2 emissions

Meaning of the indicator

This indicator records the amount of CO_2 emissions that changes as a result of the implementation of the circular measure.

Classification in the circular strategies and measures

The indicator for the amount of CO_2 saved can be used to determine the circularity efficiency through the following circular measures (cf. Figure XI):

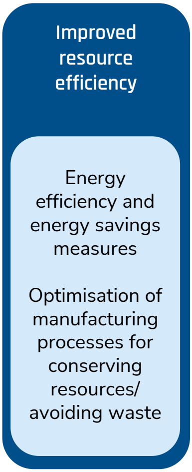

Figure XI: Classification of the "reduced CO_2 emissions" indicator in circular strategies and measures[165]

Calculation

Figure XII shows the calculation of the indicator. The amount of CO_2 saved is stated in tonnes (t), for example in tonnes (t).

[165] **VDI ZRE figure.**

Figure XII: Calculation of the "reduced CO_2 emissions" indicator[166]

1.1.1.4 Reduced space requirement

Meaning of the indicator

This indicator records the area utilised that changes as a result of taking the circular measure (e.g. storage area).

Classification in the circular strategies and measures

The indicator for reduced space requirement can be used to determine the circularity efficiency through the following circular measures (cf. Figure XIII):

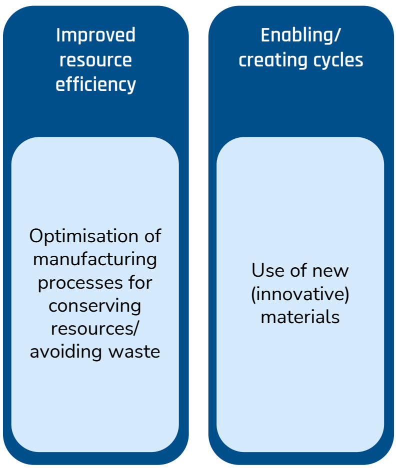

Figure XIII: Classification of the "reduced space requirement" indicator in circular strategies and measures[167]

[166] VDI ZRE figure.

[167] VDI ZRE figure.

Calculation

Figure XIV shows the calculation of the indicator. The area saved is specified, for example, in square metres (m²).

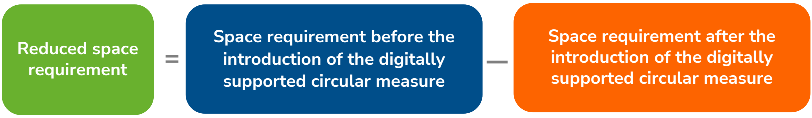

Figure XIV: Calculation of the "reduced space requirement" indicator[168]

1.1.1.5 Reduced water consumption

Meaning of the indicator

This indicator records the amount of water consumed that changes as a result of the implementation of the circular measure.

Classification in the circular strategies and measures

The indicator for the amount of water consumed can be used to determine the circularity efficiency through the following circular measures (cf. Figure XV):

[168] VDI ZRE figure.

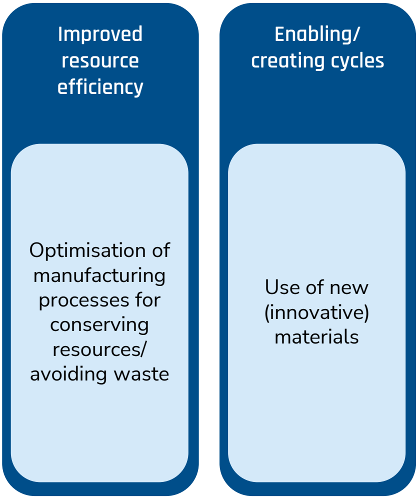

Figure XV: Classification of the "reduced water consumption" indicator in circular strategies and measures[169]

Calculation

Figure XVI shows the calculation of the indicator. The amount of water saved is specified, for example, in cubic metres (m^3).

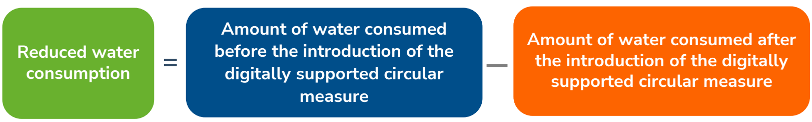

Figure XVI: Calculation of the "reduced water consumption" indicator[170]

[169] VDI ZRE figure.

[170] VDI ZRE figure.

1.1.1.6 Reuse/recycling/recovery rate

Meaning of the indicator

This indicator quantifies the proportion of products that are reused/recycled/recovered as energy. The prioritisation according to the waste hierarchy must be observed here, in which reuse is to be preferred to recycling and the latter in turn to energy recovery. With regard to circularity efficiency, the aim is to maximise this proportion in order to conserve primary raw materials. The actual quantity of primary raw materials saved is analysed using a separate indicator, however. The indicator presented here on the reuse/recycling/recovery rate only quantifies the proportion of products in the product range that are reused/recycled/recovered for energy. The recycling and recovery process does not have to take place within company boundaries, but can also take place along the value creation chain.

Classification in the circular strategies and measures

The indicator for the reuse/recycling/recovery rate can be used to determine the circularity efficiency through the following circular measures (cf. Figure XVII):

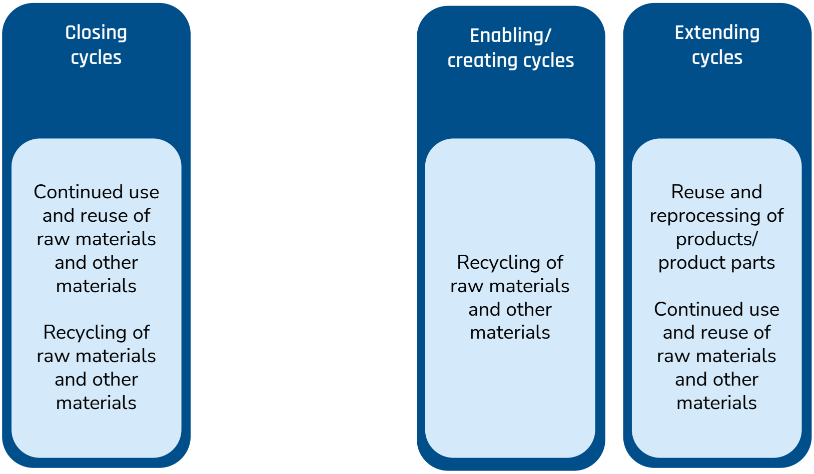

Figure XVII: Classification of the "reuse/recycling/recovery rate" indicator in circular strategies and measures[171]

Calculation

Figure XVIII shows the calculation of the indicator. The reuse/recycling/recovery rate is stated as a percentage (%).

Figure XVIII: Calculation of the "reuse/recycling/recovery rate" indicator[172]

1.1.1.7 Proportion of products that take ecodesign into account

Meaning of the indicator

This indicator quantifies the proportion of products that already fulfil the principles of eco-design during the design phase (e.g. modular structure,

[171] VDI ZRE figure.

[172] VDI ZRE figure.

design for recycling, etc.). Ecodesign is an approach to product design with the aim of reducing environmental impact over the entire life cycle through improved product design. With regard to circularity efficiency, the aim is therefore to design as many products as possible according to the principles of ecodesign.

The actual effect (e.g. longer service life, conservation of primary raw materials and higher energy efficiency) occurs throughout the product's life cycle, however. It is important that these effects along the value creation chain are not counted twice by different companies so as not to overestimate the overall effects.

Classification in the circular strategies and measures

The indicator for taking ecodesign into account can be used to determine circularity efficiency through the following circular measures (see Figure XIX):

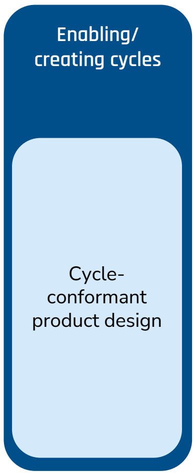

Figure XIX: Classification of the "proportion of products that take ecodesign into account" indicator in the circular strategies and measures[173]

[173] VDI ZRE figure.

Calculation

Figure XX shows the calculation of the indicator. The proportion of products that take ecodesign into account is given as a percentage (%).

Figure XX: Calculation of the "proportion of products that take ecodesign into account" indicator[174]

1.1.1.8 Avoided waste

Meaning of the indicator

This indicator records the amount of waste generated that changes as a result of the implementation of the circular measure. The waste being considered includes, for example, production waste, which can usually be reduced through the use of digital technologies, as well as offcuts and planned waste.

Classification in the circular strategies and measures

The indicator for the amount of waste avoided can be used to determine the circularity efficiency through the following circular measures (cf. Figure XXI):

[174] VDI ZRE figure.

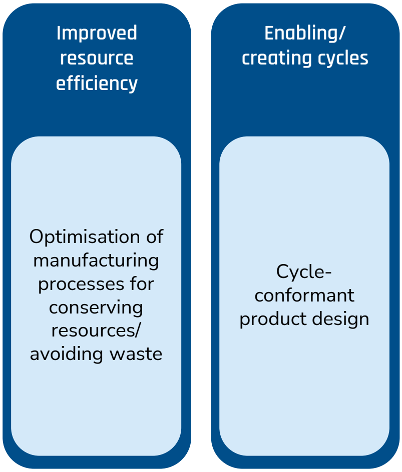

Figure XXI: Classification of the “avoided waste” indicator in circular strategies and measures[175]

Calculation

Figure XXII shows the calculation of the indicator. The quantity is specified, e.g. in kilograms (kg) or tonnes (t).

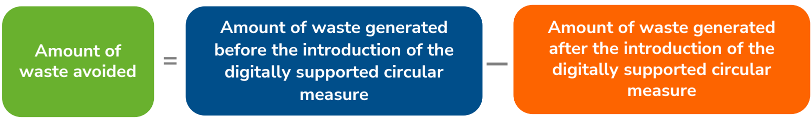

Figure XXII: Calculation of the “avoided waste” indicator[176]

1.1.1.9 Avoided packaging waste

Meaning of the indicator

This indicator records the amount of packaging waste generated that changes as a result of the implementation of the circular measure. In terms

[175] VDI ZRE figure.

[176] VDI ZRE figure.

of circularity efficiency, the aim is to reduce the amount of packaging waste.

Classification in the circular strategies and measures

The indicator for the packaging waste avoided can be used to determine the circularity efficiency through the following circular measures (cf. Figure XXIII):

Figure XXIII: Classification of the "avoided packaging waste" indicator in circular strategies and measures[177]

Calculation

Figure shows the calculation of the indicator. The quantity is specified, e.g. in kilograms (kg) or tonnes (t).

[177] VDI ZRE figure.

Figure XXIV: Calculation of the “avoided packaging waste” indicator[178]

1.1.1.10 Product service life extension/intensification (benefit factor)

Meaning of the indicator

This indicator records the proportion of products that experience an extension of their service life or intensification of use as a result of the circular measure. The product service life describes the period during which the product is technically usable. With regard to circularity efficiency, the primary goal is to maximise the service life and usage intensity of products.

For example, product service life can be extended by using different manufacturing processes or new materials. A higher utilisation intensity can be achieved through better capacity utilisation, for example by sharing and renting machinery and equipment.

Classification in the circular strategies and measures

The indicator for product life extension/intensification can be used to determine circularity efficiency through the following circular measures (cf. Figure XXV):

[178] VDI ZRE figure.

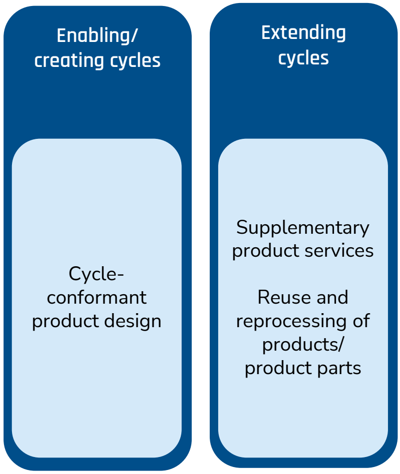

Figure XXV: Classification of the "product life extension/intensification" indicator in the circular strategies and measures[179]

Calculation

Figure XXVI shows the calculation of the indicator. The figure can be given as a percentage (%) of the total portfolio, for example. Alternatively, an individual product can be specified in a unit of time, such as months or years.

Figure XXVI: Calculation of the "product life extension/intensification" indicator[180]

[179] VDI ZRE figure.

[180] VDI ZRE figure.

1.1.1.11 Use of secondary raw materials

Meaning of the indicator

This indicator records the quantity of secondary raw materials used that changes as a result of the implementation of the circular measure. Secondary raw materials are obtained through treatment processes (e.g. through recycling) and therefore used again. If no raw materials are procured but preliminary products or already processed materials are purchased, the proportion of secondary raw materials must be estimated or enquired about from the suppliers.

With regard to circularity efficiency, the aim is to increase the use of secondary raw materials. At the same time, this indicator usually also reduces the "use of primary raw materials" as a result of raw material substitution.

Classification in the circular strategies and measures

The indicator for the use of secondary raw materials can be used to determine circularity efficiency through the following circular measures (cf. Figure XXVII):

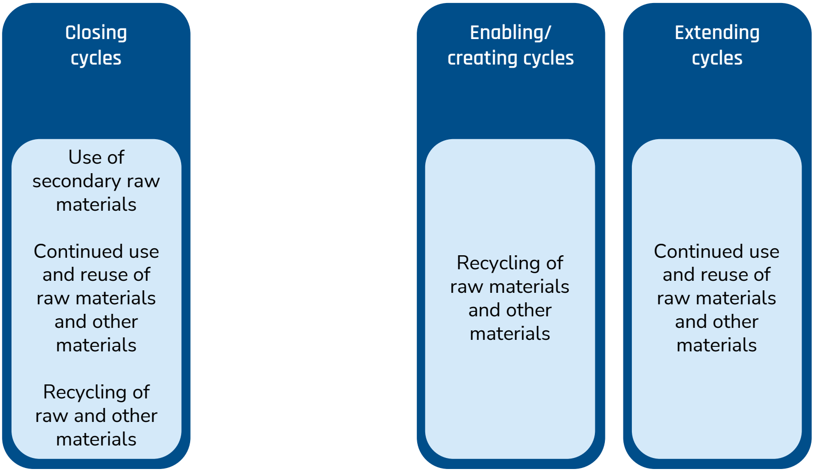

Figure XXVII: Classification of the "use of secondary raw materials" indicator in circular strategies and measures[181]

Calculation

Figure XXVIII shows the calculation of the indicator. The quantity is specified, e.g. in kilograms (kg) or tonnes (t).

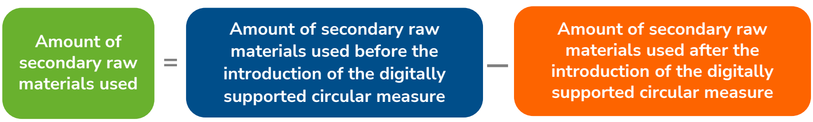

Figure XXVIII: Calculation of the "use of secondary raw materials" indicator[182]

1.1.1.12 Repair and upgrade expenses (cost of materials)

Meaning of the indicator

This indicator records the amount of material used for product repairs and upgrades that changes as a result of the implementation of the circular

[181] VDI ZRE figure.

[182] VDI ZRE figure.

measure. Repairs and remanufacturing of products can lead to longer product life cycles, but require additional material, such as spare parts. This, in turn, conserves primary material, as fewer new products need to be manufactured.

With regard to circularity efficiency, the main objective is therefore to increase this material input, as the need for primary raw materials is reduced compared to the manufacture of new products. Repaired and upgraded products therefore ensure that fewer new products are (or have to be) manufactured.

Classification in the circular strategies and measures

The indicator for repair and upgrade costs can be used to determine circularity efficiency through the following circular measures (cf. Figure XXIX):

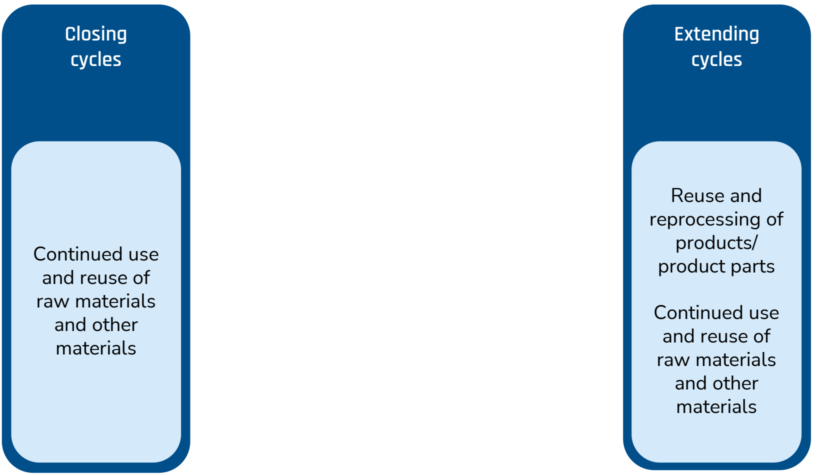

Figure XXIX: Classification of the "repair and upgrade expenses" indicator in circular strategies and measures[183]

[183] VDI ZRE figure.

Calculation

Figure XXX shows the calculation of the indicator. The quantity is stated in kilogrammes (kg) or tonnes (t), for example.

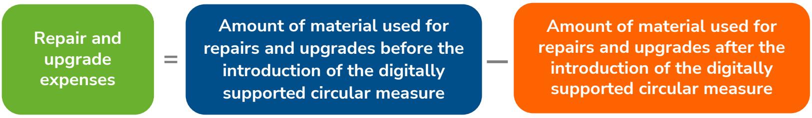

Figure XXX: Calculation of the "repair and upgrade expenses" indicator[184]

1.1.2 Overarching indicators

1.1.2.1 Strategic management of circular measures in place

Meaning of the indicator

This indicator describes whether strategic management of circular measures in the sense of strategic resource management is already in place at the company. This is important, for example, in order to be able to map and assess the overall effects of the application of these measures and the interaction of different measures as a whole, but also to be able to plan the use of said measures in a targeted and effective manner. This indicator is a binary indicator with the values yes/no (1/0).

1.1.2.2 Information systems for circularity in place

Meaning of the indicator

This indicator describes whether information systems and therefore data exchange for circularity are in place. This includes systems for data exchange within the company as well as systems for enabling data exchange across the entire value creation chain. In-house systems include digital applications that are used in or enable operational processes as part of

[184] VDI ZRE figure.

circularity. Examples include the use of cloud computing and common standard applications (such as ERP – enterprise resource planning and PDM – product data management systems). The exchange of data across company boundaries is of particular importance, however. EDI (Electronic Data Interchange) systems are highly relevant here, as they optimise processes, for example, and facilitate recycling by providing data on the materials used.

These information systems are important in that they increase the effectiveness and efficiency of individual measures through appropriate coordination/monitoring. This indicator is a binary indicator with the values yes/no (1/0).

1.1.2.3 Development of new sources of revenue

Meaning of the indicator

This indicator shows whether new sources of revenue can be tapped through the use of digitally supported circular measures. This indicator is a binary indicator with the values yes/no (1/0).

1.1.2.4 Development of new markets or a larger market share

Meaning of the indicator

This indicator shows whether new markets or a larger market share can be opened up through the use of digitally supported circular measures. This indicator is a binary indicator with the values yes/no (1/0).

1.1.2.5 Initial and ongoing costs for the integration of digital technology

Meaning of the indicator

This indicator records the amount of initial and ongoing costs for the use of a digital technology. The initial costs include the costs for integrating the digital technology, for example the acquisition costs. Ongoing costs can relate, for example, to additional software licences or higher programming costs that are incurred on an ongoing basis during the use of digital technology.

1.2 Method

A method is presented below for determining the efficiency of the use of digitally supported circular measures with regard to the pursuit of circular strategies. It should enable SMEs to determine the effects of the digitally supported circular measures taken on circularity efficiency independently and in a targeted manner. The method is carried out in four successive steps (see Figure XXXI). The first step is for the company to identify the right circular strategy for themselves. They can either concentrate on a single strategy or select several strategies at the same time. These strategies are assigned digitally supported circular measures, from which the company selects suitable measures in the second step.

To determine the circularity efficiency of these measures and to be able to compare or weigh up the measures against each other, indicators (cf. Sections 1.2.1 and 1.2.2) must be calculated in the third step. Finally, in the fourth step, the circularity efficiency can be determined, which answers the question of which measures contribute to achieving a particular circularity strategy and how well they do it.

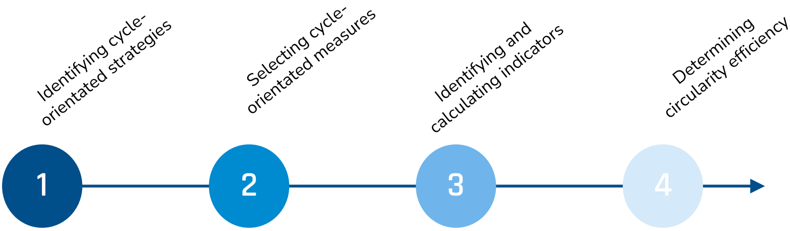

Figure XXXI: The procedure for determining circularity efficiency in four steps[185]

[185] VDI ZRE figure.

This method is described in detail below.

Demonstration example – Description

To illustrate the method, a fictitious, medium-sized company with 60 employees from the plastics processing sector is considered. The company with the fictitious name Plastiko GmbH purchases primary raw materials in various forms (e. g. as granulate or powder) and processes them into simple components using extrusion and 3D printing processes. These components are then delivered to customers. Customers manufacture more complex products using parts supplied by other companies. Plastiko GmbH collects its rejects and offcuts and forwards them to a recycling company.

1.2.1 Step 1: Selecting relevant circular strategies for the company

Of the four circular strategies (cf. Figure XXXII), the one that is relevant for the company should be selected in this step. If several strategies are being pursued, it makes sense to run through the procedure separately for each strategy, as the comparison of the efficiency of the digitally supported circular measures is carried out for each circularity strategy.

To support the selection of the appropriate circularity strategy, they are listed with their description in Figure III. The selection of the right strategy depends, among other things, on where the company are in the value creation chain and what options for circularity exist in the industry.

Figure XXXII: Selection of the right circular strategy[186]

Demonstration example – Selection of the circular strategy

Plastiko GmbH are a small supplier in the overall value creation chain and are focussed on the requirements of their customers. The customer base consists mainly of medium-sized suppliers and a few large companies, with the latter accounting for around 80 percent of turnover. Plastiko GmbH's products form only a small part of the end product, which is not returned to Plastiko GmbH at the end of its life. In order to make the company more circular, the management would therefore like to close internal cycles and make greater use of secondary raw materials. Accordingly, they opt for the "closing cycles" strategy.

1.2.2 Step 2: Selecting relevant circular measures for the identified strategy

Corresponding digitally supported circular measures are assigned to the strategies (cf. Figure XXXIII). In this step, the relevant measures are to be selected for the strategy identified in Step 1. Which digitally supported circular measures are best suited to the company depends, among other things, on the industry and the positioning of the company within the value creation chain. For example, the measure of circular product design is only relevant for those companies that also have an influence on the design of the products they manufacture. If, on the other hand, products are manufactured exclusively according to customer specifications, there is no possibility of influencing the product design phase. Another example is the

[186] VDI ZRE figure.

recycling of raw materials and other materials as a circular measure for the "closing cycles" strategy. While recycling is common practice in some industries, for steel manufacturers, for example, in other areas, the textile sector, for example, depending on the requirements for the material properties, recycling has so far been less common among SMEs.

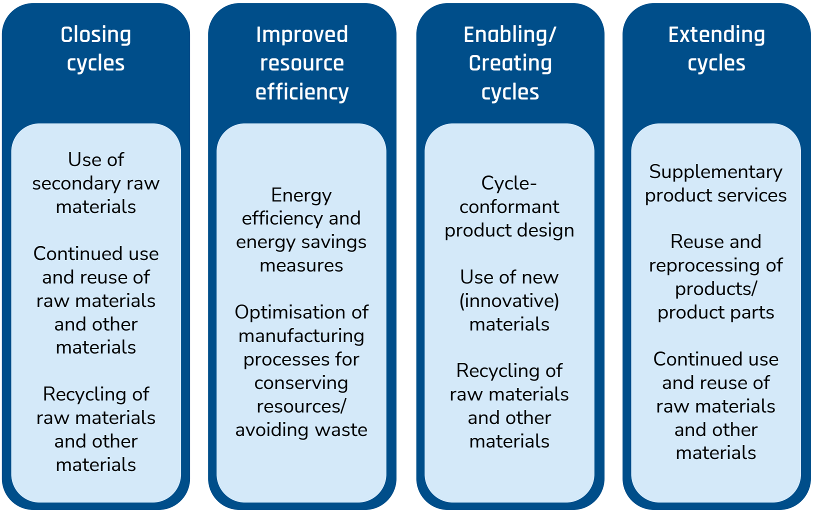

Figure XXXIII: Assignment of circular measures to the four strategies[187]

Additional overarching measures that contribute to all strategies

- Strategic management of circular measures
- Information systems for circularity

Strategic management of circular measures ensures co-ordination between the overall corporate strategy, the circularity strategy and the measures to be taken. This allows the use of different measures to be planned and co-ordinated effectively. The use of strategic management of

[187] VDI ZRE figure.

circular measures makes particular sense if several circularity measures or circularity strategies are to be implemented at the company.

Information systems for recycling management can increase the effectiveness and efficiency of recycling-oriented measures by collecting the relevant data (e.g. via interfaces to machines), store (e.g. in databases, data warehouses), process (e.g. structuring, analysing) and processing (e.g. as dashboards). This enables data-based monitoring of the effects and, based on this, the coordination and management of measures.

Demonstration example – Selection of circular measures

As explained above, due to its position in the supply chain, Plastiko GmbH has little influence on product design and no options to access the products it places on the market after their end of life. Against this backdrop, the company focuses on internal savings potential and alternative sources of raw materials as part of its chosen strategy (closing cycles). An internal analysis shows that material consumption accounts for a large proportion of operating costs. Accordingly, the primary aim is to reduce material consumption with the help of digital solutions. The company are planning two measures to achieve this:

Measure 1: "Reuse and recycling of raw materials and other materials" aims to improve the reuse of printing powder within the company. With the selective laser sintering (SLS) process used, up to 70 percent of the printing powder currently remains unsintered. Some of this used powder is already mixed with fresh powder and reused. At present, however, mixing is carried out according to a fixed ratio with a high safety margin in order to avoid any possible loss of quality. A maximum of 10 percent used powder is added during production. Due to a lack of storage capacity, up to 30 percent of the used powder has to be disposed of by an external recycling company. This proportion is to be minimised by means of digitally supported quality monitoring. This measure can therefore reduce material waste and at the same time cut material and disposal costs.

Through **measure 2: "Use of secondary materials"**, the use of secondary materials in production is to be examined and, if necessary, established. Plastiko GmbH currently use only primary raw materials, as the fluctuating quality of secondary raw materials represents too high an economic risk. With the help of digital solutions, it should now be possible to use them without the quality of the products deteriorating. This measure will enable the company to reduce the carbon footprint of their products in particular, making them more attractive to customers.

1.2.3 Step 3: Identifying and calculating indicators of digitally supported circular measures

The indicators listed in Section 1.2 of these guidelines are used to determine the circularity efficiency of digitally supported circular measures. Table I shows an allocation of the indicators to the circular measures. The number of indicators used to assess the efficiency of a measure is variable. The indicators are merely an initial set that is to be continuously developed.

These assigned indicators (cf. Table I) can be used to assess the efficiency of a measure. The respective values of the indicators must be calculated for each measure selected in Step 2. Only those indicators that have changed through the use of the digitally supported circular measure are to be calculated. The reason for this is that the indicators always refer to a reference scenario. This reference scenario is defined in such a way that it describes the status quo without the effect of the digitally supported circular measure.

Table I: Allocation of the indicators to the circular measures[188]

	Circular measures	Indicators
Product level/Business models	**Use of new materials**	• (Conserved) primary raw materials • (Reduced) CO_2 emissions • (Reduced) space requirement • (Reduced) water consumption
Product level/Business models	**Use of secondary raw materials**	• (Conserved) primary raw materials • (Reduced) CO_2 emissions • Use of secondary raw materials
Product level/Business models	**Circular product design**	• (Reduced) CO_2 emissions • Proportion of ecodesign conformant products • (Avoided) waste • Product life extension/intensification (resource life)
Product level/Business models	**Supplementary product services**	• (Reduced) CO_2 emissions • Product life extension/intensification (resource life)
Product level/Business models	**Reuse and -reprocessing of products/parts**	• (Conserved) primary raw materials • (Reduced) CO_2 emissions • Reuse/recycling/recovery rate • Product life extension/intensification (resource life) • Repair and upgrade expenses
Product level/Business models	**Energy efficiency and energy savings measures**	• (Saved) energy • (Reduced) CO_2 emissions
Process level	**Optimisation of manufacturing processes for conserving resources/avoiding waste**	• (Saved) energy • (Reduced) CO_2 emissions • Reduced space requirement • (Reduced) water consumption • (Avoided) waste/packaging waste
Process level	**Reuse and recycling of raw materials and other materials**	• (Conserved) primary raw materials • (Reduced) CO_2 emissions • Reuse/recycling/recovery rate • Use of secondary raw materials • Repair and upgrade expenses
Process level	**Recycling of raw materials and other materials**	• (Conserved) primary raw materials • (Reduced) CO_2 emissions • Reuse/recycling/recovery rate • Use of secondary raw materials
Process level	**Strategic management of circular measures**	• Strategic management of circular measures in place
Process level	**Information systems for circularity**	• Information systems for circularity in place
Superordinate		• Development of new sources of revenue • Development of new markets/greater market share • Initial and ongoing costs for the integration of digital technology

[188] VDI ZRE figure.

Demonstration example – Selection of indicators

At Plastiko GmbH, the following indicators are used for both measures in accordance with the measures selected in Step 2:

(1) Conserved primary raw materials

(2) Reduced CO_2 emissions

(3) Use of secondary raw materials

(4) Initial and ongoing costs for the integration of digital technologies

(5) Development of new markets/greater market share

In addition to the indicators assigned to the individual circular measures, there are the following business indicators:

- Development of new sources of revenue (yes/no)
- Development of new markets/greater market share (yes/no)
- Initial and ongoing costs for the integration of digital technology

1.2.4 Step 4: Determining circularity efficiency based on the indicators

The results of the indicator calculation, which was carried out for each measure in Step 3, now serve as a starting point for determining the circularity efficiency of the measures taken.

- Circularity efficiency is determined using two indices. This results from the two categories of indicators: non-binary and binary, meaning that one circularity index is calculated for the non-binary indicators and one for the binary indicators.
- The indicators for a measure are first calculated individually.
- All values of the indicators for a measure are then totalled based on a subjective assessment of their impact on change.

<u>Assessment of non-binary indicators</u>

The non-binary indicators (e.g. the quantity-based indicators) are all those indicators which can have more than two different values. Unlike binary indicators, they can therefore not only assume the values 0 or 1. They indicate changes compared to the reference state without the effect of the measure, with a positive sign, for example, the reduced energy consumption or the reduced consumption of primary raw materials. However, they can also have a negative sign if they lead to additional costs rather than savings. This is described in more detail in the following section.

Subjective assessment of the indicators by the company

The company now make a subjective assessment of the extent of this change. This assessment is made on a scale of –2 to +2 with the following significance and is based on the values determined for the non-binary indicators (cf. Table I):

Table II: Assessment of non-binary indicators

Value of the scale	Meaning	Example
-2	significant deterioration	significant increase in energy consumption
-1	slight deterioration	slight increase in space requirements
0	no change	
1	slight improvement	slight decrease in consumption of primary raw materials
2	significant improvement	significantly reduced CO_2 emissions

The evaluation of the indicators and changes that represent these take place on a 5-point scale. The classification along the scale is based on the company's subjective assessment. An objective assessment scale was not feasible (at least in the context of this study), as this would require, among other things, a sufficiently large database on the effects of digitally supported circular measures from a wide variety of industries in order to be able to make a comparison with a representative average value. In the authors' view, the existing knowledge of their own company is sufficient to make an informed decision when assessing the savings achieved by a particular measure in the context of the company's performance to date. For example, if CO_2 emissions have already been reduced by various measures in the past, an improvement of a few percentage points may already be considered a significant improvement, whereas for companies that have not yet taken any measures in this area, this would only mean a slight improvement in the status quo.

Determination of the first circularity index per measure

The sum of the indicators for a measure taken forms the first circularity index. At this point, companies can also make the individual decision to prioritise some indicators over others. This is not a general rule for all SMEs in the manufacturing sector, but rather should be considered on a case-by-case basis. If there are no obvious reasons for weighting the indicators, the simple sum can be determined as described here.

Demonstration example – Determining the first circularity index

Measure 1: The procurement and implementation of the necessary hardware and software for digitally supported powder management involves considerable investment. There are also ongoing operating costs for the additional software applications. The proportion of printing powder that can be reused has been increased by 20 percent, meaning that only 10 percent of used powder has to be disposed of. As a result, less fresh powder needs to be purchased.

The management of Plastiko GmbH come to the conclusion that, although the initial and ongoing costs of the measure are high (–2), the reduction in terms of both primary material (+2) and CO_2 emissions (+2) can also be categorised as high. The use of in-house secondary materials is also rated as very positive (+2).

Consequently, the first circularity index for Measure 1 is:

Conserved primary raw materials	+2
Reduced CO_2 emissions	+2
Use of secondary raw materials	+2
Initial and ongoing costs for the integration of digital technology	-2
Resulting circularity index 1 for Measure 1	**+4**

Measure 2: Here, too, high investments are required for the implementation of an AI-supported solution (-2). However, the AI solution makes it possible to use up to 50 percent secondary raw materials without compromising the quality of the products (+2). As a result, up to 50 percent of primary materials (+2) and corresponding CO_2 emissions (+2) can be saved.

The first circularity index for measure 2 is therefore:

Conserved primary raw materials	+2
Reduced CO_2 emissions	+2
Use of secondary raw materials	+2
Initial and ongoing costs for the integration of digital technology	-2
Resulting circularity index 1 for Measure 1	**+4**

Assessment of binary indicators

The binary indicators only query the existence of a measure or a specific benefit of a measure. The assessment is carried out accordingly on a scale of 0 or 1.

Assessment of the indicators compared with the reference state

The 1 corresponds to the existence of a measure or benefit. In concrete terms, this means:

- Development of new sources of revenue: yes
- Development of new markets/greater market share: yes
- Strategic management of circular measures in place: yes
- Information systems for circularity available: yes

The 0 corresponds to the nonexistence of a measure or benefit. In the event that an estimate cannot be made (option: “don’t know”), a 0 is also assigned.

Determination of the second circularity index per measure

The sum of the indicators forms the second circularity index for the measure taken.

Demonstration example – Determination of the second circularity index for binary indicators

For **Measure 1** , the improved reuse of the printing powder has only a minor impact on the carbon footprint of products manufactured using the SLS process. As a result, Plastiko GmbH are unable to open up new markets or increase their existing market share. **Consequently, the second circularity index is 0**.

For **measure 2**, Plastiko GmbH have introduced an AI-based application that enables the use of secondary raw materials in production. Measure 2 also reduced the carbon footprint of all products, enabling Plastiko GmbH to serve new customer segments where scope 2 and 3 emissions play a relevant role in procurement. This effectively increased the market share (1). **Consequently, the second circularity index is 1**.

Two circularity indices determine the circularity efficiency

As described above, the contribution of a measure to achieving a circularity strategy is shown accordingly using two separate circularity indices. The indices of different measures can be compared with each other to weigh up which measure should be implemented to pursue a particular circularity strategy. A higher value therefore indicates a more positive cost-benefit ratio and therefore a higher circularity efficiency of this measure.

Demonstration example – Determination of circularity efficiency

From the perspective of Plastiko GmbH, **Measure 2** (use of secondary materials) has a higher circularity efficiency than **Measure 1** (reuse and recycling of raw materials and materials): While the value of +4 for the first index is identical for both, Measure 2 achieved a better result than Measure 1 (value: 0) for the second index.

As a result, the company could come to the conclusion that **Measure 1** will not be pursued further and available resources will be focussed on **Measure 2**. Depending on the company's overall strategy, however, they may also decide to continue with both measures.

2 PROFILES

As part of the study, interviews were conducted with experts from SMEs to ensure practical relevance. Corresponding statements in the relevant chapters have already provided insight into the day-to-day business of the nexus between digitalisation, the circular economy and resource efficiency. To provide readers of this study with further in-depth insight, three examples of companies were selected and presented below as profiles. The presentation as a profile makes it possible to quickly grasp essential information and compare the examples. The examples were selected based on the criteria of company size, sector affiliation and exemplary character with regard to the circular economy and resource efficiency. The consent of the respective company regarding publication also had to be taken into account, however.

Jeske Plast GmbH	
Size	The company fall into the size class of 0–9 employees.
Sector	The company are active in the field of plastic injection moulding and focus on industrial companies.
Status quo of resource efficiency, especially with regard to the circular economy	Virtually no waste is produced. Plastics can be easily recycled and reused. There is virtually no return of the products, however, as they are used for a long time and are only part of an end product.
The importance of digitalisation for the circular economy	The company rely on digital solutions and are paperless. "Statistics are the be-all and end-all": Data form the basis for planning, optimisation etc. There is hardly any data flow across company boundaries, however.
(Potential) resource savings through digitally supported circular measures	Products are not traceable when they leave the company. The industry needs more incentives, e.g. specifications for recyclable plastic and centralised collection/sorting. Data exchange or a database on the raw material can be an important tool for leverage here. Data must be collected and maintained. There is also a lack of interfaces for cross-company cooperation.
Measurement of the increase in resource efficiency through these measures	The waste bin is the indicator of efficiency: The company produce less waste than some households. An alternative energy management system was also established a few years ago in accordance with Section 4 (6) SpaEfV established[189].

[189] Cf. BMJ (2013).

Maag GmbH	
Size	The company fall into the size class of 50–249 employees.
Sector	Maag GmbH specialises in the manufacture of flexible packaging solutions, e.g. for meat, baked goods, snacks and sweets.
Status quo of resource efficiency, especially with regard to the circular economy	The company have been 100 percent circular since 2023. The main points for achieving this characteristic are the use of easily recyclable plastics, the use of lean management[190] to increase the efficiency of processes and production, and the optimisation of warehousing. The company are virtually self-sufficient in terms of energy and voluntarily produce a sustainability report.
The importance of digitalisation for the circular economy	From the company's perspective, digitalisation is the decisive leveraging tool for the circular economy. By exchanging data on increasing efficiency along the value chain, potential can be realised (e.g. less surplus production, transfer of material properties, process optimisation).
(Potential) resource savings through digitally supported circular measures	The use of circular plastics can be optimised. The exchange of data on plastics, the packaging produced and the quantities sold to customers can save resources and enable the introduction of a circular economy.

[190] Cf. Kyrer, A. (2001), p. 330.

Measurement of the increase in resource efficiency through these measures	Due to additional measures implemented by the company, it is difficult to precisely allocate the effects. The following improvements have been achieved since 2016: 30 percent more output achieved using the same production facilities, 46 percent less CO_2 emitted, 36 percent less greenhouse gases emitted, 16 percent lower energy consumption, 11 percent lower electricity consumption, 32 percent lower gas consumption, 39 percent less water consumption. The amount of waste has been reduced by 60 percent since 2010.

Seeger Lasertechnik GmbH	
Size	The company fall into the size class of 50–249 employees.
Sector	Seeger Lasertechnik GmbH specialise in metal processing (sheet metal working, welding, bending, folding, laser marking etc.).
Status quo of resource efficiency, especially with regard to the circular economy	The company use steel in particular, 99 percent of which is recycled. The company are endeavouring to increase the energy efficiency of the machines, use renewable energies and combine waste heat with heat pumps and geothermal energy (expensive and complicated, but efficiency increases considerably).
The importance of digitalisation for the circular economy	The company are focusing on digitalisation internally. An ERP for knowledge standardisation was introduced back in 2016. Cross-location production planning and an overall increase in efficiency are the result. In addition, an online shop (including automated quotation generation), a live cam for customers and, in some cases, the use of AI were implemented.
(Potential) resource savings through digitally supported circular measures	Very little further potential is still seen. In addition, everything has to be economically viable: The clientele consists mainly of micro-enterprises. Automated data exchange and the establishment of interfaces are not worthwhile for what little potential is still possible.
Measurement of the increase in resource efficiency through these measures	CO_2 emissions are not measured (although they are low due to the heat pump and geothermal energy). Energy consumption was reduced by 25 percent. Otherwise, energy consumption is optimised and materials are recycled.

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