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# Digital Enablers of the Circular Economy

Christoph M. Schmidt and Thomas Weber (Eds.)

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NATIONAL ACADEMY OF SCIENCE AND ENGINEERING

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# acatech STUDY series

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# Foreword

One of the major social and political challenges to be addressed this century is how to enable all people worldwide, including those in the "Global South", to enjoy material prosperity and a decent life in the long term without hardship or misery and with fair access to all important resources while simultaneously remaining within planetary boundaries. The excessive extraction of raw materials and their consumption in the industrial age have left deep scars in many parts of the world and destroyed local ecosystems, and the waste volumes generated have risen to almost overwhelming levels. And there is no end in sight to this rise. There can be little doubt that humanity is on the point of exceeding our planet's environmental limits in many different respects.

A way must be found to achieve the ambitious goal of globally sustainable material prosperity. Seeking to achieve this by turning our backs on progress and growth and simply redistributing existing resources is at best an unrealistic utopian dream which is incompatible with the realities of day-to-day life. Instead, some way must be found to make more efficient use of existing resources in future and so effectively decouple global economic growth from resource consumption.

Such decoupling entails changes to the global economic system and raw material use, comparable to the efforts already under way for an energy transition away from the use of fossil fuels to renewables. A systemic, i. e. comprehensive, Circular Economy offers a convincing vision for shaping this paradigm shift: in contrast to the "linear" business practices that have so far prevailed, existing materials and products are kept in the economic cycle for as long as possible and as makes sense in quality and energy consumption terms. This minimises raw material consumption and waste while at the same time ensuring that global prosperity can continue to rise. From a national standpoint, a transformation to a Circular Economy also leads to greater resilience and sovereignty in terms of raw materials supply as dependence on raw material imports is reduced in the long term.

Although the Circular Economy concept provides the necessary theoretical basis for a sustainable economy, it can only be successfully put into practice if technology and businesses are capable of meeting the numerous challenges of transformation and the legislative and economic environment is supportive of the development of a Circular Economy. This means that the costs of environmental use will have to be factored more strongly into private consumption decisions and business planning in future. However, the corresponding business and regulatory environment, above all market-based mechanisms, must first be put in place. Only then will the Circular Economy be able to start to compete economically with the previously dominant linear economy.

Digital technologies are an indispensable tool for implementing circularity since developing a comprehensive Circular Economy requires a huge volume of accurate and timely information that has to be shared between the numerous stakeholders in circular value chains. Digital technologies allow stakeholders to network and so develop and scale new circular business models. These technologies also create the necessary transparency within value networks and cut the cost of circular production methods.

Despite different industries facing similar challenges, the requirements for "digital enablers" vary, with circular approaches also varying from product to product. Well-defined use cases and their business and regulatory environment must therefore always be carefully considered. In addition, using digital technologies is no guarantee of a more sustainable economy; rather, the relationship between the benefits of a digital technology application and its energy consumption and the environmental impact of the digital technologies themselves must always be weighed up on an individual basis.

This is where this STUDY comes in: taking examples from construction, electronics and textiles, the digital options for appropriate circular approaches are analysed and compared with the current situation in each of these three sectors. This analysis is in turn the basis for identifying suitable sector-specific and overarching options for shaping the development and expansion of a Circular Economy and defining the role of digital technologies in greater detail. This STUDY is thus a contribution to promoting an integrated and opportunity-focused outlook on Circular Economy transformation. The more systematically circularity is implemented, the greater the positive effects in terms of sustainability, while implementation will in turn be based in each individual case on a very specific combination of Circular Economy knowledge, digital technologies and sector- and product-specific requirements and processes.

**Prof. Dr. Dr. h. c. Christoph M. Schmidt**
acatech Vice-President

# Executive summary

The Circular Economy is one of the key levers for achieving climate and environmental policy goals at national and European level. At the same time, it is indispensable for Europe's strategic sovereignty in raw materials. Restructuring the economic system to a Circular Economy goes hand in hand with digital transformation as digital technologies are central enablers for the successful implementation of circularity strategies.

This acatech STUDY provides an analysis of the role of digital technologies in the Circular Economy in the light of this "twin transformation". This analysis was based on demand-related examples of products from sectors which either have a particularly large environmental footprint (construction) or generate huge volumes of waste (electronics and textiles sector) and the sustainable and circular transformation of which involves particularly complex challenges. Specifically, three products from three sectors were investigated (a single-family dwelling, a washing machine and a T-shirt), after which approaches to idealised circular value creation were developed and finally the digital technologies were identified that are crucial to successfully establishing a Circular Economy. These examples differ greatly in terms of the lifespan of the products and the materials used, which means that the analysis covers a wide range of circular strategies and digital enablers.

An analysis of the three examples reveals that all three of the economic sectors under consideration have significant potential for making value chains circular in the future. However, numerous obstacles remain to be overcome, both cross-sectorally and on a sector- and product-specific basis, if this potential is to be exploited. For instance, in the construction sector, the regulations around the use of recycled and sustainable materials should be simplified to promote circularity. In the electronics sector, on the other hand, there might be a need for incentives to gear appliance design towards longevity. Promising approaches in the textile sector, in contrast, are focused on the intensity of use and durability of clothing products as well as better structures for collecting, sorting and recycling textile materials.

This STUDY identifies four fundamental functions of digital technologies when implementing circular approaches: 1) data generation and collection to create a comprehensive and stable information base; 2) connecting different stakeholders to build complex value networks; 3) modelling, for example for designing circular products; and 4) automation of digital or physical processes to boost their efficiency.

The analysis also shows that digital technologies can play a decisive role not only in establishing circular value chains but also in overcoming sector-specific obstacles. This is because, compared with the linear economy, the Circular Economy requires more intensive data exchange between all the stakeholders in a value chain. The digital product passport, which forms the basis for end-to-end, transparent data sharing along the entire value chain, enables just such data exchange for all three examples. Online platforms and data spaces that can bring stakeholders together in service-based business models or when trading used products, components and materials are also important.

The digital toolbox required to establish a Circular Economy is largely already available. However, if digital technologies and applications are to be put to effective use, then on the one hand, the underlying digital infrastructure must be available and, on the other, the various applications (e.g. product passports and data spaces) must be coordinated with one another. Further vital prerequisites are good data availability and quality together with compatible interfaces and data formats for data exchange. Building data ecosystems for circular value creation networks is therefore more important than (further) developing individual technologies. There is a need to leverage the enormous potential for synergy offered by such interlinking of digital enablers, such as digital twins, product passports, data spaces and AI, with their communities.

However, it will only be possible to realise the full potential of digital technologies in the future if the overall business and regulatory environment is made more conducive to a Circular Economy. A successful transformation to the Circular Economy thus means that environmental costs must be made visible and be appropriately priced, recycled products, components and materials must be approved and circularity-friendly standards and certificates introduced. There is additionally a need for functioning markets for circular products and corresponding services, which may need to be supported initially for a limited time by incentive systems so that they can become competitive as quickly as possible. Finally, funding initiatives for transferable projects spanning value chains should be established in order to ease the move into and scaling of the Circular Economy. Ultimately, however, the transition to a comprehensive Circular Economy can only succeed if society supports and helps to shape the transformation.

# Project

## Project management

- Prof. Dr. Dr. h. c. Christoph M. Schmidt, RWI – Leibniz Institute for Economic Research/acatech Vice-President
- Prof. Dr.-Ing. Thomas Weber, acatech President

## Experts

- Martin Benfer, Karlsruhe Institute of Technology (KIT)
- Prof. Dr.-Ing. Mesut Cetin, Technical University of Applied Sciences Augsburg
- Prof. Dr.-Ing. Hanaa Dahy, University of Stuttgart
- Prof. Dr. Christina Dornack, Dresden University of Technology
- Prof. Moritz Dörstelmann, Karlsruhe Institute of Technology
- Christian Dworak, BSH Hausgeräte GmbH
- Christian Eckert, ZVEI – German Electrical and Digital Industry Association
- Max Eschenbach, TU Darmstadt
- Prof. Dr.-Ing. Johannes Fottner, Technical University of Munich/acatech
- Rafael Gramm, Fraunhofer Institute for Building Physics IBP
- Prof. Dr.-Ing. Thomas Gries, RWTH Aachen University/acatech
- Uwe Gottschalk, Vaude Sport GmbH & Co. KG
- Susanne Mira Heinz, Circular Thinking Innovation Network
- Dr. Susanne Kadner, UnternehmerTUM GmbH
- Prof. Dr. Sami Kara, University of New South Wales Sydney
- Prof. Dr.-Ing. Kerstin Kuchta, Hamburg University of Technology
- Prof. Dr.-Ing. Werner Lang, Technical University of Munich
- Prof. Frank Lattke, Nuremberg Tech
- Prof. Dr.-Ing. Anica Meins-Becker, University of Wuppertal
- Anja Merker, Confederation of the German Textile and Fashion Industry
- Kai Nebel, Faculty of Textiles and Design – Reutlingen University
- Prof. Dr.-Ing. Stephan Ramesohl, Wuppertal Institute for Climate, Environment and Energy
- Bernhard Roth, Miele & Cie. KG
- Dr. Frieder Rubik, Institute for Ecological Economy Research (IÖW)
- André Rückert, ECOLOGICON GmbH
- Dr.-Ing. Georg Schiller, Leibniz Institute of Ecological Urban and Regional Development (IOER)
- Heinrich Schimmel, Bad & Heizung Schimmel GmbH/Gaia-X domain "Planning, Building, Operating"
- Prof. Dr.-Ing. Rainer Stark, Technical University of Berlin/acatech
- Sibyl Steuwer, BPIE – Buildings Performance Institute Europe
- Jonas Stracke, Confederation of the German Textile and Fashion Industry
- Prof. Dr.-Ing. Oliver Tessmann, TU Darmstadt
- Prof. Dr. Steffen Warmbold, German Association of Consulting Engineers (VBI)
- Christoph Wendker, Miele & Cie. KG
- Prof. Dr.-Ing. Katja Windt, SMS Group GmbH

## Project coordination

- Dr. Mareike Berger, acatech Office
- Dr. Anna Frey, acatech Office

## Authorial team

- Dr. Mareike Berger, acatech Office
- Dr. Berit Erlach, acatech Office
- Prof. Dr. Dr. h. c. Christoph M. Schmidt, RWI – Leibniz Institute for Economic Research/acatech Vice-President
- Dr. Johannes Simböck, acatech Office
- Dr. Thomas Steiner, acatech Office

## Assisted by

- Jan Fischer, acatech Office
- Maximilian Heiser, acatech Office
- Felix Kappert, acatech Office
- Dr. Lisa Risch, acatech Office
- Theresa Scheule, acatech Office
- Dr. Joachim Sedlmeir, acatech Office
- Dr. Karl Wienand, acatech Office
- Clemens Wolf, acatech Office

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# 1 Background and approach

## 1.1 Burgeoning Circular Economy and remaining knowledge gaps

Global extraction and use of natural resources has tripled in the past 50 years, and this growth trend, which relates to organic and inorganic raw materials, is continuing.[1] However, this increase has not only supported global economic growth, but has also led to a steady increase in waste streams. In the USA, for example, the volume of municipal solid waste increased by a factor of 2.4 between 1970 and 2018,[2] while in the European countries of the Organisation for Economic Co-operation and Development (OECD), waste volumes have risen by as much as a factor of 2.85 since 1985, despite increasing efforts to manage resources sustainably.[3] These numbers underline the urgency of an economic paradigm shift: away from a linear economy in which products are produced, used and finally disposed of, towards a Circular Economy (CE) that keeps products and their components in circulation after their initial use.[4]

The Circular Economy is thus a system of production and consumption in which existing materials and products are shared, leased, reused, repaired, refurbished and recycled for as long as possible in order to use resources sustainably and massively reduce waste (see also section 2).[5] However, much still remains to be done to establish a genuine circular economy in Germany, as secondary raw materials are currently only used for around 13 per cent of economic activities in Germany and only around 7 per cent globally.[6, 7]

The environmental impact of the current economy and the dependence of the European Union (EU) on imports of various raw materials illustrate just how necessary the transformation to a circular economy is: according to the United Nations International Resource Panel, the extraction and processing of raw materials[8] currently accounts for around 55 per cent of global greenhouse gas emissions.[9] In 2024, the European Commission (EU Commission) set out measures in an EU Regulation for ensuring a secure and sustainable supply of critical raw materials.[10] With a view to ensuring secure future access to raw materials, the EU Commission has also been publishing a regularly updated list of critical raw materials for the EU since 2011. This list currently contains 30 materials and is constantly being expanded; the materials listed are essential for all industrial sectors and for implementing modern technological solutions, and the EU is heavily dependent on just a few countries for procuring them.[11] A German Mineral Resources Agency (DERA) study confirms this finding of dependency for mined, refined and traded products with regard to a total of 63 metals and industrial minerals. According to this study, 46 per cent of the investigated products are subject to elevated procurement risks. DERA is therefore recommending that German companies review their procurement strategies along the supply chain for potentially critical raw materials and, where necessary, develop alternative strategies.[12]

In view of such findings, the Circular Economy is a crucial tool for achieving the EU's ambitious climate and environmental policy goals and for strengthening Europe's strategic sovereignty in the supply of raw materials. This assessment is already part of

1 | See Rechlin et al. 2023.
2 | See United States Environmental Protection Agency 2023.
3 | See European Environment Agency 2020.
4 | The terms "Circular Economy" (CE) and "circularity" are treated as synonyms in this document.
5 | See European Parliament 2018.
6 | See Eurostat 2023.
7 | See Circle Economy Foundation 2024.
8 | This relates to the cultivation and harvesting of biomass, the extraction of mineral and fossil raw materials and the processing of materials, fuels and foodstuffs. The analysis is based on a combination of time series recording the quantity of the particular resource used and input-output tables from the Exiobase 3 database on 163 industrial sectors.
9 | See United Nations Environment Programme 2024a.
10 | See Regulation (EU) 2024/1252.
11 | See European Commission 2020a.
12 | See German Mineral Resources Agency 2023.

various policy guidelines: for instance, in March 2020, the EU Commission published the *New Circular Economy Action Plan* as an important component of the *European Green Deal*.[13] One major building block for practical implementation of the action plan is the Ecodesign for Sustainable Product Regulation (ESPR) which came into force in 2024.[14] At a national level, Germany's first roadmap for establishing a circular economy across society as a whole was also published in 2021 as part of the *Circular Economy Initiative Deutschland* (CEID) funded by the Federal Ministry of Education and Research (BMBF).[15] Moreover, in April 2024, the Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV) presented a draft National Circular Economy Strategy (NKWS).[16] Designed as a framework strategy, the NKWS draft defines the Circular Economy as a cross-sectoral issue and takes account of overlaps with numerous other strategies and legislative initiatives at German and European level. The 2023 *Deutsche Normungsroadmap Circular Economy*[17] in turn points out the serious need for standards and specifications in this context and identifies, among other things, specific needs in the electronics, construction and municipalities, and textiles sectors which this STUDY will examine in greater detail.

Restructuring of the global economic system towards a circular economy is taking place as part of a "twin transformation", namely hand in hand with the digital transformation since digital technologies are key enabling factors or "enablers" for implementing circularity strategies.[18] Examples of such enablers include the digital product passport as a basis for end-to-end, transparent data sharing along the value chain as well as online platforms and data spaces for connecting stakeholders in service-based business models.[19] The momentum behind the creation and development of digital technologies or applications (e.g. artificial intelligence or data spaces) is currently very strong, meaning that there is ever greater scope for implementing sustainable solutions in manufacturing and services.

Against this backdrop, a large number of studies have examined the potential applications and effects of digital technologies in the context of the Circular Economy. These have focused, on the one hand, on a discussion of possible applications of digital technologies in the Circular Economy and, on the other, on an analysis of existing technological use cases in a specific sector.[20, 21, 22, 23]

When it comes to providing a realistic assessment of the potential that digital technologies have with regard to establishing a circular economy, what is needed above all is analyses of specific applications. Such analyses make it possible to determine which technology elements are critical to success, i.e. vital to the production of a functional product or material cycle, and where shortfalls still remain. Depending on the economic sector, applications of digital technologies can be designed differently, since products in the various sectors have very different characteristics (e.g. in terms of material composition, lifetime or usage profile). However, in most sectors of the economy there is still a lack of specific examples of comprehensive digitally based implementation of circularity.

This acatech STUDY is dedicated to this aspect and complements existing studies by analysing the role of digital technologies in the circular economy on the basis of application examples from three economic sectors that are central to the transformation. Idealised circular value creation cycles[24] are developed below for one specific product per sector and the possible role of digital technologies as enablers[25] is investigated (see Figure 1).[26] The

13 | See European Commission 2020b.
14 | See Regulation (EU) 2024/1252.
15 | See Circular Economy Initiative Deutschland 2021a.
16 | See BMUV 2024.
17 | See DIN et al. 2023.
18 | See Chauhan et al. 2022.
19 | See Barteková/Börkey 2022.
20 | See Chi et al. 2023.
21 | See Berndorfer et al. 2023.
22 | See.Ramesohl et al. 2022.
23 | See Han et al. 2023.
24 | The circular value creation cycles are based on the application of "R" strategies, see section 2.1.
25 | In this STUDY, the term "digital enabler", also known as a digital driver, refers to digital technologies that enable the digital transformation and restructuring of the economic system towards a Circular Economy.
26 | The R strategies shown in figure 1 are explained in section 2.1 while the difference between "digital technologies" and "digital applications" is explained in section 2.3.

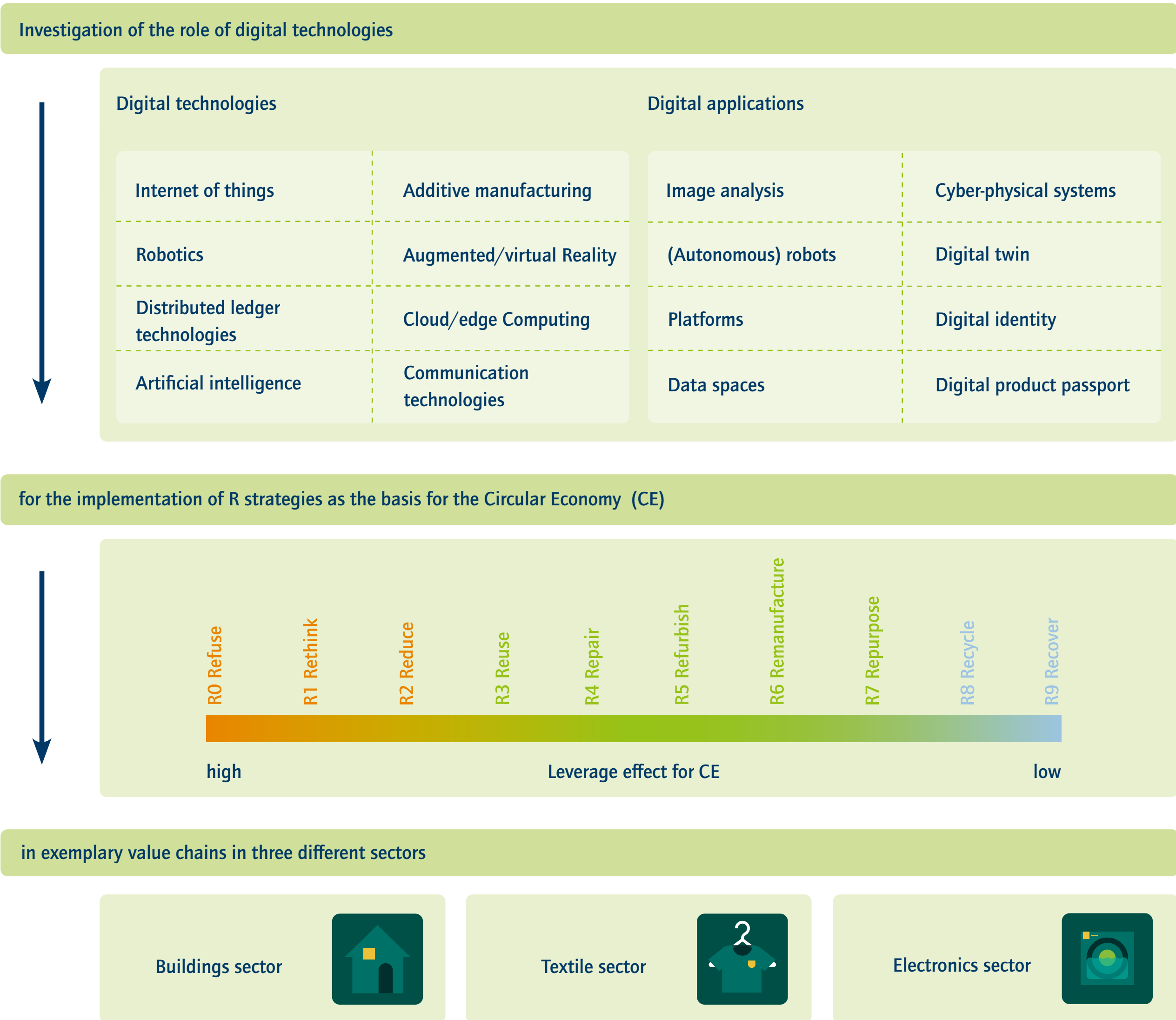


Figure 1: Research framework for this acatech STUDY (source: own presentation)

three products – single-family dwelling, washing machine and T-shirt – differ in terms of their lifespan and material composition, among other things, which means that a wide range of circular strategies and digital enablers is covered. Finally, a comparison of the application examples with the current technological and legislative situation, particularly in relation to Germany and Europe, makes it possible to outline technological and economic policy options for the development of a stable and sustainable circular economy.

## 1.2 Three-stage approach to deriving policy options

The results of this STUDY were compiled in three steps (see Figure 2). In the first step, **application examples** were selected in three sectors of the economy classified as relevant. In addition, digital technologies intended to enable restructuring of the value chain in terms of circularity were identified. The second step involved analysing which digital technologies were of particular relevance to the respective **application examples.** The current situation and existing obstacles to implementation of the identified circularity concepts were then investigated. Finally, the third step was devoted to **deriving policy options.** This was done by evaluating the differences between the current situation and the technological, political, economic and social potential identified by way of example.

**Identification of application examples**

The following criteria had to be considered when **selecting the economic sectors** in which the application examples were to be located:

- strong leverage effect expected in terms of sustainability through the introduction of the circular economy, given the mass flows produced in the sector in question;
- wide range of lifetimes or usage periods, usage profiles and usage intensities of sector-specific products;
- wide range of material groups for sector-specific products;
- existing analyses in the respective sector that describe starting points for the use of digital technologies.

Based on the stated criteria, this STUDY looks at the building, textiles and electronics sectors. The stated sectors were also assessed as relevant to transformation in the *EU Action Plan for the Circular Economy*; and they differ significantly in terms of the lifespan of their products (building: average 50 years; electronics: average 8 years; textiles: average 5 years) and the materials used. When **selecting the products,** it was also important to ensure that they were common products to which as many different circularity strategies (see section 2.1, R strategies) as possible could be applied and which had a large leverage effect for the circular transformation. The following sections describe in more detail exactly how the individual products were selected.

| Process step | Identification of application examples | Analysis of application examples | Derivation of policy options |
|---|---|---|---|
| Activities | Desk research via secondary data & literature analysis | Semi-structured expert interviews and secondary data & literature analysis | Semi-structured expert interviews & expert workshop |
| Results | ▪ Three **application examples** with a major leverage effect in sectors of relevance to the Circular Economy<br>▪ List of the **digital enablers** that are helpful for implementing R strategies together with the **main potential** of these technologies for the Circular Economy | ▪ List of the most relevant **approaches to promoting the Circular Economy** in the respective application examples<br>▪ Assessments of the relevance of the **digital enablers** to the implementation of circular approaches | ▪ Evaluation of **technological development needs** based on a comparison between current situation and application examples<br>▪ Sector-specific and general **policy options** for strengthening the Circular Economy |

Figure 2: Procedure for preparing this acatech STUDY (source: own presentation)

In order to systematically record the potential that digital technologies have for establishing a Circular Economy, the relevant primary and secondary literature was first analysed to identify those digital technologies that research had already classified as being relevant to the circular economy or that are currently already being used in value creation cycles.[27, 28, 29, 30, 31] The resultant list of candidates was then further expanded following a comparison with the *2022 Technology and Trend Radar* published by the Federal Ministry for Economic Affairs and Climate Protection (BMWK)[32] and interviews with experts. Details and specific results from this selection process will be described in the following section.

**Analysis of application examples**

**Semi-structured interviews** with experts on the Circular Economy, digital technologies and the selected economic sectors constituted the core component of the process of analysing the application examples. The first stage of these interviews was to discuss and validate the study concept. The second stage involved discussing existing circularity strategies and their potential relevance in the context of the particular application. The role that digital technologies and digital applications might play in the implementation of these strategies and the development of new circular business models was also discussed, as were the challenges that the various stakeholders in the German and European economic system have to overcome when establishing a successful, digitally supported Circular Economy.

**Derivation of policy options**

In the final step, the expert interviews and an expert workshop then served as the basis for identifying sector-specific and cross-sector **obstacles** that are currently standing in the way of creating digitally supported value creation cycles and thus of establishing a comprehensive circular economy in Germany. On this basis, sector-specific and cross-sector **policy options** were also discussed, which could help to overcome the identified obstacles and translate the circular economy concept into real-world production processes. The policy options presented in the context of the application examples thus combine the results of the study project's literature and data analysis with the experts' qualitative assessment.

27 | See Barteková/Börkey 2022.
28 | See Berndorfer et al. 2023.
29 | See Han et al. 2023.
30 | See Ranta et al. 2021.
31 | See Plattform Lernende Systeme 2024.
32 | See Stich et al. 2022.

# 2 Conceptual fundamentals: R strategies, business models and technologies

## 2.1 Fundamental Circular Economy strategies

In the public mind, the term "Circular Economy" often boils down to the idea of recycling but the concept of a Circular Economy – or circularity – goes far beyond this. In fact, it encompasses a whole range of approaches aimed at **closing material and product cycles, reducing the consumption of primary raw materials**[33] **and avoiding waste**. This accordingly involves taking a product's entire life cycle into account from design and use to disposal or the return of product components to the material cycle. Such a comprehensive perspective also underlies the current BMUV draft for a *National Circular Economy Strategy* which states its goal to be a "root-and-branch reorientation from linear to circular, starting with circular product design, through resource-efficient production and circular business models to sustainable consumption".[34]

Circularising Germany's and Europe's economies could significantly reduce **greenhouse gas emissions** and other environmental impacts associated with the extraction and processing of primary raw materials and the disposal of waste. Since many primary raw materials (e. g. lithium, cobalt, rare earths, platinum group elements and many other metals)[35] are largely imported into the EU from third countries, reducing demand for such raw materials could significantly reduce dependence on sometimes just a small number of supplier countries and so help increase **security of raw material supplies and strategic sovereignty** in both Germany and Europe.

The various circularity strategies that relate to an idealized product life cycle can be systematically summarized as **"R strategies"**. The number and content of the R strategies are not uniformly defined in the specialist literature; we use the 10R's model[36] (see Table 1). This model is widely established and is used in a similar form *inter alia* by the United Nations Environment Programme (UNEP), European Commission[37] publications and by the German Institute for Standardization (DIN)[38], although the energy recovery strategy represented by "R9 – Recover" is often not considered part of the circular economy. [39] The recently proposed Reinvent strategy, which aims to completely decouple resource consumption and economic growth and to make various physical products superfluous through new business models, is subsumed here under "R0 – Refuse".[40] The R strategies can in turn be categorised, depending on their respective impact on material and product streams, as **Narrow, Slow and Close** (see Table 1).

**R strategies are often presented in an order of precedence** in which the strategies in the "Narrow" category (R0 – Refuse, R1 – Rethink, R2 – Reduce) are considered to have the greatest potential for contributing to reducing environmental impact and therefore also the greatest need for innovation.[41] Higher ranked R strategies can generally reduce environmental impact more than lower ranked ones. For instance, less energy is often consumed to repair a product than to produce a new product from recycled raw materials.

This STUDY distinguishes between **product design, production, use** and **end-of-life** as **phases in a product's life cycle**. Figure 3 shows the effects on materials streams associated with the various R strategies and assigns them to the product life cycle phases. The R strategies are not always assigned one-to-one to the four life cycle phases, for example many circular measures during production or use are only enabled by appropriate product

33 | Primary raw materials are materials that are extracted from nature (e. g. metal ores, sand and wood).
34 | See NKWS, p. 20.
35 | See European Commission 2023a.
36 | See Mast et al. 2022. Since the numbering of R strategies starts from "R0", it is also often referred to as the 9R's model.
37 | See European Commission 2020c.
38 | See United Nations Environment Programme 2024a
39 | See DIN 2024.
40 | See Kara et al. 2022.
41 | See Stich et al. 2022.

| | | | |
|---|---|---|---|
| **Narrow** Reduce demand for products or materials by more efficient use or production | R0 | Refuse | Make product superfluous, provide function in another way |
| | R1 | Rethink | Intensify product use (e.g. by sharing or multiple use) |
| | R2 | Reduce | Reduce materials usage (e.g. by production processes that are less wasteful of materials) |
| **Slow** Extend product or component lifespan | R3 | Reuse | Reuse the product for same function by another user |
| | R4 | Repair | Restore a product's original function by repair and maintenance |
| | R5 | Refurbish | Refurbish, restore or update old products |
| | R6 | Remanufacture | Install parts of an old product in a new product with the same function |
| | R7 | Repurpose | Install parts of an old product in a new product with a different function |
| **Close** Close material cycles by reusing materials | R8 | Recycle | Recover materials and reprocess them as raw materials |
| | R9 | Recover | Recover a material's energy content (by incineration and heat recovery) |

Table 1: Approaches to the Circular Economy (based on Mast et al. 2022 and Deutsche Energie-Agentur 2023)

design which means they can be assigned not only to the production and use phases but also to the design phase.

Restructuring the current economic system into a functioning circular economy is not an end in itself, but involves all-encompassing socioeconomic change that aims to provide products and services in a way such that **planetary boundaries** are not exceeded.[42] This overarching goal requires a major reduction in greenhouse gas emissions in particular, but also in pollutant emissions as well as a significant reduction in resource consumption. Germany's draft National Circular Economy Strategy (NKWS) accordingly set the goal of virtually halving the "raw material footprint" from today's 15.3 tonnes per capita to 8 tonnes per capita by 2045. Achieving the central climate policy **target of greenhouse gas neutrality** (by 2045 in Germany,[43] by 2050 in the EU[44]) will additionally mean ending the use of fossil resources. This will require fundamentally different production processes and possibly also different products and product components – for example, plastics will in future have to be produced from biomass or $CO_2$ rather than petroleum, or be replaced by alternative materials. In addition to strategies focusing on production, there is also a need for circular business models and a change in consumer behaviour in order to reduce demand for products and the associated materials streams.[45] On the basis of current knowledge, merely gradually improving climate-damaging production and usage processes within an ongoing linear economy without socioeconomic system change would not be enough to establish a truly sustainable way of life.[46]

Strategies for establishing a Circular Economy should not solely aim to close resource loops but also to reduce the energy required to do so and the corresponding greenhouse gas emissions (e. g. when processing recycled raw materials or transporting materials). A product's **entire life cycle** including the "upstream chain" (e. g. emissions and environmental impact from extracting ores, energy sources and other primary raw materials or from logging) must be taken into consideration. The environmental impact caused by production, operation and disposal when using digital technologies must also be included.

42 | See Richardson et al. 2023.
43 | See Bundes-Klimaschutzgesetz 2021.
44 | See European Commission 2021.
45 | See Sachverständigenrat für Umweltfragen 2024.
46 | See Kara et al. 2022.

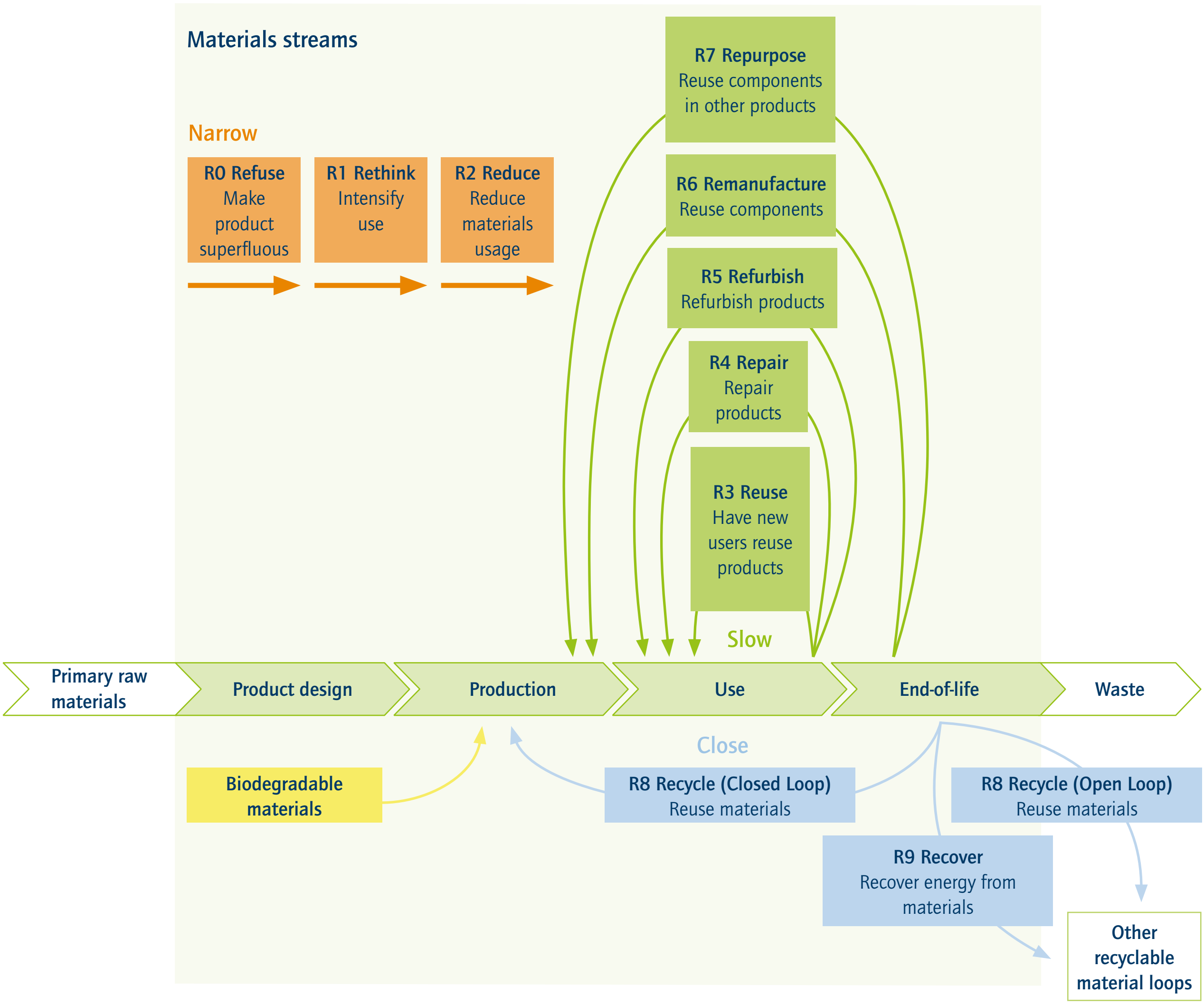


Figure 3: Impact of R strategies on the four-phase product life cycle (green background). The R strategies in the "Narrow" category relate to all product life cycle phases (source: own presentation).

More efficient manufacturing methods and recycling can in many cases reduce a product's **environmental impact** per unit or per tonne. The energy demand, greenhouse gas emissions and water consumption involved in processing secondary raw materials are often (but not always) significantly lower than when extracting primary resources.[47] Ultimately, however, circular approaches must be measured by the extent to which they contribute to an **absolute reduction in environmental impact** (e.g. fewer tonnes of emitted $CO_2$). In addition to the environmental impact per unit or per tonne of product, the quantity of product manufactured and consumed is decisive when it comes to making this assessment. If, for example, the emissions per tonne of a product are halved by more efficient production processes, but demand for the product quadruples at the same time, the absolute emissions will double. Rising global demand for raw materials such as steel can therefore counteract the emission savings achieved through more environmentally friendly production processes. Supply-side and demand-side climate protection

47 | See Angerer et al. 2016.

measures should therefore be implemented together wherever possible in order to achieve an absolute reduction in environmental impact.[48]

On the demand side, it is necessary to take account of **"rebound" effects** which may result from adaptation behaviour on the part of users and counteract the intended reduction in absolute emissions:[49] if the specific environmental impact per unit of a particular product is reduced, this can lead to a reduction in costs and consequently in prices, so that consumers may consume more of the product or purchase other environmentally harmful products with the money saved. In the worst case, this can even increase absolute environmental impact. For example, if car engines become more efficient, fuel consumption costs will fall and consumers may respond by buying a more powerful vehicle, driving longer distances or spending the money saved on air travel.[50] Rebound effects must therefore always be taken into account when evaluating circular economy strategies.

In a comprehensive circular economy, the need for primary raw materials should be avoided as far as possible. This means that primary raw materials need to be replaced by secondary raw materials in all production processes. Recycling should therefore aim to **recover materials without any loss of quality**, so that they can be used for the same function as primary raw materials. **"Downcycling",** i.e. using secondary materials for lower quality functions (e.g. in the production of cleaning cloths from old clothing) contributes to waste prevention, but does not close material cycles, as the need for primary raw materials for the original product is not reduced. However, making comprehensive reuse of recycled product components and materials to manufacture an equivalent product entails an appropriate product design that is itself sustainable (circular design). Nevertheless, especially in the case of long-lasting products, it is just as important to integrate **existing products**, which were designed and manufactured without any reference to circularity, as effectively as possible into a Circular Economy.

## 2.2 Business models in the Circular Economy

Such restructuring of the economic system with its previously predominantly linear value chains into a system with closed, functional value creation cycles sometimes entails a complete transformation of the **processes** in the life cycle of the products concerned. This begins with product design, which will have to take circular principles into account in future, and then also requires a root and branch overhaul of all downstream economic processes, i.e. manufacture, distribution, maintenance and product return. Some companies in certain sectors are already trying as far as possible to keep all components and products in their own cycle with take-back schemes and internal recycling processes (e.g. MUDJeans for denim products). However, a corporate perspective is ultimately not enough to create sustainable value creation cycles for complex products – this requires **circular ecosystems**.

In comparison with the linear value creation system, the Circular Economy is characterised by stronger connections between economic stakeholders whose value-adding activities also complement each other to a greater extent. For example, an electrical appliance manufacturer in a circular economic system will have to cooperate closely with dealers, repairers, recyclers and users to extend the appliance's lifespan and enable its return and recovery at its end-of-life (see Figure 4). This requires a **circular vision** that is shared by all stakeholders. **One particular challenge is therefore that costs and benefits** have to be distributed in such a way that all stakeholders involved want to remain committed to the ecosystem in the long term.

Establishing a functional Circular Economy means that the business models of existing companies will in future have to be geared towards circularity and sustainability and new business models that meet the requirements of a Circular Economy will have to be trialled. Against this background, the *Circular Economy Initiative Deutschland* has developed a detailed **typology**

48 | See Wang et al. 2021.

49 | See Sachverständigenrat zur Begutachtung der gesamtwirtschaftlichen Entwicklung 2019.

50 | This is one of the reasons why carbon pricing is so strongly advocated in economics as a climate policy measure. This is because the associated increase in the cost of climate-damaging behaviour does not lead to counterproductive income effects; in conjunction with flat-rate (!) financial compensation (such as the "climate bonus") – i.e. not linked to intensity of fossil energy source use – carbon prices are therefore a powerful and socially balanced climate policy instrument, unlike emission standards, for example.

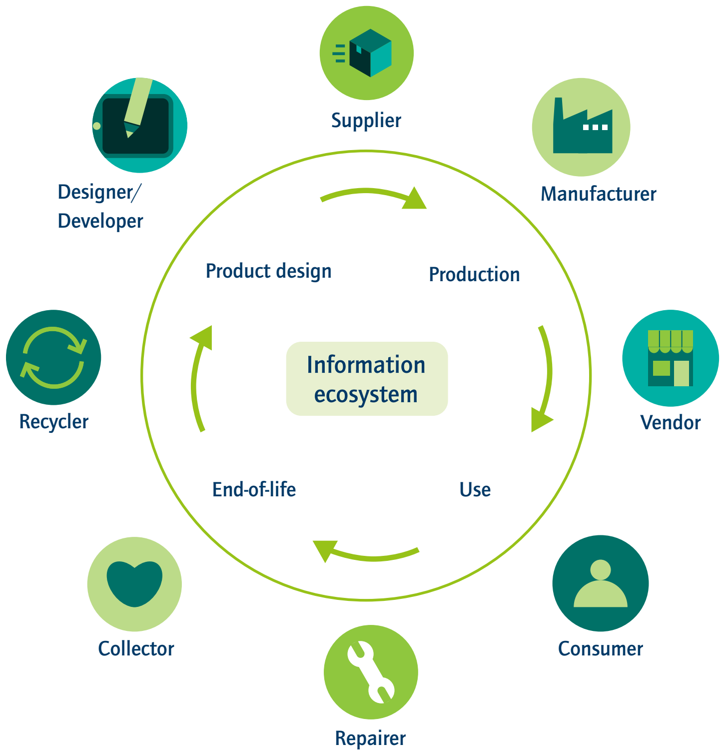


Figure 4: Circular value chain with information ecosystem (source: own presentation)

**with 22 business models** for business to business (B2B) and business to consumer (B2C) transactions that can help promote circular business practices.[51]

A key approach here is to switch from product-based to service-based business models based on the **"product as a service" (PaaS)** principle. Instead of selling a product, such as a printer, once, the customer pays to use the product rather than to buy it. The provider also provides numerous services such as maintenance, repair and recycling of the printer, so offering the customer added value. As the printer remains the property of the provider in this case, the provider also has an inherent interest in a high-quality product with a long lifespan. PaaS models do not, however, always result in greater sustainability and longer-lasting products. For example, service-based e-scooter mobility solutions are often still not very circular, and they may well only rarely replace high-emission car traffic, more often probably replacing more resource-efficient public transport services or bicycles.[52] This is why truly future-proof sustainable PaaS models have to be based on a circular vision.

There is no doubt that digital technologies and applications will play a central role in establishing circular business models in the future as they make it possible to collect product- and service-related data and share them with partners and stakeholders in the value creation cycle. One such digital tool is the "digital product passport" which provides product information along the entire value chain and so enables new business models in the areas of maintenance/repair, reuse, reconditioning and recycling. Manufacturers can then use sensor-based digital monitoring in order to replace individual components when they are sufficiently worn, so maintaining product functionality. Using such digital technologies makes remanufacturing and refurbishment both technically feasible and economically viable. Digital

51 | See Circular Economy Initiative Deutschland 2021b.
52 | See Umweltbundesamt 2023a.

technologies can thus create an **information ecosystem** (see Figure 4) that enables and promotes circular business models. In addition, digital technologies can be used to simulate corresponding business models without major effort and to test their feasibility, although such ex-ante simulations will never be able to fully replace practical testing.

## 2.3 Digital technologies for the Circular Economy

In order to provide a systematic analysis of the potential of digital technologies for the Circular Economy and current barriers to their effective use, a total of 16 technological concepts were identified.[53, 54, 55, 56, 57] These are both stand-alone enabling technologies and digital applications arising from a combination of several enabling technologies. For simplicity's sake, the term "digital technologies" will be used below, so encompassing digital applications.[58]

These digital technologies and digital applications are (see Figure 5):

- **Digital technologies:** internet of things (IoT), robotics, distributed ledger technology (DLT), artificial intelligence (AI), additive manufacturing (3D printing),[59] simulation, cloud and edge computing and communication technologies
- **Digital applications:** image analysis, autonomous robots, online platforms, data spaces, cyber-physical systems (CPS), digital twins, digital identities and digital product passports.

Digital technologies make it possible to implement the various circular strategies and circular business models in the real economy, which is why they can generate huge environmental and economic added value. However, a quantitative assessment of actual environmental and economic benefits requires a critical case-by-case analysis using life cycle assessment (LCA) or other suitable tools that take account of the fact that the production, use and disposal of digital technology solutions often consume many resources.

Nevertheless, although the environmental and economic added value of digital technologies can only be precisely quantified on a case-by-case basis, four basic functions of digital technologies can be identified that are capable of advancing the transformation to a Circular Economy and act as an indicator in assessing the circular economic benefits of digital technologies (see sections 3, 4 and 5):

- by **generating and collecting data**, digital technologies create the information basis for tracing complex value chains and directly identifying reusable or refurbishable components and materials;
- digital technologies ensure stronger **connections** between the various stakeholders and seamless availability of data along the entire value chain, so enabling supply and demand for circular goods and services to be coordinated. They also **lower the threshold for communication** between all the stakeholders in the value chain;
- digital **modelling** not only enables the implementation of R strategies but also allows circular products and business models to be planned, tested and evaluated on the model. In addition, the combination of data collection and modelling can make environmental costs transparent by simulating and predicting the environmental impact of value chains;
- increased, digitally driven **automation** of digital or physical processes allows R strategies and circular business models to be scaled and so made economically viable.
- The digital technologies and applications identified in the first selection step can be assigned in a second step to these four basic functions (see Figure 5). We have combined technologies with a similar technological basis (online platforms[60] and data spaces, robotics and autonomous robots, simulation and digital twins) and omitted technologies with

53 | Vgl. Stich et al. 2022.
54 | See Barteková/Börkey 2022.
55 | See Berndorfer et al. 2023.
56 | See Han et al. 2023.
57 | See Neri et al. 2023.
58 | Explanations of the individual digital technologies and applications are provided in the Glossary.
59 | Additive manufacturing and robotics are not just digital technologies, but also involve actual mechanical engineering
60 | As described in the Glossary, this publication defines online platforms as digital platforms that enable data exchange between different stakeholders.

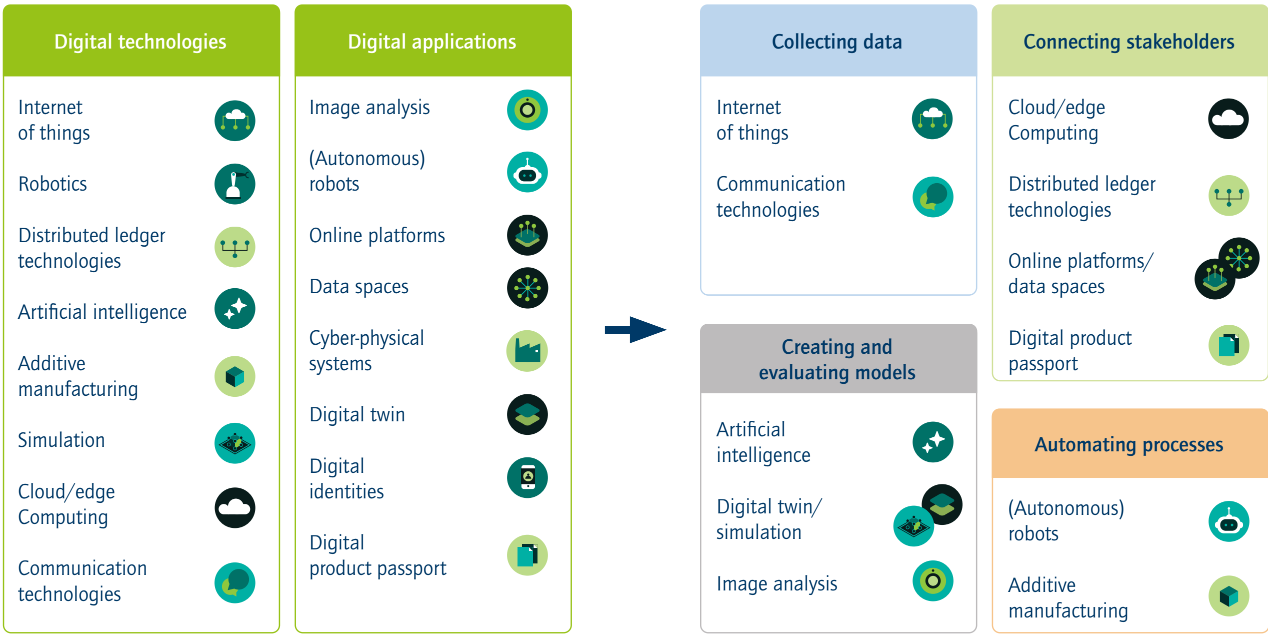


Figure 5: Digital technology solutions in the Circular Economy and their functions (source: own presentation).

limited independent effectiveness in implementing the Circular Economy (digital identities) or subsumed them under other technologies (cyber-physical systems subsumed under internet of things).

In the following, three idealised value chains from three different sectors of the economy will be used to show how these four functions can be achieved by using the appropriate digital technology solutions, what obstacles still exist to their implementation and what policy options arise from this process.

# 3 Buildings and construction sector

## 3.1 Major material requirements in the buildings and construction sector

The construction sector,[61] which, in addition to buildings, also includes civil engineering infrastructure such as roads, waterways and sewers, consumes huge quantities of resources: some 50 per cent of the raw materials – mainly nonmetallic minerals – extracted in the EU are used in the construction sector.[62] The construction of buildings consumes 65 per cent of the cement, 33 per cent of the steel, 25 per cent of the aluminium and 20 per cent of the plastics used throughout the EU.[63] This makes construction products the second largest application for plastics after packaging.[64] Estimates from the Material Economics consultancy and the Ellen MacArthur Foundation suggest that circular economy strategies could reduce greenhouse gas emissions caused by the use of cement, steel, plastics and aluminium in the construction sector by over 30 per cent by 2050.[65]

The construction sector likewise accounts for a very large proportion of waste generation: in the EU, the construction sector is responsible for 35 per cent of waste generated,[66] and in Germany construction and demolition waste accounts for as much as 55 per cent of total waste volumes.[67] Of this, just under half is attributable to rock and earth excavated for construction projects. At 2.5 tonnes per capita per year, Germans generate some ten times as much construction waste as household waste.[68] While 83 per cent of the construction and demolition waste from demolished and dismantled buildings is already recycled in the EU, the majority of this is less sustainable downcycling, much of the material being used for backfilling in road construction. Only 19 per cent of construction materials for new buildings come from recycled or renewable raw materials.[69]

Due to the high consumption of resources and correspondingly high level of emissions in the production of construction materials, refurbishing existing buildings is generally more sustainable than demolition and subsequent new construction.[70] Nevertheless, in 2022, planned replacement construction on the same site was the most common reason for the demolition of residential buildings in Germany.[71] However, for both residential and non-residential buildings, the number of demolitions has been on a downward trend over the past 20 years and is relatively low compared to the number of new builds.[72] In 2022, the demolition of 4,900 residential buildings was set against the construction of more than 100,000 new residential buildings.

In today's existing buildings, the majority of greenhouse gas emissions occur during operation, with the provision of heating energy, cooling and electricity being responsible for the greatest part of these emissions. A total of 36 per cent of carbon emissions in the EU is attributable to the use phase of buildings.[73] In Germany, moreover, heat generation is responsible for



61 | Different statistics define and delineate sectors differently, the construction and buildings sector conventionally being accounted for across a number of sectors over its life cycle. For instance, in the definition of the Federal Climate Protection Act, the buildings sector only includes those emissions that are physically generated within buildings by burning fossil energy sources (primarily in gas and oil heating systems), while emissions for purchased electricity and district heating are attributed to the energy sector and emissions from the manufacture of construction products to the industrial sector. The definition of economic sectors used in official statistics attributes the construction of buildings to the construction industry, while the operation of buildings is assigned to the energy supply and real estate and housing sectors, among others. The terms are not always clearly differentiated in everyday usage.
62 | See European Commission 2020b.
63 | See Küstner et al. 2022.
64 | See Umweltbundesamt 2023a.
65 | See Deutsche Energie-Agentur 2023.
66 | See European Commission 2020b.
67 | See Umweltbundesamt 2023a.
68 | See Deutschlandfunk 2022.
69 | See Circle Economy/BAIN & Company 2022.
70 | See Steger et al. 2022.
71 | See Deutsche Energie-Agentur 2024.
72 | See ibid.
73 | See Schmatzberger et al. 2022.

90 per cent of carbon emissions from the operation of private household buildings, largely, around 75 per cent, through burning heating oil and natural gas.[74]

Some 60 per cent of all residential buildings in Germany were built before the first Thermal Insulation Ordinance came into force in 1977. Such old buildings built up to and including 1976 are responsible for around three quarters of Germany's final energy consumption in residential buildings. If climate targets are to be met, a large proportion of existing buildings must therefore be renovated to make them more energy-efficient. Scenario studies showing pathways to achieving a climate-neutral Germany by 2045 conclude that achieving reduction targets means increasing the renovation rate from approximately 1 per cent per year (as of 2021) to around 1.3 to 2.5 per cent per year by 2030.[75, 76] Some scenarios extending to 2050 even assume average renovation rates of up to 3.9 per cent.[77] The reality, however, shows a different trend: the renovation rate actually fell to 0.7 per cent between 2021 and 2023.[78] As part of its *A Renovation Wave for Europe*[79] strategy, the EU Commission has set the target of doubling the annual renovation rate for the entire Union, which would require the renovation of 35 million buildings by 2030.[80]

As the energy efficiency of buildings increases and the proportion of renewables in energy production grows, the proportion of greenhouse gas emissions is increasingly shifting from energy-related emissions from the operation of buildings to "grey" emissions, which are generated during the production and transportation of construction materials and during the construction and disposal of buildings. A comparison between a new build constructed in accordance with the statutory minimum energy standard and more energy-efficient buildings shows that the more energy-efficient the building, the higher are the construction-related greenhouse gas emissions, but the lower are the overall emissions.[81] In the future, grey emissions will increasingly become the dominant emission factor in a building's life cycle.

Since housing is a basic need, social aspects are of great importance in shaping the buildings and construction sector. Providing sufficient affordable housing is therefore a key political goal for the Federal government.[82] Potential solutions are being developed, for example, as part of the BMBF-funded acatech project *Building & Living: a platform for networking, synthesis, and transfer*.[83] However, the task of providing sufficient living space while conserving resources and the environment has by no means become easier over time, as the average living space per capita in Germany more than doubled between 1965 and 2020 from 22.3 square metres to 47.7 square metres.[84] The concomitant sealing of previously mostly agricultural land in turn fragments ecosystems and impairs the environmental function of soils and the water balance.[85] In addition, the increase in living space is leading to increased energy consumption, which counteracts the savings made by increasing energy efficiency.[86]

And last but not least, when planning buildings, adaptation to the increasing consequences of climate change must also be considered: protection against heat, heavy rain and flooding.

## 3.2 Regulatory framework for the Circular Economy in the buildings and construction sector

Buildings are complex, unique products with an extremely long life. The differing lifespans of a building structure (several decades) and the related building services (15 to 20 years) means that building services have to be upgraded a number of times during a building's service life. R strategies can therefore be

74 | See Umweltbundesamt 2019a.
75 | See Stiftung Klimaneutralität et al. 2022.
76 | See Umweltbundesamt 2019a.
77 | See ibid.
78 | See BuVEG 2024.
79 | See European Commission 2020d.
80 | See Deutsche Energie-Agentur 2023.
81 | See Schlegl et al. 2019.
82 | See BMWSB 2023.
83 | See acatech 2024.
84 | See Umweltbundesamt 2023a.
85 | See Circular Economy Initiative Deutschland 2021b.
86 | See Bierwirth 2023.

applied both at the level of the building as a whole and at component level (including building services and interior fittings).

Until a few years ago, the focus of German environmental policy in the building sector was on the goal of reducing carbon emissions during the use phase by increasing energy efficiency and using renewables to provide heating. However, as mentioned above (see section 3.1), the grey emissions generated during a building's construction have recently been identified as an important factor in its environmental footprint, with the result that these grey emissions are increasingly the subject of policy measures at both the national and European level.[87]

The construction sector is defined as a priority action area in key German and European Circular Economy strategy documents such as the *draft National Circular Economy Strategy*[88] from the Federal Ministry for the Environment (BMU) and the EU Commission's *Circular Economy Action Plan*[89]. The EU Commission's *Renovation Wave*[90] framework strategy from 2020, mentioned above, also aims to improve the energy efficiency of European building stock by doubling the renovation rate by 2030. This strategy makes consideration of a building's entire life cycle and the Circular Economy central guiding principles for building renovation. The strategy sets out numerous specific measures relating to the Circular Economy and digitalisation, including reviewing the EU Construction Products Regulation, expanding reuse and recycling platforms to promote an internal market for secondary raw materials, rolling out digital building logbooks[91] and promoting digitalisation in the construction sector. These various projects are currently at different stages of implementation.

The recast version of the EU Directive on the Energy Performance of Buildings adopted in April 2024,[92], which must be transposed into national law by May 2026, requires life cycle emissions to be progressively taken into account, starting with new builds and renovations. For new buildings, life cycle emissions must be documented in the building's Energy Performance Certificate from 2028 or 2030 (depending on the size of the building). From 2030, Member States will be required to take the entire life cycle into account when setting minimum requirements for the energy efficiency of new buildings. A standardised method for calculating the life cycle emissions of buildings can be found in standards DIN EN ISO 14040, DIN EN ISO 14044 and DIN EN 15978; *Level(s),* the voluntary European reporting framework[93] defines a certification method. However, Germany's Buildings Energy Act[94] as yet takes no account of grey emissions.

According to the EU Energy Performance of Buildings Directive, each Member State must also draw up a building renovation plan, including a national database into which building Energy Performance Certificates are to be uploaded. The database is to be interoperable with the (voluntary) digital building logbooks but such digital building logbooks are not yet in use in Germany. The introduction of a digital building resource passport[95] is, however, already planned in the coalition agreement.[96] Digital building logbooks are already in use in Sweden, France and Belgium.[97]

The Construction Products Regulation also defines uniform EU-wide product and testing standards for construction products. The recast version[98] adopted by the European Parliament in April 2024 requires manufacturers to provide information about defined environmental indicators for their products. The new regulation, which will be binding on Member States, will be implemented gradually to give them time to adapt their national legislation.[99] The establishment of a digital product passport system for construction products is to be governed by delegated acts. In order to get the market for used construction products

Buildings and construction sector

87 | See Schmatzberger et al. 2022.
88 | See BMUV 2023.
89 | See European Commission 2020b.
90 | See European Commission 2020d.
91 | A digital building logbook collates data on a building over its entire life cycle, for example information about materials used and energy efficiency. Updates during the operational phase (e.g. details regarding conversions and changes of ownership) ensure the data are always kept up to date.
92 | See Directive (EU) 2024/1275.
93 | See European Commission 2023b.
94 | See Gebäudeenergiegesetz 2023.
95 | A building resource passport contains information about materials used, together with their circularity and life cycle assessment.
96 | See SPD/DIE GRÜNEN/FDP 2021.
97 | See Gebäudeforum Klimaneutral 2023.
98 | See European Parliament 2024.
99 | See Handwerksblatt 2024.

off the ground, the regulation moreover provides the possibility of developing harmonized technical specifications for used construction products.

Expanding the recycling of construction materials is also an EU goal, codified in the European Waste Framework Directive.[100] The non-binding guideline *Protocol on the Management of Construction and Demolition Waste*[101] and the *Guidelines for Pre-Demolition Waste Audits*[102] as well as the DIN SPEC 91484 guideline for drawing up pre-demolition audits, which is still under development, additionally aim to enable better management of demolition waste and increase confidence in recycled construction materials. In Germany, the planned End-of-Waste Ordinance[103] is set to supplement the Replacement Construction Materials Ordinance[104], which came into force in 2023, and facilitate the use of mineral replacement construction materials as high-quality recycled products in building construction and other areas.

When dismantling and renovating buildings and recovering construction materials, proper handling of harmful substances, especially asbestos, must be ensured to avoid endangering people and the environment. The handling of harmful substances is governed by the Hazardous Substances Ordinance[105]. The amendment to the Hazardous Substances Ordinance passed by the Federal Cabinet in August 2024 has been criticised by several construction industry associations for its failure to require investigation for asbestos prior to construction work.[106]

Last but not least, the EU Taxonomy Regulation[107], which aims to direct investment into climate-friendly projects, is also of relevance to buildings as capital goods. The taxonomy defines the transition to a Circular Economy as a sustainability criterion. The EU Corporate Sustainability Reporting Directive (CSRD)[108], which came into force in January 2023, is also of significance, requiring as it does companies above a certain size to submit an annual sustainability report using uniform European standards – the European Sustainability Reporting Standards (ESRS).

## 3.3 Application example: existing single-family dwelling

Numbering around 13 million buildings, single-family dwellings[109] account for two thirds of all residential buildings in Germany.[110] Many of these are of a poor energy standard and will have to be renovated over the next 20 years if building operation is to be climate-neutral. In addition to improved thermal insulation, studies have shown that converting heating to renewable energies is crucial to achieving this goal, for which reason heat pumps and an expansion of heating networks (local and district heating) will play a central role.[111]

From an environmental standpoint, single-family dwellings are a rather unfavourable form of residential development. Compared to compact designs such as multi-occupancy dwellings, heating and cooling requirements, greenhouse gas emissions and resource consumption over the building's entire life cycle are higher for single- and even two-family dwellings.[112] The low population density in single-family dwelling areas tends to lead to higher car mobility, as public transport connections are often poor and destinations (e.g. workplace, shopping facilities, places for leisure activities) are not within walking distance. There is therefore a need for concepts that take account of these factors to enable the large stocks of single-family dwellings to be used as sustainably as possible in the future.

100 | See Directive 2008/98/EC.
101 | See European Commission 2016.
102 | See European Commission 2018.
103 | See BMUV 2023.
104 | See Ersatzbaustoffverordnung 2023.
105 | See Gefahrstoffverordnung 2024.
106 | See Bundesvereinigung Bauwirtschaft et al. 2024.
107 | See Regulation (EU) 2020/852.
108 | See Directive (EU) 2022/2464.
109 | The stated figure only includes single-family dwellings as narrowly defined, i.e. buildings with a single residential unit. Some statistics include the 3 million dwellings with two residential units in the number of single-family dwellings
110 | See Deutsche Energie-Agentur 2024.
111 | See Ragwitz et al. 2023.
112 | See Umweltbundesamt 2023a.

While the use of digital working methods is today already standard for new builds, digital technologies, despite their undeniable benefits, are still much less widely used in the refurbishment of existing buildings.[113] As building construction companies generate almost 70 per cent of their revenue from existing buildings,[114] there is therefore still great potential for growth in the use of digital technologies and applications tailored to renovation projects.

The conversion or renovation of an existing single-family dwelling is therefore analysed as an application example for the potential of such digital enablers in the buildings sector. Many of the approaches listed below are, however, also relevant to the construction of new builds. The circular approaches identified for the four phases of the life cycle are summarised in Figure 6 and associated with the various R strategies. It is additionally shown which of the digital technology functions identified in section 2.3 are of relevance to implementing the circular approaches. Measures relating to design of the conversion or refurbishment are associated in Figure 6 with the "product design" phase. The overall refurbishment is additionally listed in the "use" phase.

The following analysis focuses on the use of the relevant R strategies for reducing raw materials volumes and waste generation. Measures for saving energy during the use phase (e.g. by optimised ventilation procedures or efficient heating settings) are not considered in detail here. However, they are undoubtedly a further, complex area in which digital technologies and applications – especially in the context of building automation – can play a major role in climate and environmental policy terms.[115]

**Product design**

As with other products, a building's design lays the foundations for it to be put to efficient and extended use and for components and materials to be recovered at end-of-life. Due to the very long technical service life of buildings, an adaptive design is advantageous so that they can be adapted to a different type of use and other requirements at a later date. Modular units that can be reused at a different location at a later date also increase flexibility. Connection methods that facilitate subsequent disassembly (e.g. screw connections) should also be selected to facilitate component and material reuse.[116] The European *Buildings as Material Banks* (BAMB) project has already developed detailed strategies for "reversible" buildings which enable both such changes of use and disassembly.[117] One important aspect for the sustainable design of a building is the regional availability of reclaimed or natural materials, which varies from case to case.

**Create sustainable living space in existing buildings:** due to the significant grey emissions associated with the construction of a new building, existing buildings should be used whenever possible and adapted to a new use as required. In the case of single-family dwellings, conversion into a building with a number of residential units by adding extra storeys can help to create more living space on the same ground area and so avoid further land sealing. Separating the floors, on the other hand, makes it possible to divide the existing living space into smaller residential units and thus put it to more efficient use. However, a good pool of data is required if existing buildings are to be used efficiently and neighbourhoods sustainably designed. Digital planning tools are already commercially available; the start-up Urbanistic, for instance, has designed a digital urban planning tool for urban planners, architects, project developers and local authorities to shorten in particular the early architectural planning phase of appropriate construction projects.[118]

**Plan cooperatively with building information modelling (BIM):** clients, architects, construction and inspection engineers as well as the trades involved in implementation – in a construction project, many parties must work together as efficiently as possible. Building Information Modelling (BIM) is a digital application for 3D building planning that enables all project partners to work on a shared digital data model and track changes directly in the "coordination model". Object-based communication and the integration of several specialist models into a common BIM model assist efficient planning. However, binding, open standards, which do not yet exist, are crucial for efficient data exchange between the stakeholders. A linked data model is even more important in circular planning than in linear planning to enable a response to the availability and specific properties of

113 | See Mittelstand-Digital 2020.
114 | See ibid.
115 | See bitkom 2021.
116 | Research is also currently being carried out into soluble plaster and reversible adhesive bonds.
117 | See Durmisevic 2019.
118 | See Tischer 2021.

| Product lifecycle stages | Approaches to the Circular Economy | R strategy | Technology functions | | | |
|---|---|---|---|---|---|---|
| | | | Data collection | Con-necting | Mod-elling | Auto-mating |
| | Create sustainable living space in existing buildings | refurbish | ● | ● | ● | |
| | Plan cooperatively with building information modelling | all | | ● | ● | |
| Product design | Create a 3D model of the building | refurbish | ● | | ● | |
| | Integrate life cycle assessments into planning software | reduce | | | ● | |
| | Use circular materials for construction | reuse | | | ● | |
| | Use digital assistants | all | | ● | ○ | |
| | Produce components from nature-based materials | reuse | ○ | | ○ | ● |
| | Reuse entire components | remanufacture | ● | | ○ | ● |
| Production | Prefabricate for modular construction | reduce | | | ○ | ● |
| | Establish digital benchmark projects | all | | ● | ○ | |
| | Make flexible use of building through new housing concepts | rethink | ● | ● | | |
| Use | Carry out (serial) refurbishment of buildings | refurbish | ● | | ○ | ● |
| | Monitor building and component condition in real-time | repair | ● | | ● | ○ |
| | Create digital twins of neighbourhoods | rethink | ○ | ○ | ● | |
| | Establish material exchanges and registers | reuse | | ● | | |
| | Use product passports for buildings and components to share information | reuse | ● | ○ | | |
| End-of-life | Evaluate and certify component condition | reuse | ● | | ● | |
| | Establish take-back systems for components | reuse | | ● | | |
| | Deconstruct rather than demolish buildings | remanufacture | ● | ○ | | |

Relevance of technology function to implementation of the approaches:

● very high

○ high

Figure 6: Digitally assisted circular economy approaches to converting or modernising an existing single-family dwelling. (Source: own presentation)

recycled components and materials. It is also worthwhile to link BIM models with simulation software in order to combine planning with impact assessments (e.g. energy requirements, life cycle analysis, interior quality, acoustics). While planning using BIM is already relatively widespread for multi-storey buildings, it has rarely been used in the construction of single-family dwellings for cost reasons. However, it is particularly in this area that the ability to visualise planning states offers opportunities to communicate the advantages of circular approaches to clients. This is because private building owners of single-family dwellings, who mostly use their property themselves, are often largely unfamiliar with the possibilities of used materials and components. Demonstrating circular design in the model can increase acceptance of such a construction method. When it comes to converting existing buildings, a 3D model of the building in question must first be created and entered into the BIM system.

**Create a 3D model of the building:** an accurate computer-aided design (CAD) model, i.e. a drawn 3D structural model of the existing building, is an important first step in refurbishment and conversion projects using BIM. This is done by firstly using a laser scanner to create a dot cloud (dots depicting the scanned surface). The subsequent creation of a surface model from the dot cloud – a kind of digital representation of the building – is a labour-intensive step that can only be carried out by experienced professionals. (Partial) automation of this step using AI might in future help to reduce the cost of creating a CAD model and so also make this tool economically attractive for renovation and conversion work on single-family dwellings.

**Integrate life cycle assessments into planning software:** as a building consists of many different components and materials, determining its environmental impact is complex. Not least, account must be taken not only of the production of the components but also of the anticipated greenhouse gas emissions during the use phase. For instance, the question may arise as to whether it is more climate-friendly to save on grey emissions by using used windows or to install new windows with lower heat loss. A life cycle analysis provides answers to such questions and makes it possible to compare different planning variants in terms of their likely environmental impact. Some tools are already commercially available. For example, Madaster offers a carbon calculator that calculates a building's life cycle emissions on the basis of data from a BIM model and machine-readable Environmental Product Declarations (EPDs) as well as life cycle assessment data from the online ÖKOBAUDAT database provided by the Federal Ministry for Housing, Urban Development and Building (BMWSB).[119] The better the data available on specific products from specific suppliers, the more accurately can the environmental impact be estimated. The planning software should therefore be continually further developed and brought into line with the latest scientific findings. In the long term, suitable interfaces between the planning software and component and material exchanges could even enable the software to respond to available offers and make suggestions as to how environmental impact could be further reduced.

**Use circular materials for construction:** nature-based materials (e.g. straw, clay, various kinds of wood) sometimes have different properties from conventional construction materials and these must be taken into account in the geometry of components and buildings. If recycled components are used, the design may also have to be adapted to those. Appropriate digital design tools are required for this purpose. Since circular materials are also only available in limited quantities, the aim should be to use materials as sparingly as possible (e.g. through lightweight construction).

**Use digital assistants:** planning and implementing a building renovation or even a major conversion is a complex project. Architects, various specialist planners, tradespeople and financial service providers have to be coordinated, approvals have to be obtained and numerous legal regulations and standards have to be taken into account. It is difficult for clients to keep track of everything. Private individuals in particular, such as single-family dwelling owners, can quickly become overwhelmed and may shy away from the modernisation of their home that is actually necessary. Further factors may be that they lack knowledge about financing and funding options or are overlooking the potential for circularity and sustainability. AI-based digital assistants such as chatbots or avatars can support homeowners here by evaluating specialist knowledge, preparing it for specific target groups and coordinating the parties involved. Machine-readable documents are essential at every stage of the process.

**Production**

Achieving circularity in the construction sector entails not only manufacturing in a manner that is less wasteful of materials (e.g. 3D printing) and reusing components and recycled materials, but also replacing climate-damaging materials such as steel



119 | See Madaster 2022.

and concrete with sustainable natural raw materials. The logistics of closed-loop materials management differ completely from those involved in processing primary raw materials. This offers potential for new business models, but also poses obstacles, including in terms of stockholding and end-to-end supply chains.

**Produce components from nature-based materials:** to date, there is extensive experience with the use of softwood as a building material (for business and regulatory environment and policy options for timber construction, see also acatech POSITION PAPER *Wood-based Bioeconomy. Sustainable, Circular, Climate-resilient*[120]). Climate change (rising temperatures, drier periods of weather and more severe storms) is, however, making it increasingly difficult to grow conifers, especially spruce, which has been widely used in construction to date. In future, the focus should therefore be on other natural raw materials that are likely to be more readily available and also more advantageous in terms of their environmental impact during cultivation. These include deciduous trees and plants such as willows or reeds that can be cultivated on rewetted marshland. Using residual materials such as straw or wood offcuts is also attractive from an environmental standpoint. However, suitable processes still need to be developed for processing such materials in today's construction industry. Digital technologies such as robotics and tailored fibre placement can help to automate processing of these generally relatively non-homogeneous materials into customised or standard components, which would enable production to be scaled up and costs to be reduced.

**Reuse entire components:** remanufacturing and subsequent reuse of entire components saves energy and emissions compared to the production of new components – even if the latter are made from recycled materials. Concrete components are one striking example of this approach. The need for cement is particularly problematic in concrete production, as producing cement is highly climate-damaging and, even in the future, will remain difficult to decarbonise due to its unavoidable process emissions. These emissions cannot be avoided by using recycled concrete as the production of recycled concrete also requires cement. Reusing entire concrete components, on the other hand, can reduce cement requirements. Digital technologies can assist with testing reclaimed components, refurbishing them (e.g. by cutting to size or creating new connections) or repairing them by additive manufacturing.

**Prefabricate for modular construction:** prefabricating entire building components instead of individual construction products enables more economical use of materials due to reduced on-site generation of scrap. It can also help to increase productivity in the construction industry. Automation-related digital enablers are of relevance to the manufacture of components on production lines. The start-up Triqbriq[121], for example, has developed a modular timber construction system in which timber building blocks are slotted together on the construction site and locked in place with dowels. This means that when an appropriately designed building is dismantled, the building blocks can be taken apart and then reused.

**Establish digital benchmark projects:** digital benchmark projects that model the various steps of a circular planning and construction project could be developed for different categories of buildings and made available to the relevant stakeholders. Project teams could then use these as a basis for their planning and construction project and adapt them individually. In this way, time and costs could saved by implementing the appropriately preplanned, standardised workflows. The Gaia-X structure developed by the planning/building/operating domain[122] for the construction sector offers suitable digital infrastructure for developing and providing such benchmark projects (see "Use" section, "digital twin of neighbourhoods").

**Use**

Single-family dwellings are usually owned by private individuals who often occupy them themselves for many decades; even if their living situation changes (e.g. the children move out), the barriers to moving are high. In the case of older buildings with poor energy performance, extending the life of the building in its current state is not an environmentally friendly option due to the high energy-related emissions for heating, so energy-efficient refurbishment is urgently required.

**Make flexible use of building through new housing concepts:** more flexible use of the housing stock could help to intensify the use of living space and thus counteract the environmentally problematic growth trend in per capita living space in Germany. Possible intensification concepts include home swaps, communal forms of living such as multigenerational housing and communal areas. Such concepts are easier to implement if the design of the building already provides for adaptability to

120 | See acatech 2022.
121 | See Triqbriq 2024.
122 | See Gaia-X Hub 2024 in the process of publication.

changing requirements, for example homes that are structurally easy to divide. This requires, among other things, ensuring the availability of water and wastewater connections through several piping runs. Digital technologies can be used in this context to provide information tailored to the target group and to interconnect stakeholders (e.g. via digital home swap platforms).

**Carry out (serial) refurbishment of buildings:** energy refurbishment can considerably reduce a building's energy requirements. Installing renewable energy systems (e.g. photovoltaics, geothermal energy) can further reduce greenhouse gas emissions during use. In serial refurbishment, custom-made components for the building to be refurbished are factory-prefabricated so that they can then be installed within a short time. Manufacturing to fit avoids construction waste. A further advantage is that on-site time is reduced. One important requirement for this is a 3D building model with very precise dimensions (for information about creating such models, see "product design" section). Up to now, serial refurbishment in Germany has almost exclusively been used for multi-occupancy dwellings. However, certain aspects, such as the prefabrication of components and the associated reduction in on-site time, would also seem to be attractive for single-family dwellings. There is also an interesting interface between serial refurbishment and remanufacturing if replacement elements for serial refurbishment can be prefabricated when reclaimed components are being remodelled.

**Monitor building and component condition in real time:** the condition of buildings and components can be monitored in real time by sensor systems and evaluation of the captured data, so enabling needs-based maintenance and repairs (predictive maintenance). This can save costs and extend the lifespan of buildings or components. Building use data can be used for smart control of building services (e.g. predictive, automated control of heating/cooling). Coupling the BIM model with the facility management model can unlock potential energy savings.

**Create digital twins of neighbourhoods:** it would be helpful for the future urban planning of energy-efficient neighbourhoods and for municipal heat planning to link data from the BIM models of individual buildings and so over time create digital twins of entire neighbourhoods. For those buildings for which no BIM models or digital building passports are yet available, the data could initially be estimated on the basis of comparable, already better documented buildings. This requires comprehensive data ecosystems with standardised interfaces and data exchange formats, something that is also required for material exchanges and registers (see "End-of-life" section). The goal of the *Gaia-X* project is to define the foundations for the sovereign and trustworthy use of data and so create a basis for the development of an ecosystem of European data spaces.[123] The planning/building/operating domain of the German Gaia-X hub is currently working out the construction sector's *Gaia-X* requirements. *Gaia-X* has, however, as yet seen only limited use in the construction industry, so there is a need for support services to facilitate access in the future, particularly for SMEs.

### End-of-life

If optimum use is to be made of components or construction materials from demolished buildings (also known as "urban mines" or "anthropogenic raw material deposits"), it is important to know not only which buildings, components and materials are available for reuse but also when and where. To this end, data on the building stock must be generated and made accessible to stakeholders in a circular construction industry.

**Establish material exchanges and registers:** material exchanges can bring together suppliers and buyers of reusable materials and components, minimise transport distances and, in the best case, avoid intermediate storage. Business models for assuming liability are also of relevance in this context. Some start-ups are already active in this field. For instance, Concular, a start-up founded in 2020, operates a component and product database and a matchmaking platform.[124] Digitally linking such material exchanges with planning tools could enable planners or architectural firms to take account of regionally available supplies of circular materials from the outset of the design process. Material registers of building stocks for cities and regions could in turn reduce transaction costs for information procurement by providing spatially differentiated information on materials in the building stock and current levels of activity and so provide the information basis for developing circular business models and for raw material policy strategies. The information from product passports may in future be helpful for setting up corresponding material registers. However, since such passports are generally only produced for new builds, the types and quantities of materials in (older) buildings will have to be estimated on the basis of their type and year of construction.



123 | See Gaia-X Hub 2024.
124 | See KfW 2022.

**Use product passports for buildings and components to share information:** in the buildings sector, product passports that contain a material inventory are usually referred to as "material passports", "building resource passports" or "(material) building passports".[125] These are complemented by the already well established Energy Performance Certificates, which relate solely to energy consumption during a building's use phase. A digital building resource passport summarises a building's environmental impact and circularity in a specified format. The information it contains about materials used and possible harmful substances makes it easier to estimate the value of the building, of components and of materials and to make circularity-friendly decisions about refurbishment or the recovery of components and materials. The German Sustainable Building Council (DGNB) has developed a freely available format for the building resource passport, the content requirements of which are already being integrated into some commercially available building documentation tools (including those from Concular and Madaster).[126] If a BIM model of the building is available, the data required for the building resource passport can often be extracted from this model. The passport data can in turn contribute to the development of regional material registers and thus to the step-by-step specification of typology-based information. This entails access rights to the data being settled beforehand. Digital building resource passports together with other documents such as renovation roadmaps can ultimately also be incorporated into "digital building logbooks" which manage and provide information as a kind of dynamic building passport from the planning stage through all the particular building's use phases until the end of its life. Product passports for individual components can, moreover, prevent information of relevance to reuse being lost when they are removed from the building. Standardised formats and data interfaces are essential to ensuring compatibility of the various instruments – building resource passports, building logbooks, component product passports, manufacturer information such as EPDs, BIM and material registers. Since the data will be of particular value at the end of a building's service life, i. e. 50 to 80 years after its construction, particular attention must be paid to permanent, secure storage and accessibility of the data for the relevant stakeholders. Among other things, this requires clarifying which institution is to store the data.

**Evaluate and certify component condition:** the safety and quality of components must be tested and certified. Appropriate procedures and regulations must be developed to enable the approval of recycled building materials for wider use. More extensive certification of quality characteristics could also increase user confidence in reclaimed components. In any event, on-site assessments are a key requirement for making component reuse economic. Various digital technologies such as image recognition and computed tomography can be used for testing material quality.

**Establish take-back systems for components:** decreasing availability of certain raw materials can provide companies with incentives to recover the components or materials they use at the end of the service life of the buildings concerned. Even for raw materials which are geologically sufficiently available, such as sand, regional availability can be an issue , , , as extraction of natural deposits is often restricted by nature conservation regulations and social resistance to extraction, and supra-regional transport of these raw materials is economically unattractive due to the high costs. Even gypsum, which is currently mainly a by-product of flue gas desulfurisation in coal-fired power plants, could become scarce in the future as the energy sector decarbonises. Across the board development of take-back systems can enable manufacturers to recover their components in future and thus save on primary raw materials. Lindner SE, for example, already offers to take back used raised flooring panels made of gypsum fibre and wood-based materials.[127] Due to buildings' long lifespans and the many parties involved in the construction process, it is often the case that neither manufacturers nor building owners know which products are installed where and how. Digital technologies can help to collect the necessary information, store it for the long term and make take-back offers better known. In this connection, leasing models for components also offer an interesting alternative to take-back systems.

**Deconstruct rather than demolish buildings:** controlled deconstruction can ensure that reusable components are removed undamaged and that materials are as far as possible reclaimed by type. The building in question should firstly be systematically audited to identify reusable components and materials and any harmful substances (pre-demolition audit; contamination survey). It is important to optimise construction site logistics during deconstruction in order to minimise time and cost disadvantages compared with building demolition. Dismantlable designs

125 | See Schiller et al. 2022.
126 | See DGNB 2023.
127 | See BBA 2022.

and separable component structures are required to simplify this process in the future.

## 3.4 Obstacles and sector-specific policy options

The action areas discussed below (see Figure 7) for promoting the Circular Economy are relevant to the entire buildings and construction sector. Refurbishing a single-family dwelling is, however, particularly challenging, as it is often more difficult to achieve cost-effectiveness compared to larger buildings due to the lower value of the building and the smaller quantities of materials used. Moreover, digital tools have not previously been used as extensively in such renovation projects as they are in new builds or in the renovation of multi-occupancy dwellings, commercial/office and public buildings. Figure 7 lists examples of digital enablers that can nevertheless be effective here.

**Facilitate environmentally friendly decisions in the planning and construction process**

Construction projects involve a great many stakeholders with varying degrees of, sometimes incomplete, knowledge about circular approaches working together under changing circumstances. Although digital tools such as BIM-capable software for collaborative planning processes are already available, there is often still a lack of binding, open standards that enable the efficient transfer and use of data by the various stakeholders and their software systems. Due to the many different components and materials involved, calculating a construction project's environmental impact is also highly complex. As buildings are unique products and meaningful circular approaches depend on the regional availability of reclaimed components and materials, among other things, there can be no one-size-fits-all standard solution – so new, creative solutions have to be developed time and again. Therefore, despite standardisation being desirable in many areas, there is still scope for architectural innovation.



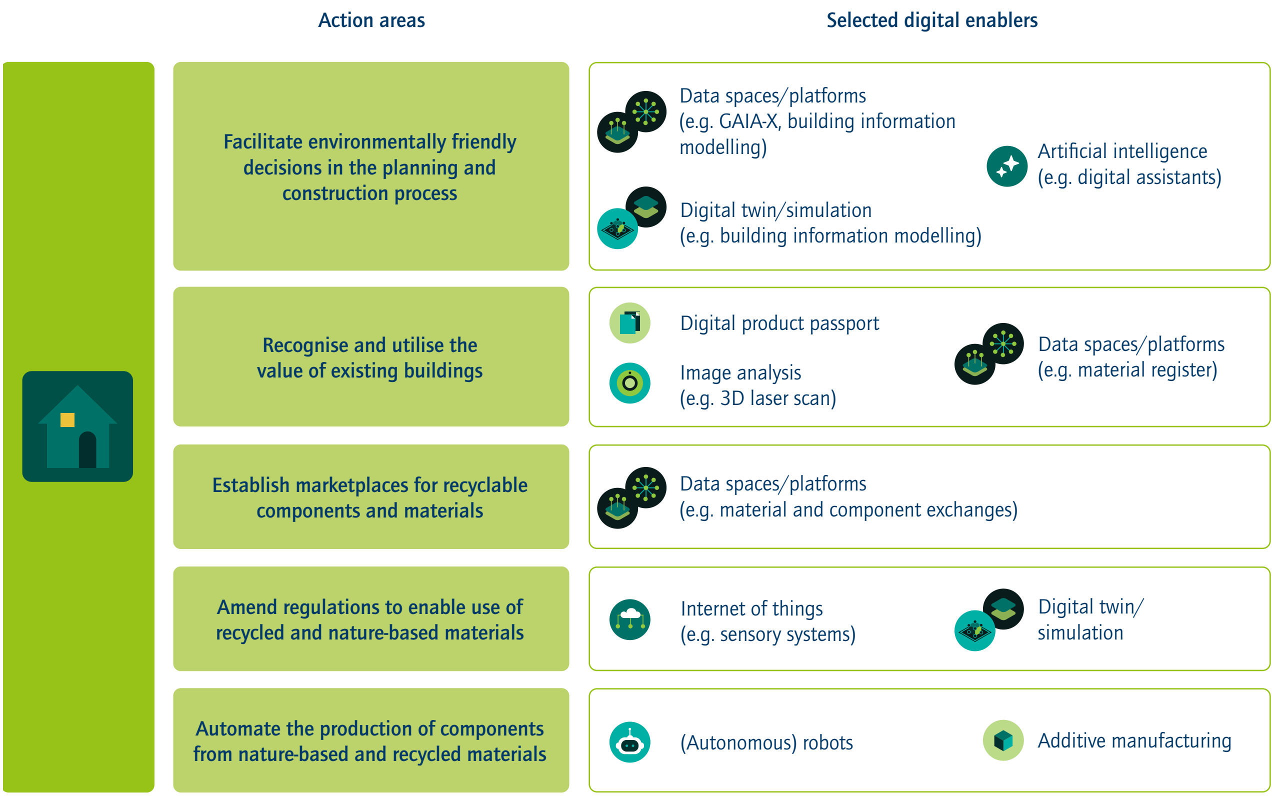


Figure 7: Central action areas for the single-family dwelling application example (source: own presentation)

**How can digital enablers help?** Digital applications can help with comparing different planning variants while taking account of their respective life cycle assessments. In addition to software for professionals such as BIM-capable system solutions, construction tools and digital construction project twins for various building categories, digital assistants such as chatbots can be used to provide information in an easily understandable form for clients, for example.

**What support can policy makers provide?** Calculating the environmental impact of a construction project requires data on numerous materials and components. Statutory obligations to provide such data in standardised form (e. g. building resource passports, environmental product declarations) can help to create the information basis for environmentally friendly, circular building planning. Financial support could in turn help to overcome obstacles to the establishment of digital tools in the construction sector and to further develop digital ecosystems – including those based on Gaia-X – in practical applications. For example, initiatives to develop digital, circular benchmark projects could be funded and made available as a starting point for future construction projects. Finally, in order to promote connections between stakeholders, policy makers could support regional networks offering and implementing digitally documented solutions regionally.

### Recognise and utilise the value of existing buildings

For many older buildings, their construction history, material stock and other information relevant to refurbishment are rarely adequately documented; and if they are, the relevant documentation is generally not available in digital form. The potential for making further or changed use of buildings and for recovering components and materials, which are an important starting point for sustainable urban development and raw material strategies, is still too little known and has therefore been underutilised to date.

**How can digital enablers help?** A digital 3D model of an existing building can be generated on the basis of a 3D laser scan, for example as the basis for (serial) refurbishment or a conversion. In addition, central information about materials used can be stored in a digital building resource passport. In the future, it will also be possible to combine BIM models of individual buildings to create a digital twin for an entire neighbourhood – useful for municipal heat planning under the Buildings Energy Act (GEG), for example.[128] Type-based building data and their application to 3D geodata can serve as a basis for the creation of regional material registers and thus make the potential of recoverable raw materials visible.

**What support can policy makers provide?** Pre-demolition audits make it possible not only to establish the value of building components and materials at an early stage, but also to identify and properly dispose of any harmful substances in existing buildings. Whether it makes sense for there to be a statutory obligation to carry out such audits or whether financial incentives should instead be provided depends on the relationship between costs and benefits from the client's perspective, which is why corresponding policy measures for different building types should be given nuanced consideration. Specifications for documenting building, component and material properties in standardised digital formats (e. g. digital 3D construction plans, building resource passport), on the other hand, in any event enable interaction between different tools and so facilitate data handling by different stakeholders and thus also more intensive use on a broad scale. Supporting the across-the-board creation of digital material registers also helps to maintain a broad, publicly accessible database for anthropogenic raw material deposits and to reduce transaction costs arising from data procurement.

### Establish marketplaces for recyclable components and materials

In order to reduce costs and simplify transport, used components and materials should as far as possible be reused regionally and without intermediate storage. However, this first requires appropriate marketplaces that serve as a platform for trading recycled products in the construction sector. Because circular construction products have previously been insufficiently standardised, there is too much uncertainty regarding the quality of the specific material that is available. The Circular Economy requires complex value chains and new business models. New stakeholders should also be involved in the development of business models; for instance, intermediaries who test materials and guarantee component or material quality and functionality could increase confidence in used construction products.

**How can digital enablers help?** Data ecosystems with standardised interfaces and formats for data exchange are essential to the connections between the many necessary stakeholders and the development of circular business models. Digital

128 | See Gebäudeenergiegesetz 2023.

building resource passports, among other things, can play an important role here.

**What support can policy makers provide?** Application-related research and development (R&D) projects involving small and medium-sized enterprises can help to develop suitable data infrastructures and transfer them for use in the construction sector. Policy makers can support the necessary development of standards, for example for digital building resource passports, construction product passports and the certification of building components, through regulatory requirements. Issues of warranty and liability over the long lifespan of buildings and installed components are another important factor requiring regulatory clarification.

**Amend regulations to enable use of recycled and nature-based materials**

Restrictive regulations and very stringent standards relating to fire protection and statics, as well as very strict requirements regarding the maximum content of various harmful substances, are complicating and sometimes preventing the use of innovative recycled and nature-based materials.

**How can digital enablers help?** Digital sensor systems and modelling can help with assessing the properties of innovative materials and designs and demonstrating their safety. This would make it possible to use such materials and designs without having to compromise on safety standards.

**What support can policy makers provide?** When reviewing statutory regulations and binding standards, greater consideration should be given to suitable innovative methods for testing and guaranteeing the quality of recycled and natural materials.

**Automate the production of components from nature-based and recycled materials**

Recycled and nature-based raw materials are frequently non-homogeneous, which means that it has so far proved difficult to process such materials by machine.

**How can digital enablers help?** Robotics can be used to automate the production of standard or custom components from non-homogeneous raw materials, so reducing costs. Additive manufacturing technologies such as 3D printing and tailored fibre placement make it possible to produce components from various starting materials, including nature-based fibres, in a manner that is less wasteful of materials.

**What support can policy makers provide?** Financial support for R&D projects relating to digital machine processing of recycled materials and nature-based raw materials can assist with the development of innovative processes for producing construction materials.

# 4 Electronics sector

## 4.1 Critical waste volumes in the electronics sector

The need to expand circular approaches in the value chains of the electronics sector arises primarily from two observations. Firstly, the quantity of electronic and electrical goods produced and placed on the market has been rising steadily for years, from 62 million tonnes in 2010 to 92 million tonnes in 2022. Secondly, electrical waste volumes have likewise been growing steadily in parallel (2022: 62 million tonnes), and forecasts suggest that, by 2030, they will grow significantly faster in percentage terms even than total waste volumes.[129, 130, 131]

There are many reasons for the increasing volumes of waste in the electronics sector: the declining service life and durability of appliances is the result, among other things, of new technological trends, particularly in small electronic devices, consumer demand for new devices, or the obsolescence of many devices due to software that is incompatible or no longer supported (mobile phones, tablets, notebooks, etc.). In the event of faults, repair is often not possible either due to the product's design or a lack of spare parts, or is not competitive in price terms due to the internal logic of a linear economy. Although Germany has established structures and statutory requirements for the collection of end-of-life appliances, the actual collection rates are well below these requirements in the case of electronic devices (target for 2021: 65 per cent, actual: 38.6 per cent).[132]

However, these figures are not entirely reliable, especially for durable appliances such as washing machines. This is because, while the statutory requirements for calculating collection quantities refer to the average of the quantities placed on the market in the past three years, the actual collection rate in the case of washing machines depends on the quantities placed on the market ten or 15 years ago. In addition, washing machines are often traded on the secondary market on platforms such as eBay after their first use. The service life of a washing machine is therefore estimated to be even longer than the ten to 15 years of initial use, although there are no reliable figures on this. In growing markets and in the case of appliances with a service life of over three years, the calculated three-year average can therefore be significantly higher than the quantities actually placed on the market ten or 15 years ago, which is why the calculated rate would in turn be too low.

Irrespective of the specific procedure used to calculate the collection rate, there is also significantly less public awareness of collection options in the electronics sector compared to paper and plastics recycling, for example. Taking washing machines by way of example, a survey of 1,000 consumers revealed that respondents had an average of 0.6 faulty/unused ("hibernating") appliances per household, which have therefore been removed from economic circulation.[133]

Recycling end-of-life appliances requires certification as a specialist disposal company due to current provisions of waste legislation in Germany and is therefore not very profitable for the manufacturers themselves due to the necessary logistical and operational costs. When recycling electrical appliances, the focus is currently mainly on the recovery of bulk metals (e.g. steel, ferrous metals), while less than one per cent of rare earths are recycled.[134] This is partly due to the technical challenges of recycling and thus the high investment costs for operators of recycling plants for extracting rare earths which, moreover, are typically only used in small quantities in appliances and are difficult to separate without complete manual dismantling of the appliances.

In addition to the stated challenges in the collection of end-of-life appliances, their often illegal disposal continues to result in major losses of raw materials such as copper, lithium and rare earths. In the context of raw materials availability and local supply chain resilience, it should also be noted that Germany

129 | See Unitar 2024.
130 | See Kaza et al. 2019.
131 | Forecasts: 68 per cent growth in electrical waste from 2016 to 2030, 23 per cent growth in total waste volumes from 2016 to 2030.
132 | See Umweltbundesamt 2023c.
133 | See Oliver Wyman 2023.
134 | See BMUV 2023.

is currently largely or entirely dependent on imports from just a few supplier countries for these resources.[135, 136]

In addition, appliance, raw material and information loops are often not closed because there is no direct feedback between the stakeholders involved. This relates, for example, to the lack of connections between manufacturers and consumers in the B2C sector as the basis for service-based use of more durable appliances as the devices are not sold directly by the manufacturers but by retailers. Similarly, end-of-life appliances are typically collected not by manufacturers but instead by municipal providers and retailers. And finally, there is still room for improvement in the exchange of information on recycling or product design between manufacturers and recyclers.

In the light of described challenges and high raw material and energy requirements over the entire life cycle of electronic appliances, the business and regulatory environment has already been put in place or planned for various aspects of the electronics sector in order to boost sustainability. This is briefly set out in the following section, in particular with regard to its contribution to promoting the Circular Economy in the electronics sector.

## 4.2 Regulatory framework for the Circular Economy in the electronics sector

The majority of the resource requirements for electrical and electronic equipment[137] arise during the use phase through the consumption of energy and, in some cases, also water.[138, 139] This aspect has accordingly been prioritised alongside the collection and recycling of waste equipment in the course of legal regulation to reduce resource requirements and promote sustainability.

With regard to energy efficiency, the 2017 EU Regulation on energy labelling, in its version from 2021, including the pending delegated regulation for individual product groups, aims to assist consumers in choosing energy-efficient products and to create an incentive for manufacturers to develop more energy-efficient products.[140] April 2023 also saw the adoption of the EU Regulation on reducing the energy consumption of electrical equipment in standby mode.[141]

The Electrical and Electronic Equipment Act applicable in Germany (as amended in 2022) contains further requirements for the disposal, collection and recycling of waste equipment and also implements the content of EU Directive 2012/19 on waste electrical and electronic equipment (WEEE Directive). This is intended, on the one hand, to prevent the unplanned and unauthorised release of harmful substances and, on the other, to organise the proper take-back of waste equipment to promote reuse. In this connection, manufacturers are obliged, among other things, to register their appliances for the purposes of traceability, to ensure that the disposal of waste equipment is funded and to inform customers about the options for returning waste equipment. Depending on the circumstances, these obligations may also be transferred to distributors. Municipal collection points, which are now available throughout Europe, have been set up to organise and promote the return of old appliances; in addition, a minimum collection rate of 65 % was introduced in 2019.

In addition, recently introduced regulatory measures are primarily aimed at reducing the use of raw materials in the electronics sector. The EU Ecodesign Directive, which was replaced in July 2024 by the associated EU Regulation establishing a framework for defining ecodesign requirements for sustainable products, has so far been the keystone of the legal framework. The focus of this regulation is on establishing minimum requirements for implementing ecodesign principles, introducing digital product passports as part of the extended information obligations of economic operators and preventing the destruction of unsold consumer products in the textiles sector. When drawing up the work plan for implementing the regulation, priority will also be given to the electronic equipment product group.

135 | See BGR 2023.
136 | See IW Consult/Fraunhofer ISI 2024.
137 | Electrical appliances generally refer to appliances that are powered by electricity. Electronic appliances additionally contain at least one active component, for example for controlling current flow.
138 | See Yuan et al. 2016.
139 | See Roy 2016.
140 | See Regulation (EU) 2017/1369.
141 | See Regulation (EU) 2023/826.

A new EU Directive promoting a "right to repair" for damaged or defective goods was also adopted as recently as May 2024. The Directive applies to various classes of goods, including large electrical appliances and consumer electronics. The Directive provides, among other things, an obligation for manufacturers to provide repairs within the warranty period if technically feasible, a European Repair Information Form containing clear information about repairs (timings, prices etc.) and a plan to establish a European online platform through which consumers can easily find repair services.[142]

In addition to the stated legislative provisions, there are also initiatives from business and society for promoting the Circular Economy in the electronics sector. In 2021, the Federation of German Industries (BDI) launched the *Circular Economy* initiative, which aims to promote the Circular Economy as a whole, and a number of electronics companies are among the 60 participating stakeholders.[143] In addition, DIN – the German Institute for Standardization, VDI – The Association of German Engineers and the German Commission for Electrical, Electronic and Information Technologies in DIN and VDE published the *German Circular Economy Standardisation Roadmap* in 2023. This roadmap identified 43 standardisation requirements for implementing the Circular Economy in the electronics and ICT sector.[144]

Finally, the *I4R Platform*, jointly operated by the European Association of Producers of Household Appliances (APPLiA) and the International Association of Electronic Waste Producer Responsibility Organisations (WEEE Forum), provides operators of treatment and recycling facilities and of preparation for reuse facilities with access to information on the recycling of WEEE in accordance with the requirements of Directive 2012/19/EU (WEEE Directive).

## 4.3 Application example: washing machine

The reasons for selecting washing machines as the product type for this analysis are, on the one hand, the great sustainability potential arising from the considerable volume of washing machines placed on the market and, on the other, the various possible applications of digital enablers in the implementation of circular approaches in this area. Washing machines are responsible for around one fifth of the environmental impact of using household electronics.[145] This is mainly due to the large number of existing machines: around 96 per cent of German households owned their own washing machine in 2021.[146] That corresponds to around 36 million appliances which are moreover used on average for just 4 per cent of the available time.[147]

In terms of resource consumption (energy, water) during use, washing machines have now been optimised to such an extent due to technical innovation and the previously mentioned statutory requirements that any further efficiency gains here might possibly have other negative environmental effects. For instance, on the basis of the "Sinner's Circle"[148], which describes the basic factors of cleaning processes, any further reduction in washing temperature while simultaneously achieving the same washing result would, for example, require more detergent or a significantly longer exposure time. However, as a result, more microplastics would be released from clothing or the textile fibres would be exposed to more stress during the washing cycle. Accordingly, the circular approaches presented below focus on intensifying the use of appliances and keeping them in use for longer overall. Figure 8 sets out the circular approaches for the value chain of a washing machine.

**Product design**

The product design phase is a major lever for increasing washing machine circularity, as it is here that the foundations are laid for durable, easy-to-repair products that can be used in various business models.

142 | See Directive (EU) 2024/1799.
143 | See BDI 2024.
144 | See DIN et al. 2023.
145 | See Hischier et al. 2020.
146 | See Statistisches Bundesamt 2022.
147 | See Bressanelli et al. 2017.
148 | See Rust 2004.

| Product lifecycle stages | Circular approaches | R strategy | Technology functions | | | |
|---|---|---|---|---|---|---|
| | | | Data collection | Con-necting | Mod-elling | Auto-mating |
| | Carry out virtual testing of product properties | reduce | very high | | very high | high |
| Product design | Use additive manufacturing for product parts | rethink | very high | | very high | high |
| | Create modular and durable designs | rethink | | | very high | high |
| Production | Refurbish old components | remanufacture | very high | very high | very high | very high |
| | Carry out predictive maintenance | repair | very high | high | very high | |
| | Provide personalised support for repairs | repair | very high | very high | | |
| Use | Establish service-based business models | rethink | very high | very high | | |
| | Share appliances | rethink | very high | very high | | |
| | Modify washing behaviour | rethink | very high | | | |
| | Recondition appliances at end-of-life | refurbish | very high | very high | high | high |
| End-of-life | Reuse components | repurpose | very high | very high | high | very high |
| | Recycle materials | recycle | very high | very high | high | very high |

Relevance of technology functions to implementation of the approaches:

- very high
- high

Figure 8: Digitally assisted circular economy approaches for making extended, intensified and more sustainable use of washing machines. (Source: own presentation)

**Create modular and durable designs, carry out virtual testing of product properties:** at present, the development of new washing machine models also requires extensive testing with real prototypes, for example to allow adequate modelling of wear over a service life of at least ten years; while simulations are already being carried out in some cases, the focus is still on real-world testing due to statutory warranty requirements. Complete or at least more wide-ranging virtualisation of product testing using simulation and digital twins would simultaneously enable parallel testing of various new product designs with distinctly reduced effort. This would enable testing of new modular construction methods that would facilitate repair and recycling of the corresponding appliance model.

Such approaches to implementing the rethink strategy are currently still a major challenge for manufacturers. Changes to product construction methods to increase durability and modularity and simplify dismantling and updating of the hardware are already technically possible; for example, machines are already being developed in a more modular way to speed up assembly and repair. However, a longer lifespan and better dismantlability require high development costs, which are not yet reflected in a corresponding market advantage. Using open source solutions to ensure that the software can be updated is also only possible to a limited extent, if at all, for washing machines. The manufacturer is responsible for the safety of the machine during operation and must therefore also guarantee this in relation to the software used. This applies, for example, to software for motor control in the context of imbalance control where any errors might damage the machine or even make it unusable, which obviously runs counter to the goal of an extended life cycle. Software updates will therefore probably continue to be carried out exclusively by the manufacturer in the future too. Open source solutions, which are generally seen as a way of increasing product circularity, are therefore unlikely to offer any added value here.

**Use additive manufacturing for product parts:** if a product design specifies greater use of 3D printable parts, spare parts can be sourced more flexibly in the event of a repair and not just from the manufacturer itself. However, this must also be made legally possible under appropriate license terms and application is likely to be limited to components that have no structurally load-bearing function. This is because 3D-printed parts are generally mechanically weaker than conventionally (e.g. subtractively) manufactured components and are also less economical to produce in large volumes. Some component types, such as ball bearings or electronic relays, are unlikely to be additively manufacturable in the future.

The possibilities described above might, however, in future allow various components of a washing machine to be specifically designed as 3D printable elements on the basis of operational damage information and digital modelling. However, sufficient high-quality data must be available for modelling these elements. Corresponding data are already available as a result of real-world testing, which is currently still usual, and the database could be expanded even further in the future by extending the sensor systems in existing devices.

**Production**

The production of new washing machines is already highly optimised thanks to the use of Industry 4.0 approaches. The Circular Economy, however, creates new challenges as production must be made more flexible, for example to include old components or additional processes for reconditioning end-of-life appliances.

**Refurbish old components:** in production, digital technologies enable efficient recycling of components from old or defective appliances, regardless of the type of washing machine produced. Technologies for connecting manufacturers and consumer households or manufacturers and recycling facilities can coordinate the recovery of old appliances and components. Once a component has been returned to the manufacturer, digital interfaces allow data about its previous use to be read out and thus conclusions to be drawn about its remaining service life; these data can also include information about necessary steps for reconditioning, such as disassembly options. The digital product passport outlined in the current EU Ecodesign Regulation does not yet provide for the storage of individual device usage data and would therefore have to be updated accordingly.

Starting from this point, data evaluation, similarly to the above-described product design approaches, could be assisted by modelling. Technologies such as artificial intelligence are also of relevance in this connection as they coordinate the use of recovered components with ongoing production. Automation technologies such as robotics also form the basis for applications in the field of reverse logistics to become economically viable, it being necessary to consolidate mass flows in the recirculation process. Interconnecting digital technologies can in turn contribute to this by bringing together both manufacturers and recycling facilities in data spaces so as to increase the predictability of recycling.

**Use**

For washing machines, the use phase is the biggest Circular Economy lever. As a result of the energy and water consumption efficiency that has now been achieved, the length of time that appliances remain on the consumer market should be extended. Manufacturers already have established repair services, partly due to the statutory obligation to provide spare parts and repair instructions for professional repairers and private individuals. A survey conducted in 2024 by the European household appliance association APPLiA showed that 94 per cent of repair orders received by manufacturers were successfully completed. However, according to a consumer survey conducted by the market research institute GfK, in 75 per cent of cases consumers prefer to have their defective appliance replaced rather than repaired. The main reasons for this were the desire for a new appliance and lower replacement costs.[149]

**Carry out predictive maintenance, provide personalised support for repairs:** digital technologies are the prerequisite for predictive maintenance. Expanded collection of condition data for individual appliances together with modelling for maintenance or repair make it simpler to plan the corresponding work and

149 | See ZVEI 2024.

prevent damage that would lead to appliance failure in good time. This also gives manufacturers the opportunity to actively involve users in the repair process, provided the product is designed accordingly. Digital networking and active communication with the consumer household as well as smart, personalised support for repairs and maintenance can empower users to carry out repairs themselves in various cases. This could significantly reduce repair-related costs, waiting times and downtime. The main cost driver for repair and maintenance is currently service personnel costs; reducing these costs, for example by eliminating numerous customer visits, would directly increase the economic attractiveness of repair compared to buying new.

**Establish service-based business models:** product-as-a-service business models are based from the customer's standpoint on appliance usage rights rather than ownership, meaning that the manufacturer remains the owner of the product and offers additional services such as maintenance and repair or even a full service promise in return for usage and service fees. This is a superior benefit proposition in contrast to currently prevailing business models. The longer a product remains in use, the more profitable such business models become, and easier repairability and longer service life of materials and components are naturally favourable in this respect. On completion of the rental period, the appliance is then returned directly to the manufacturer, so reducing loss in value compared to recovery in the overall waste stream. The manufacturer then has an opportunity to siphon off the added value by using high-quality components and materials in its own production cycle.

Digital technologies for collecting usage data and connecting manufacturers and users are the basis for efficiently managing such business models since, because each usage transaction has to be processed individually, contract management is more complex than in the classic sales model. Such PaaS models can also be combined with other circular economy approaches. For example, both new and reconditioned appliances can be offered at different rental prices.

PaaS solutions for washing machines have long been established in the B2B sector (e.g. hotels) since both the manufacturer and the user are in direct contact with one another and both parties are aiming to ensure long-term appliance use. However, in the B2C sector, other than launderettes, such models are still not very widespread for private individuals, partly because manufacturers and customers are difficult to connect since distribution is carried out by retailers, and partly because of the unclear environmental and economic added value of PaaS models in this context.

Nonetheless, such business models have already been trialled commercially by various manufacturers for a number of years. The KTH Royal Institute of Technology in Sweden and the household appliance manufacturer Gorenje trialled usage-based business models for washing machines under real-world conditions in an EU Commission-funded project. The rental model was offered in different price categories depending on whether households received a new or reconditioned machine. Improved service for customers and greater flexibility (e.g. changing machine size in the event of a change in the size of household) were identified as advantages but these were offset by a higher price compared to buying a new machine given the average lifespan of a washing machine.[150]

BSH Hausgeräte GmbH is currently offering rental models for washing machines with a contract term of one year or more under the "BlueMovement" brand. As part of the *Papillon* project, the company is trialling a leasing model with longer terms of around ten years and lower monthly premiums. The project is being run in collaboration with a Belgian social enterprise as a way of supporting families clearly in need by providing the corresponding service. In addition to experience with the organisation of alternative business models, projects such as *Papillon* also provide valuable data about appliance behaviour and possible faults or defects after the manufacturer's warranty period. Until now, manufacturers have only had access to the appliance during the manufacturer's warranty as part of customer service. These additional data collected during use and also available to the manufacturer through the leasing model can in turn be used to optimise the design of existing basic structures with a view to longevity or reparability for all washing machine models. In both cases, however, PaaS solutions still account for a very small proportion of revenue in comparison with sales business.

**Share appliances:** another alternative usage model for washing machines is to share appliances among a number of households. This business model is already established for example in launderettes and sometimes also in blocks of flats, but could be further expanded using digital technologies. However, even with increased levels of connection, the limits of spatial networkability

150 | See European Commission 2023c.

for shared appliance use and potentially different user attitudes regarding hygiene and cleanliness must be taken into account.

If washing machines have appropriate sensor technology and a connection to a suitable online platform, even households in different blocks of flats could connect with one another. In this way, local supply and demand can be brought together, which could increase the intensity of use of individual machines and reduce the total number of machines in operation. Users would be able to view the condition and availability of suitable machines online and billing could be automated via smart contracts, i.e. automated billing processes within a blockchain.

WeWash GmbH already offers a solution for equipping laundry rooms to digitally display the availability of a washing machine, regardless of the type of appliance, and to manage both booking and payment via an app. All the appliances remain the property of WeWash GmbH for the duration of their service life. Current washing machine models typically already have an app interface for digital remote control, so the technological basis for connection to an online platform is also in place here.

**Modify washing behaviour:** if a washing machine is under- or overloaded during the wash cycle, either the cycle is not put to optimal use or the machine is subject to increased wear and tear and washing performance is degraded. Modified washing behaviour can therefore boost circularity and conserve resources by not only extending the time the machines are in operation but also reducing the resources they use. Today's washing machines have load recognition and adjust water and energy consumption accordingly. Although efficiency is better with larger loads, any gains are potentially limited by the number of textiles owned and therefore the actual amount of laundry per household.

Digital technologies, together with suitable appliance sensors and interfaces for user communication, can today help to optimise washing machine usage. Current appliances already have WLAN interfaces for remote control or querying machine status. They should be supplemented by the provision of circular usage information about optimum loading and detergent use. Corresponding requirements are already part of the current Ecodesign Regulation; in addition, appliances with an automatic dispensing function are already in existence. In the future, digital technologies could take greater account of the sustainability of energy consumption during washing cycles; by linking the washing machine to smart meters, for instance, individual households could coordinate energy-intensive washing cycles with power availability on the grid and so selectively relieve power generation loads and reduce generation from climate-damaging energy sources.

**End-of-life**

In terms of retaining value, a circular approach to end-of-life washing machines ideally means recycling at appliance and component level rather than material level. There are various lines of approach for digital technologies to promote such value retention at end-of-life and make it economically viable through scaling and automation.

**Recondition appliances at end-of-life:** circularity means that, at the end of their initial period of service, washing machines are either quickly passed on if they are still in working order or, if necessary, they are first refurbished for continued use. Digital technologies provide support here in a variety of ways, with digital sensors in the appliance providing information about the condition of the machine and individual components, so enabling an assessment of the need for reconditioning. In addition, online platforms connect households in order to bring together the supply and demand for used appliances. During reconditioning, digital applications such as digital twins make it possible to plan the necessary steps and so potentially shorten the testing required to ensure product safety.

The second-hand market for washing machines has been established for some time, with transactions so far taking place either on a private basis between individual households or through local stakeholders, typically operating on the secondary labour market on a subsidised basis, consolidating offers. However, such a business model is only profitable because the suppliers offer fewer guarantees and services than a reconditioning manufacturer. There is therefore a need in future for more systematic and efficient reconditioning and a focus on the longest possible second and third use. Miele & Cie. KG is currently running a pilot project in the Netherlands to trial a new business model with refurbished appliances in which the price of the appliances, which meet comparable testing standards to new appliances, decreases in proportion to the number of reconditioning cycles. This business model is directed at a new group of customers who cannot or do not wish to afford expensive new appliances, but in this way still have access to appliances of comparable quality. In this project, components are also removed from irreparable machines and offered for sale. Similarly to pilot projects for PaaS solutions, projects like Miele's provide valuable data about the viability of circular business models, the need for adjustments in appliance construction and possible customer groups in the market for reconditioned machines.

**Reuse components:** reusing appliance components requires intelligent pre-sorting. Despite already well developed collection solutions, complete differentiation into one container per product type is not feasible. Digital technologies, for example intelligent image analysis and robots, can assist with preclassification in the recycling process. In a first step, complete appliances could be automatically assessed on the basis of camera images to determine whether they are suitable for reconditioning or whether they should be sent for recycling and be separated at component level. In the case of recycling at component level, a database query of general product features and material properties (e.g. details of installed storage batteries) and an exchange of data between manufacturers and recyclers could assist with recycling as many of the machines concerned as possible with the least possible effort.

**Recycle materials:** if reconditioning of complete appliances or components is no longer possible, presorting at component level should be the first step in recycling the materials used in order to identify components by type or those containing high-quality materials and send them for further processing. Sorting by type is thus the basis of a sector-specific market for high-quality secondary materials. Ideally, manufacturer-independent information about the general design of the washing machine in question and the materials used should be sufficient to efficiently classify the majority of appliances during the sorting process. The communication in the value network that is necessary for this purpose, like the sorting system technology, is in turn based on digital interconnection and automation technologies.

The use of recycled materials has long been established for steel, and recycled steel now makes up a significant proportion of the total volume on the market – around 46 per cent of all crude steel used (2022).[151] This proportion is significantly lower for plastic, with a reuse rate of 11 per cent.[152] The corresponding recycled materials often do not achieve the necessary quality, are not available in sufficient quantities and are sometimes more expensive than primary raw materials due to processing complexity.

151 | See BGR 2023.
152 | See Conversio 2020.

## 4.4 Obstacles and sector-specific policy options

Although the four action areas discussed below for promoting circular approaches can be derived from the needs analysis of the washing machine product example, they are relevant to the entire electronics sector. Assuming sustainable product design, appliances in this sector have the potential for long-term use in various business models. However, leveraging this potential requires changes to the regulatory framework (see Figure 9).

**Action area: promote planning certainty in materials use**
The long lifetimes of washing machines of up to 20 years and more are a particular challenge for circular design and use. The raw materials used in planning today must still be usable at the end of the life cycle, this applying not only in terms of necessary material quality but also of the regulatory framework that must authorise such recycling. For example, the EU Regulation currently at the planning stage on the use of per- and polyfluorinated alkyl compounds (PFAS) could in future mean that the majority of plastics used in washing machines currently on the market will only be permitted to be recycled for energy recovery at the end of the product life cycle. In addition, the use of recycled materials in the production process leads to warranty problems, as they have to meet similar regulatory requirements as virgin material, which is difficult for recyclers to guarantee.

**How can digital enablers help?** Digital technologies can help to improve the flow of information along the value chain in order to optimise processing in terms of circularity and make legal compliance of the corresponding recycling processes transparent. Achieving this, however, means all necessary information about raw material sources, raw material processing and the material's exposure to stresses during use must be available. When it comes to using recycled materials for long-term product designs, digital technologies can also accelerate product development by modelling and simulating potential stresses during the life cycle.

**What support can policy makers provide?** The legislative framework should leave a corridor in which circular design is possible and also makes economic sense from the perspective of long-term development planning for washing machines and other durable

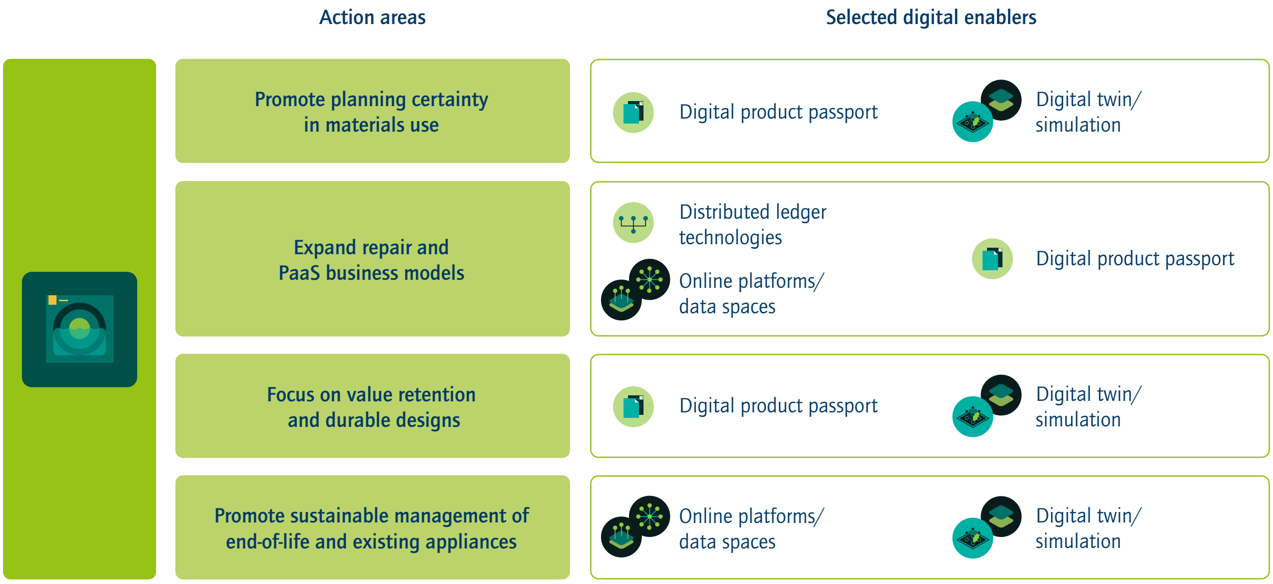


Figure 9: Overview of sector-specific action areas for promoting the Circular Economy in the electronics sector (source: own presentation)

electronic appliances. Accordingly, there is a need to carefully consider regulatory measures at the material level and coordinate them with circularity goals in order to enable long-term and predictable use of raw materials in the electronics sector.

**Action area: expand repair and PaaS business models**
PaaS business models are significantly more costly for manufacturers to implement than previous linear models due to the more complex contract management and additional expenses (servicing, regular testing etc.). The additional shipment distances, in part due to regular refurbishment of the machine, also increase the environmental footprint of PaaS business models, which are currently not attractive to households due to poor cost-effectiveness compared to purchasing a new machine. An extended right to repair for new appliances could potentially still further increase this price pressure compared to new appliances as households would then receive a service quality comparable to PaaS models beyond the previously applicable warranty period. Repair services are also currently underutilised due to poor cost-effectiveness compared to new purchases. Finally, it remains to be seen whether consumers will be willing to accept the outdated appearance of the machines.

**How can digital enablers help?** Digital technologies can help to reduce the transaction costs of PaaS models through automation (e. g. smart contracts based on digital ledger technologies). Better, digital connections between manufacturers and local service providers can also reduce shipment distances. Enhanced connections between manufacturers and customers, for example via the digital product passport, could ultimately raise consumer awareness of repair options and also involve users more closely in the production cycle.

**What support can policy makers provide?** In addition to incentivising the population to use circular products, ensuring market surveillance is a key lever for making recyclable products economically competitive. This concerns, for example, the effective enforcement of existing and future rules on ecodesign, including for products imported from outside Europe. However, this requires test criteria whose compliance can actually be monitored, but without overburdening smaller manufacturers in particular with excessively broadly framed duties of documentation. The digital product passport would be a suitable, regulatorily defined tool for this purpose. However, it must be ensured that the information provided is accurate and, in addition to the existing requirements set out in the Ecodesign Regulation, it will in future also be necessary to make it possible to update the product information dynamically during its service life.

**Action area: focus on value retention and durable designs**
A durable washing machine design is already technically possible but is currently not attractive for manufacturers as it does

not generate any direct market benefits. This is because durability and circularity still play a lesser role in purchasing decisions than price, and consumers have an underlying fear that damage will ultimately occur and the high purchase costs will not pay off. There is currently too little planning certainty in relation to the above-discussed point about long-term material usage. Manufacturers currently have little incentive to bring more durable and therefore higher-quality products onto the market, as they can only recover them to a very limited extent via existing collection schemes.

**How can digital enablers help?** Digital technologies and applications, specifically in this case the digital product passport, can help to make the value of an appliance originally introduced onto the market by the manufacturer more assessable and traceable in relation to the quality of materials and manufacture. Digital technologies are thus the basis for incentives to manufacture and sell high-quality machines.

**What support can policy makers provide?** Legislation could place greater emphasis on the value of raw materials in the product. The digital product passport is a good lever for creating transparency and traceability. However, openly sharing information along the value chain must not in turn result in other market participants being able to freely use the manufacturer's own value streams without consultation, i. e. intellectual property and development work must be protected. In addition, a proactive communication strategy directed to the general public would be helpful, as circular washing machines based on European specifications for design and production are more expensive than those from a linear system. The environmental and economic advantages of such durable, sustainable products should therefore be explicitly emphasised so that they can ideally carry greater weight in purchasing decisions.

**Action area: promote sustainable management of end-of-life and existing appliances**

The existing washing machines should be utilised as fully and effectively as possible within the Circular Economy. However, the extension of service life resulting from repair and refurbishment is questionable from an environmental point of view due to the higher electricity and water consumption of some of these appliances. If they were reclassified for energy efficiency, refurbished appliances would largely fall within the lowest efficiency class. Apart from higher consumption, using end-of-life or reconditioned appliances is currently also unattractive to customers in price terms compared to buying new. If end-of-life appliances are to be reutilised within the Circular Economy, they would all have to be collected, which is not currently the case.

**How can digital enablers help?** Digital technologies can make the repair and refurbishment of existing appliances more efficient and assist with scaling. The same applies to subsequent performance improvements that can be implemented as software-based over-the-air updates, provided the particular model of machine has this capability. In addition, digital modelling makes it possible to predict the anticipated environmental impact of making continued use of existing appliances, and so make a sustainable decision about continued use or recycling. Finally, online platforms provide the digital infrastructure for creating greater local connections between consumer households and recyclers, which allows collection activities to be optimised and information to be provided.

**What support can policy makers provide?** Building on existing collection systems, federal and state governments can increase awareness of them through appropriate information campaigns. The economic attractiveness of using reconditioned appliances and the general acceptance of doing so among consumers could also be increased by targeted measures, for example by establishing trustmarks to build confidence.

# 5 Textile sector

## 5.1 The challenge of "fast fashion" in the textile sector

Textiles being an essential part of everyday life, the textile sector is playing a decisive role in the circular transformation of the economic system in the EU and in Germany. Textiles are not only used for clothing, but also for home textiles, furniture and technical products such as medical equipment or protective gear, for buildings and vehicles.[153] At the same time, the textile sector is an important branch of Europe's and Germany's economy.[154] In Germany, some 61 per cent of fibre output is converted into industrial textiles, 26 per cent into home textiles and 13 per cent into clothing.[155, 156]

Over the past two decades, global textile fibre production has almost doubled from 58 million tonnes in 2000 to 109 million tonnes in 2020, and is expected to rise to 145 million tonnes by 2030.[157] This huge increase is associated with the increasing prevalence of fast fashion, with increasing numbers of clothing collections being brought out every year at very low prices and with ever shorter service lives. There has been an accompanying sharp fall in the quality of clothing. During the coronavirus pandemic, this trend intensified still further with what is known as "ultra-fast fashion" (UFF), established by manufacturers outside Germany. Trading low-quality clothing directly on online platforms means manufacturing and distribution times can be reduced still further. The Chinese fashion retailer Shein, for example, estimates that it brings out 700 to 1,000 new items every day.[158, 159]

German consumers purchase on average 60 items of clothing per year, 40 per cent of which are rarely or almost never worn.[160] Many items of clothing end up being sent for disposal unsold because the style no longer meets rapidly changing customer wishes.[161] Some companies also dispose of unworn, returned items of clothing if their business model does not provide for the resale of returns.[162]

The predominantly linear value chains in the textile sector thus generate large volumes of waste. Each year, between 1 and 1.2 million tonnes of used clothing and home textiles are collected in Germany, while 370,000 to 420,000 tonnes are additionally disposed of as residual waste.[163] Altogether, this amounts to approximately 18 kilograms per person per year. Sixty per cent of the used clothing and home textiles collected are then actually circularly reused, 27 per cent being recycled into lower-quality products such as cleaning cloths or insulation material, and around 11.5 per cent is thermally recovered.[164] And every second, a truckload of textiles is landfilled or incinerated somewhere in the world; only less than 1 per cent of garments sold worldwide end up being made into new clothing through fibre-to-fibre recycling.[165] The still very low proportion of recycled fibres in clothing production is also mainly obtained from other product streams such as recycled fishing nets or PET bottles.

However, the environmental impact of a linear textile industry is also enormous in other respects: large quantities of water and land are required worldwide to grow cotton for the production of clothing. In the EU, the textile sector is the fourth largest consumer of primary raw materials and water and the fifth largest emitter of greenhouse gases.[166] In addition, large quantities of sometimes toxic chemicals are used to dye fabrics and to combat pests in cotton growing.



153 | See European Commission 2022.
154 | See Ellen MacArthur Foundation/Circular Fibres initiative 2017.
155 | See Forschungskuratorium Textil 2022.
156 | See Umweltbundesamt 2019c.
157 | See Textile Exchange 2021.
158 | See de Ferrer 2022.
159 | See Boston Consulting Group 2024.
160 | See Greenpeace 2022b.
161 | See Greenpeace 2022a.
162 | See Redelfs/Jansen 2022.
163 | See bifa Umweltinstitut 2023.
164 | See ibid.
165 | See Ellen MacArthur Foundation/Circular Fibres Initiative 2017.
166 | See European Environment Agency 2019.

In order to compete with the huge price pressure from fast fashion, the majority of clothing companies selling in Germany and the EU manufacture in developing and transition countries. However, human rights are often not recognised there, nor are international environmental and social standards observed.[167] The high level of globalisation in the clothing sector also means that production is spread across different countries and supplier networks are structured in a complex, dynamic and hard to navigate way.

Given such market conditions, circular approaches have so far been largely uncompetitive, so it is hardly surprising that the Circular Economy in the clothing industry is still in its infancy. Nevertheless, a transition to a circular clothing sector holds enormous environmental and economic potential.[168] The global market for second-hand clothing, shoes and accessories was estimated at US$100 to 120 billion in 2022 (three times higher than in 2019) and annual growth of 20 to 30 per cent has been predicted.[169] Moreover, a recent study by Greenpeace has shown that consumers are now paying more attention to sustainability when buying clothes, are buying more second-hand clothes and are increasingly reselling old clothing.[170]

In addition to clothing, there are other textile waste streams that have great circular potential due to their volume: in Germany, for example, 225,000 tonnes of mattresses and 225,000 tonnes of textile floor coverings are separately collected as bulky refuse.[171] Large quantities of industrial textile waste, used hygiene products and textile construction site waste are also generated. However, if a Circular Economy is actually to come into being in the textile sector, these materials streams will have to be consolidated for use. Achieving this will require the stakeholders from the waste sector to work more closely with the textile manufacturing industry in future.

## 5.2 Regulatory framework for the Circular Economy the textiles sector

Transforming the sustainability of the textile sector has only in recent years become the focus of attention by policy makers in Germany and the EU. The EU is driving circular change in the textile industry with the European Green Deal and European circularity strategies.[172] The EU's *New Circular Economy Action Plan (2020),* which is the cornerstone of Europe's strategy, highlights the textile industry as one of the key sectors for a circular transformation of the European economy.[173] In its *Strategy for Sustainable and Circular Textiles (2022),* the EU Commission also describes a framework and vision for the transition to a sustainable and circular textile sector by 2030,[174] according to which products should be designed to be more durable, easier to reuse and repair, recyclable and also energy-efficient.

According to the EU Ecodesign Regulation, textiles are one of the first product groups to be subject to product group-specific regulation,[175] which will include the introduction of a product passport for textiles. In addition, binding product-specific ecodesign requirements are to be defined in order not only to achieve greater durability, comprehensive reusability and reparability as well as better fibre-to-fibre recyclability, but also to limit toxic substances and enable their identification. Finally, the regulation also prohibits the destruction of unsold textiles (Article 25/Annex VII).

The recast EU Waste Framework Directive (EU) 851/2018, with its overarching goal of preventing waste and reusing it as a resource, also obliges EU member states to collect their textile waste separately from 2025.[176] The revised version of the Waste Framework Directive also includes extended producer responsibility for household textiles and shoes. The requirements for textile labelling, in particular regarding fibre composition, are expected to be tightened at the end of 2024 by a recast version

167 | See CSR 2023.
168 | See Pricewaterhouse Coopers 2023.
169 | See Boston Consulting Group/Vestiaire Collective 2022.
170 | See Greenpeace 2022b.
171 | See bifa Umweltinstitut 2023.
172 | See European Commission 2024.
173 | See European Commission 2020b.
174 | See European Commission 2022.
175 | See ibid.
176 | See Directive (EU) 2018/851.

of the Textile Labelling Regulation (EU) 1007/2011 which has already been announced.[177] The goal is to make information of relevance to the Circular Economy accessible throughout the value chain. The new Regulation (EU) 2024/1157 on shipments (export, import and transit) of waste also tightens the rules on the disposal of textile waste by export in order to promote the recovery of waste in accordance with the "waste hierarchy".[178, 179]

The textile industry has also already been highlighted as a priority action area for circular transformation at a national level in the *draft National Circular Economy Strategy* of the Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV).[180] The specific goals of this strategy in the textile sector include increasing the number of second-hand retailers and repair businesses as well as recording and increasing sales of durable clothing in circular business models.

## 5.3 Application example: cotton T-shirt

Although only very little clothing is still produced in Germany and the EU, it accounts for the largest share of textile consumption in the EU at 81 per cent (the remaining 19 per cent are household textiles); clothing therefore has a major leverage effect for transforming the textile industry away from linear value chains towards long-lasting and closed cycles.[181] Short-sleeved tops are the most common type of garment and have the shortest average lifespan after shoes: 42 per cent are worn for less than three years before being discarded.[182] This is partly because both T-shirts and shoes are used frequently and can be worn in all seasons. However, it is not only the rapid consumption of T-shirts that is environmentally problematic but also their production: around 2,700 litres of fresh water are used to produce a single cotton T-shirt, which is roughly equivalent to the amount that one person drinks in two and a half years.[183] On the other hand, the T-shirt as a product is in principle circular, as sustainable materials such as recycled cotton or other biodegradable fibres can be included in the production process. And finally, the T-shirt can be distributed in both the B2C and the B2B sector, which means that two very different but equally important market segments can be addressed.

The cottonT-shirt was therefore selected as an application example from the textile sector for this acatech STUDY. While a simple cotton T-shirt does not cover the entire product portfolio of the clothing sector, its production is relatively simple and also relatively well documented, meaning that the entire life cycle of this product type, from material procurement to production and recycling, can be easily tracked. The problem of opaque global supply chains, which is also characteristic of the clothing industry as a whole, is also evident here.

Taking the cotton T-shirt by way of example, it is shown below how digital technologies can be used to implement relevant R strategies in the textile sector in order to produce a durable and recyclable textile product. Figure 10 shows an overview of the circular approaches for the value chain of a cotton T-shirt.

**Product design**

Product design is just as important for the circular transformation in the textile sector as in other economic sectors because it is only by designing the T-shirt according to circular principles that it can be made durable, easily repaired and recycled from fibre to fibre at the end of its life.

**Design for circularity:** the requirements a circular T-shirt must meet are complex and depend on many factors. Depending on material composition, various recycling methods can be considered. For instance, a pure cotton T-shirt can be further processed into synthetic regenerated cellulose fibres such as viscose, modal or lyocell by chemical cellulose recycling.[184] Alternatively, it can be mechanically shredded with a loss of fibre quality into smaller pieces and individual fibres which are then blended with raw material fibres in a ratio of currently around 20 to 50 per cent. T-shirts can also be made from resource-efficient, biodegradable

177 | See Regulation (EU) 1007/2011.
178 | The waste hierarchy is a prioritisation system that comprises, in descending order, the principles of prevention, reuse, recycling, energy recovery and disposal of waste in order to minimise environmental impact.
179 | See Regulation (EU) 2024/1157.
180 | See BMUV 2024.
181 | See Köhler et al. 2021.
182 | See Greenpeace 2022b.
183 | See Van Woensel 2020.
184 | See Fraunhofer IAP 2020.

| Product lifecycle stages | Circular approaches | R strategy | Technology functions | | | |
|---|---|---|---|---|---|---|
| | | | Data collection | Con-necting | Mod-elling | Auto-mating |
| Product design | Design for circularity | rethink | very high | very high | high | |
| | Digitalise the design process | reduce | high | | very high | |
| ↓ | Produce using zero-waste techniques | reduce | very high | | very high | high |
| Production | Ensure closer linkage of value chains | reduce | high | very high | very high | very high |
| ↓ | Offer digital fitting | reduce | very high | | very high | |
| | Educate people about the value of clothing and how to care for it | rethink | very high | very high | high | |
| Use | Establish online second-hand platforms | reuse | very high | very high | | high |
| | Expand leasing models | rethink | very high | high | very high | high |
| ↓ | Strengthen online repair platforms | repair | | very high | | |
| | Establish smart collection solutions | recycle | very high | high | very high | |
| End-of-life | (Partially) automate sorting systems | recycle | very high | very high | high | very high |
| | Record materials streams and consolidate uniform materials | recycle | very high | very high | very high | very high |

Relevance of technology functions to implementation of the approaches:

- very high
- high

Figure 10: Digitally assisted circular economy approaches for producing a durable and recyclable cotton T-shirt (source: own presentation)

materials such as wood, hemp or linen, which must be taken into account when recycling. The dyes used to colour the fibres must be carefully selected to enable fibre-to-fibre recycling. Moreover, each recycler has its own requirements for the materials to be processed, which is why these must be taken into account right at the design stage. Circular design solutions must therefore always be developed together with the corresponding sorting and recycling technology so that products can actually be recycled. For example, sewing in radio-frequency identification (RFID) tags only makes sense if sorting businesses can read them. Companies such as circular.fashion GmbH bring together relevant stakeholders (manufacturers, repairers, collectors, recycling companies) and collect the specific requirements for the various manufacturing and recycling steps in digital material libraries. Using modelling techniques, artificial intelligence and low-threshold communication, the collected information can be incorporated into software solutions and programs that provide designers with targeted circular design support. The designers can, for example, decide on a "mono-cycle" approach, in which all the components of a T-shirt such as fabric, thread and, if present, buttons are made from the same material and can therefore be recycled together. Alternatively, there is also the "design-for-disassembly" approach, in which zippers and buttons can simply be separated in the recycling process or, possibly, by the customer before disposal. With this digital support,

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any designer, even one lacking relevant knowledge, can create circular garments.

**Digitalise the design process:** a digital design process using 3D models significantly reduces the number of development cycles. This can reduce the consumption of resources caused by the extraction of raw materials and logistics in the manufacturing process. In addition, 3D models enable collaborative textile product development by integrating customers before production and taking their feedback into account at an early stage, so reducing the production of less marketable clothing. Nevertheless, it is important to emphasise that a digital design process does not in itself increase sustainability, as this technology enables a high throughput of collections and has thus also played a decisive role in promoting the environmentally highly problematic fast fashion trend.

**Production**

Digital technologies are primarily used in the production and distribution of textiles to save resources, increase efficiency and reduce returns. In addition, globally distributed supply chains in the textile sector can be more clearly structured and optimised using digital technologies.

**Produce using zero-waste techniques:** large quantities of water, energy and chemicals are used in the production of textiles. Applications such as the internet of things can be used to digitally record resource streams during production; modelling applications such as digital twins and technologies such as artificial intelligence can then optimise processes on the basis of the collected data and save resources. Moreover, the quantity of textile offcuts and remnants can be reduced by optimised cutting patterns and unavoidable textile remnants can be sent for recycling directly from the production facilities. Using new technologies also enables massive savings in resources. 140Fahrenheit GmbH, for example, uses laser, washing and water recycling technologies to dramatically reduce the water consumption of the resource-intensive finishing process in jeans production. By automating such resource-saving production steps, efficiency can ultimately be increased and the business model made economically viable. However, as the majority of clothing sold in Germany is currently produced abroad, the resource savings that can be achieved through optimised production methods in Germany are small.

**Ensure closer linkage of value chains:** value chains should be more closely linked and more strongly locally embedded in order to make greater resource savings in production and distribution. Greater digitalisation along the entire value chain and digital applications such as the digital product passport can make a decisive contribution to increasing transparency in the global value chain. Global logistics chains can then be optimised using simulations and digital twins to save resources over long shipment distances. High labour costs in high-wage countries such as Germany also mean that automation must be dramatically increased if production sites are to remain competitive.

**Offer digital fitting:** new technologies are making it increasingly possible to try on clothes digitally when buying online. Image analysis and artificial intelligence are combined to generate a photo or video of the customer wearing the garment. Such a solution has the potential not only to reduce mispurchases and thus also returns, but also the proportion of purchased but little-worn clothing. However, further technological advances are still needed to make digital fitting as realistic as possible. In addition, digital technology will not be able to reproduce the feel and quality of fabrics in the foreseeable future, although these also play a major role in the purchasing decision.

**Use**

Increasing the intensity of clothing use is a decisive lever towards a more sustainable textile sector. On the one hand, customers' usage and consumption behaviour must become more sustainable, while, on the other, business models that provide for clothing rental or the resale of already worn clothing can intensify the use of high-quality clothing and so extend the use phase.

**Educate people about the value of clothing and how to care for it:** one major obstacle on the road to a circular economy in the textile sector is the fact that clothing as a product group is currently not highly valued, being viewed and treated as a disposable commodity. There is an urgent need for more and better information about manufacturing processes in order to combat this trend. Where and under what working conditions was the T-shirt in the boutique display produced? And what resources were used? The EU Commission's Ecodesign Regulation has initiated the introduction of an EU-wide product passport for textiles, which is expected to be mandatory from 2027. Relevant information can be stored, modified and read out from the product passport and used for various purposes. This requires the various stakeholders in complex supply chains to cooperate with one another and exchange data. Uniform data formats and standards are a vital prerequisite for this. circular.fashion

GmbH, for example, has developed circularity.ID®, an open data standard[185, 186] for the textile sector product passport. Near-field communication (NFC) tags, quick response (QR) codes or RFID threads and chips can be used for entering and reading the information. The particular distributor then stores the information and makes it accessible on a decentralised server. The collected data can be used to add information relevant to circularity regarding the lifespan or recyclability of the product in question to certificates such as OEKO-TEX or Global Organic Textile Standard (GOTS) or also to labels such as Germany's Blue Angel or Green Button marks. Low-threshold communication via transparent and reliable quality marks can help prevent "greenwashing", i.e. conveying a false impression of sustainable production and distribution methods, and therefore enable customers to base their purchasing decisions on sound criteria.

**Establish online second-hand platforms:** in addition to traditional second-hand platforms such as flea markets or clothes swaps between friends, relatives and acquaintances, buying and selling on digital online second-hand platforms such as Vinted, Sellpy or the German platform Kleinanzeigen has increased significantly. Various business models that rely on digital technologies are currently being tested in this segment. For instance, the clothing can be offered for resale on online platforms either by the retailer who collects it again after use by the customer, by customers themselves or by non-profit collection and sorting businesses. If consumers are empowered to sell their own clothes through smart and easy-to-implement solutions, this will positively change consumer behaviour and lead to less clothing in good condition ending up in collection containers. Digital process automation plays a particularly important role for non-profit sorting businesses because it makes the time-consuming and labour-intensive process of quality assessment and pricing more efficient. For example, artificial intelligence can be used to automatically generate suitable descriptive texts for the product so that the clothing can be uploaded to sales platforms with little effort.

**Expand leasing models:** a still uncommon but highly promising circular approach relates to digitally based business models for clothing rental. There are already successful pilot projects in the B2B sector, such as DiTex which rents out workwear designed to be as durable and comfortable as possible. The provider is responsible for proper care, any repairs and, finally, recycling of the clothing. Identifiers such as RFID tags, which are regularly read by the supplier, are used to track the number of wash cycles and anticipate the need for repairs in good time. Usage information is then stored in a product passport, while the use of a digital twin finally means that it is possible to forecast any need for repairs or the optimum time for recycling.

In the B2C sector too, there are some companies that have already put the rental principle into operation, such as Mudjeans International B. V., a jeans supplier that distributes its products using leasing models. It is nevertheless difficult to introduce leasing models across the board in the B2C sector, as a large number of collections are usually sold to individual customers at short intervals. Business models based on the rental principle can be tested for viability before they are introduced using previously collected data and appropriate modelling in order to reduce the risks for companies on product launch. In addition, the introduction of leasing models in the B2B sector can open up new textile markets and assist with testing relevant digital technologies and applications that can also be used in the B2C sector.

**Strengthen online repair platforms:** rebuilding local infrastructure that enables the repair of clothing on a broad scale would be a decisive step towards a circular textile sector. However, online services for repairing damaged clothing, such as those offered by Repair Rebels GmbH, can nevertheless to a certain extent counteract the lack of local infrastructure. The remaining local infrastructure with its alteration shops could also be strengthened by the introduction of digital services. Other concepts include the supply of repair kits with clothing and the provision of corresponding online tutorials by the manufacturer which enable customers to carry out repairs themselves. An additional repair service from the manufacturer has so far been tested primarily for the outdoor sector as part of a product-service package and could be expanded even further in future as an integral part of a circular business model.

**End-of-life**

A textile product's end-of-life can be divided into three stages. The clothing must first be collected and then sorted according to condition and material composition. Finally, depending on their condition and composition, the separated textiles are either resold, repaired, recycled or used for energy recovery.

**Establish smart collection solutions:** from a circular standpoint, it is essential to prevent clothing textiles from ending up

185 | See circular.fashion/Scirt 2020.
186 | See circular.fashion 2020.

in residual waste and so inevitably being lost to further use or recycling. Various smart collection solutions can be considered for implementing the EU's planned obligation to collect textiles separately in the future. For example, information about proper collection and disposal can be included in the digital product passport and read by customers from QR codes integrated in the clothing. Collection containers can also be equipped with sensors that provide information on their fill level and the material composition of the clothing placed in them. Take-back offers by vendors in which clothing can be returned in exchange for a voucher, for example, can also be a way of achieving high return rates. In addition, innovative business models can be developed in which busy locations such as supermarkets or chemist's shops additionally collect clothing and pass it on to sorting businesses or directly to recyclers.

**(Partially) automate sorting systems:** at present, used textiles that have been collected separately are still largely sorted manually. This approach leads to high costs and personnel requirements which is a critical factor in times of labour shortages. As sorting needs to be carried out at high speed to be economically viable, digital technologies capable of fully automatically sorting textiles must be used. Manually inputting a sewn-in QR code, for example, would be too slow. There is also the risk of the QR code being lost during the use phase. However, RFID threads sewn into the clothing, which cannot be removed by users, could be used to automatically read material properties and manufacturer information at high speed. For textiles that have not been provided with an RFID thread, material composition could be determined using a combination of imaging, dedicated AI algorithms and spectroscopy. Ultra-compact near infrared spectrometers are suitable for analysing and determining textiles and can reliably identify monomaterials.[187] However, clearly determining blended fabrics is technically very challenging, which is why there is still a need for development here. The clothing also has to be rated for its quality, condition and style appeal so a decision can be made regarding whether and how to reuse it. At present, this still requires human judgment, especially as tactile and olfactory factors also play a role.

**Record materials streams and consolidate uniform materials:** if the material volume necessary for economic scaling is to be achieved, as far as possible all of the materials streams arising in the textile collection sector must be recorded digitally. The digital information must also be consolidated by various stakeholders using compatible interfaces. The digital product passport could be used for digital recording. However, this would require all collected textiles to have been provided with a digital product passport. Alternatively, the technologies used for sorting could be utilised to record the materials streams digitally. In a second step, collection and recycling businesses could make the data digitally accessible in appropriate data spaces so that sufficiently large quantities of uniform textiles can be recorded and collected and any investment in the development of suitable fibre-to-fibre recycling technology is economically viable.

## 5.4 Obstacles and sector-specific policy options

The following section discusses action areas for the textile sector derived from a gap analysis between the current situation and the application example. The analysis makes it clear that there is still a great need for action in the transformation to a Circular Economy in the textile sector. The sector's highly globalised nature and Europe's high rates of consumption of cheap products pose particular challenges in this regard which require international regulation. In addition, changing consumer behaviour is a difficult obstacle to overcome and digital technologies can be of only limited assistance. However, digital technologies could make a significant contribution to creating the necessary transparency and developing connections between stakeholders, in particular in relation to introducing digital product passports and developing local infrastructure for collecting, sorting and reprocessing textiles.

**Establish circular design**

The requirements for textile recycling are highly specific and have to be taken into account right from the product design stage. On the one hand, there is still a lack of knowledge in the product design sector about circular design and the specific requirements for recycling while, on the other, there are still too few incentives to design a T-shirt or other clothing products in a circular way as this involves a great deal of additional effort and is currently of little benefit to manufacturers.

**How can digital enablers help?** Recycling requirements can be digitally stored and made accessible in data spaces and material libraries. Software solutions developed on this basis can

187 | See Fraunhofer 2023.

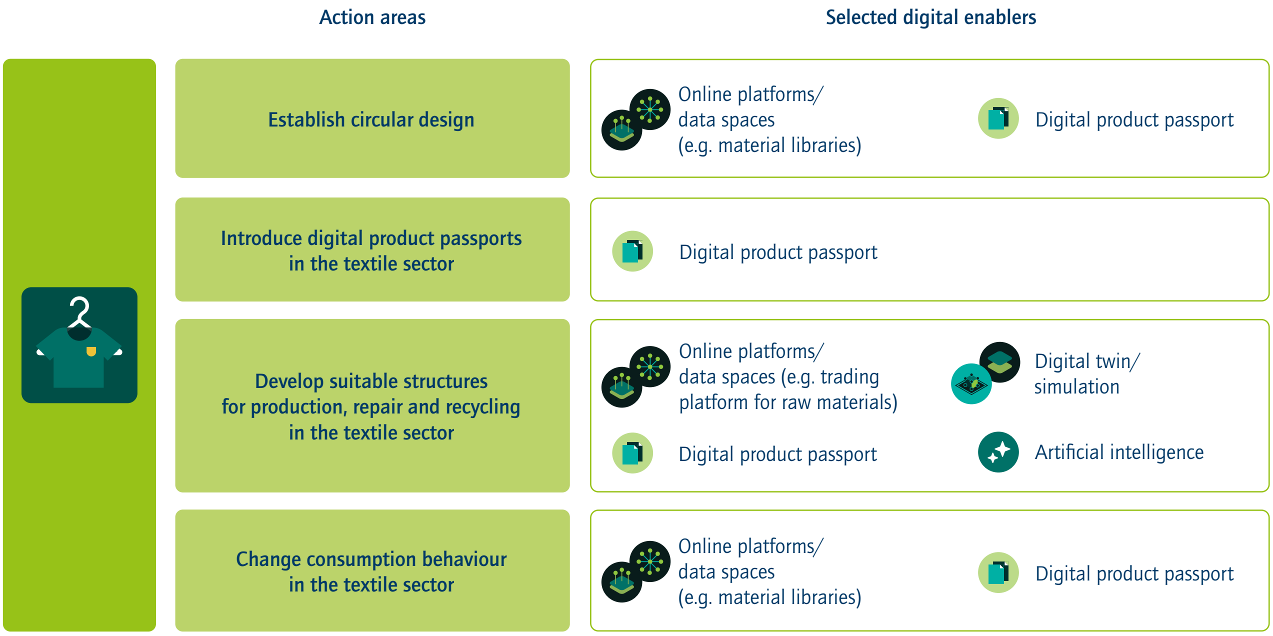


Figure 11: Overview of sector-specific action areas for promoting the Circular Economy in the textile sector (source: own presentation)

help designers create circular clothing. The various stakeholders can also connect and coordinate with each other via online platforms. Digital product passports can then share relevant information along the entire value chain.

**What support can policy makers provide?** Circular design could be made a more integral part of relevant German courses of study. In addition, standardised software solutions that support circular design could be stimulated by funding programmes. If circular design is to be worthwhile for manufacturers, textile recirculation infrastructure must first be established so that previously used materials can be put to use as secondary raw materials. Textile recirculation means that collected textiles have to be sorted and recycled, which is currently not economically viable due to high costs and small volumes of textiles with a uniform material composition. Policy makers could therefore support the expansion of secondary raw material extraction in the textile sector by targeted funding programmes. If recycling in the textile sector is to become economical, the focus should be not only on creating stronger connections between stakeholders in sorting and recycling technology via online platforms and data spaces but also on consolidating materials streams.

**Introduce digital product passports in the textile sector**
Relevant information about proper care and recycling of a T-shirt or other clothing product has to be passed along a complex supply chain in order to reach consumers. The same applies to information for assessing material and product sustainability and its certification. Although digital product passports are in principle a suitable tool for this, they are still rarely used, even in ambitious companies, as a large number of often incompatible software solutions and data formats are used along the entire supply chain.

**How can digital enablers help?** As already mentioned, a digital product passport may include information about the production process and material used for a textile product along the supply chain. Users can also be provided with care and repair instructions by printed QR codes that cannot be washed or dissolved off and can therefore be read. RFID tags or threads, which are difficult to remove, could also be used in the future to sew in quickly readable, detailed information about material composition for collection and sorting businesses.

**What support can policy makers provide?** The data formats and interfaces that should be used and the parameters and values that must be included in product passports should be

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harmonised by regulation. Advanced digital product passport initiatives in other sectors such as the *Battery Pass*,[188] can provide guidance here and act as a template for the textile sector. Sector-specific characteristics, such as the much lower complexity of a T-shirt compared to a battery, must be taken into account when designing the product passport. Given the high level of globalisation in the textile sector, it must also be clarified how the flow of information and the accuracy of the information in the product passport can be guaranteed along the complex supply chain. When designing the digital product passport, there should therefore be close cooperation with existing initiatives such as *Accelerating Circularity* in order to achieve rapid progress and prevent the emergence of different, incompatible standards. In addition, policy makers must clarify which specific functions the digital product passport is to achieve in the textile sector – is the emphasis on consumer transparency, making environmental impact visible and putting a price on it, or on the transfer of data of relevance to recycling? The answer to this question imposes different requirements on a technological solution and on information content.

**Establish suitable structures in the textile sector**

As a result of the great globalisation of the textile sector, there is a lack of infrastructure in Germany for producing, repairing and recycling textiles and for further processing corresponding recycled materials. In addition, manufacturing and cutting usually take place elsewhere than the recycling and spinning process. This means that textile remnants from production cannot be recycled without major logistical effort. Recycling textiles is also technically difficult and made more so by a wide variety of fibre blends, in particular the fabric blends used in clothing products are constantly changing. Furthermore, in comparison with other recycling sectors (e. g. plastics), textile recycling is still less digitalised and automated. In view of the fluctuating quality of the fibres to be recycled, machinery is still largely set manually and with a great deal of empirical knowledge in order to achieve the appropriate properties. The quality of the fibres produced by mechanical recycling nevertheless differs significantly from primary materials and has not yet been uniformly characterised. For example, few details about the colour and quality of recycled fibres are available, but these details are urgently needed for further processing and resale. Moreover, all established fibre processing technologies along the process chain (dissolving or shredding the fibres, spinning preparation, yarn production and manufacturing textile fabrics) have so far been designed for unvarying fibre qualities which currently operated recycling plants are not able to guarantee. And finally, used textile collections yield volumes which are scarcely sufficient to make it worthwhile for recyclers to convert their machines accordingly.

**How can digital enablers help?** Digitalised machinery, process automation and AI-models for process optimisation can increase the viability of circular business models in the textile sector. For example, recycled material quality could be characterised better and more efficiently using automated quality measurement. The acquired data can then be made available in digital data spaces and on online platforms for raw material trading in order to match material supply to demand.

**What support can policy makers provide?** In order to better characterise the quality of used textiles, facilitate their sorting and standardise recycled clothing products, there is an urgent need for standards for specifying product and material quality along the textile value chain. Policy-making stakeholders could initiate the development of such standards by national and international standardisation organisations with the involvement of relevant industry and environmental associations and representatives from the scientific community. The standardised quality data could then be passed on between the stakeholders in the value chain using digital applications such as data spaces or digital product passports. It must be clarified whether the digital product passport is to be used primarily as a tool for assessing a product's environmental footprint (its identity and origin, composition, properties and environmental impact) or also as a clearly regulated tool for passing on quality data in the textile process chain. Small and medium-sized enterprises (SMEs) in particular could be supported in the sometimes costly introduction of the relevant technologies through government funding initiatives. As already described in the first action area, there is a need for stronger connections and greater collaboration between textile processors in order to produce larger streams of homogeneous fabric blends. Consortia aimed at turning "competitors into partners" in compliance with antitrust legislation should therefore be more strongly encouraged.

**Change consumer behaviour**

Clothing has great emotional and symbolic value through which people express their status, outlook on life and identity. Second-hand or borrowed clothing is not yet generally accepted in this context. In addition, there is a profusion of greenwashing

188 | See Battery Pass 2024.

which makes it difficult for customers to identify sustainable products and include sustainability criteria in their purchasing decisions.

**How can digital enablers help?** Trustworthy certificates and labels can be made available to consumers via digital product passports and encourage them to buy sustainable and recyclable clothing. Digital platforms that ensure the quality of used clothing could also increase willingness to buy used clothing. And finally, digital technologies could be used to create incentive systems for sustainable purchasing and consumption behaviour. For example, companies could use gamified apps and social media challenges to promote sustainable purchasing behaviour or the repair of clothing and reward such behaviour with discounts on future purchases.

**What support can policy makers provide?** Obtaining labels and certificates is a bureaucratic and costly process for SMEs. For cost and efficiency reasons, no new quality certificate formats should therefore be created, but established labels and certificates (e. g. relating to corporate social responsibility and environmental compatibility) should merely be supplemented with circular economy requirements. Relevant information should also be made available to the population in a low-threshold form. Furthermore, digital information campaigns could be used to raise public awareness of the negative environmental impact of fast and ultra-fast fashion even further.

# 6 Cross-sectoral policy options

An analysis of the application examples reveals that all three of the represented economic sectors have significant potential for making value chains circular. It has also become clear that digital technologies and applications can play a decisive role in establishing circular value chains. This is because, unlike the linear economy, the Circular Economy requires **intensive exchange of information between all the stakeholders in the value chain**: the properties and conditions of products, components and materials must be recorded and in some cases kept up to date over long periods of time so that they can be made available to future users, repairers, dealers and recyclers. Digital technologies are the only efficient and affordable way of collecting, transferring and using this information.

The **digital toolbox** required for this purpose is largely already available. Simulations and digital twins can digitally model complex physical products made of various materials, while artificial intelligence allows predictions to be made about their condition and possible further use. Finally, digital product passports and data spaces can enable secure and efficient exchange of data between different stakeholders along the entire value chain. However, in order to use these digital enablers to expand the Circular Economy, there is a need for appropriate digital infrastructure and standardised, compatible applications (e. g. digital product passports and data spaces).

Although German and European policy makers have recognised the urgent need for action to introduce a comprehensive Circular Economy in the three sectors considered here and have already initiated significant measures, the **focus of specific measures is currently still too strongly on recycling** for a truly comprehensive transformation of the economic system to be achieved. The potential of higher-ranking R strategies,[189] which can only be tapped using digital technologies and are aimed at reducing total product volumes (e. g. by extended and more intensive use of products and service models), has not yet been fully exploited. Poor economic viability, a lack of data availability and quality and an absence of interoperability as a result of incompatible interfaces and data formats are therefore still standing in the way of the widespread use of digital tools for the Circular Economy.

Policy making should therefore focus on the development of data ecosystems for circular value creation networks rather than on (further) developing individual technologies. Although Germany's *National Circular Economy Strategy*, which is expected to be adopted in autumn 2024 and is currently available as a draft, also describes digital enablers as a necessary component of a transformation to a Circular Economy, the enablers will only be able to develop their full potential if the **business and regulatory environment for the Circular Economy** is improved overall in such a way that digital technologies also actually create **environmental and economic added value**. Not least, account must be taken of the technologies' sometimes major energy requirements and rebound effects[190], which can significantly reduce added value. Making beneficial use of digital enablers for the Circular Economy therefore requires an in-depth understanding of the specific processes involved. The action areas shown in Figure 12 are particularly important across all sectors.

First of all, the conditions for successful introduction of the Circular Economy must be created by **making environmental costs visible**, enabling the use of recycled products, components and materials and introducing suitable **standards and certification schemes**. In addition to these prerequisites, there is a need for functioning **markets for circular products and services** which are supported by appropriate **incentive systems** (including appropriate pricing of environmental costs) such that the competitiveness of circular products and services is increased. **Transfer-oriented funding** focusing on initiatives for linking up different value chains is required to facilitate entry into and scaling of the Circular Economy. Ultimately, however, the transition to a comprehensive Circular Economy can only succeed if **society** supports and helps to shape the transformation. These five action areas are explained in more detail below.



189 | Higher-ranking R strategies are those strategies in the 10R's model that cut down on products, intensify their use and extend their lifespan.

190 | If digital technologies lead to increased product consumption, this limits the resource savings in production, logistics and distribution brought about by the transformation.

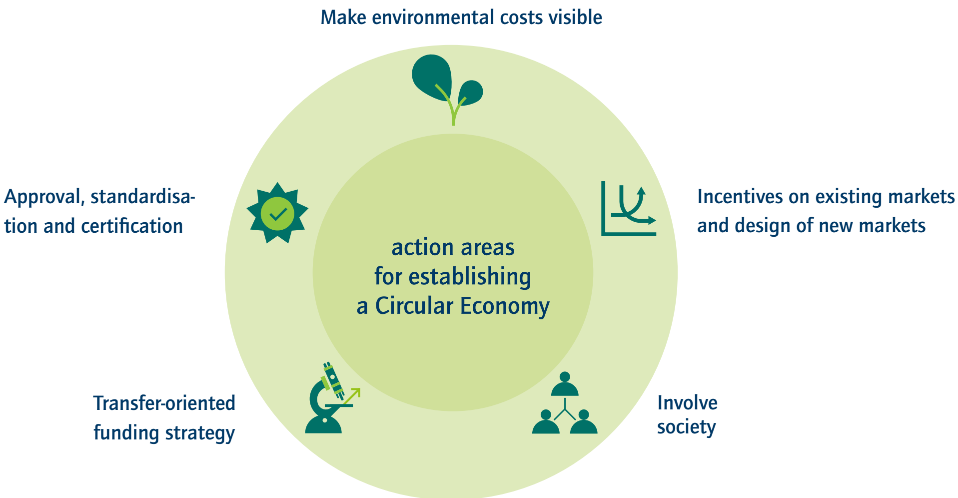


Figure 12: Cross-sectoral action areas for establishing a Circular Economy (source: own presentation)

## 6.1 Make environmental costs visible

**Poor viability** compared to linear business models is one of the most significant obstacles to the Circular Economy. The underlying problem is that **environmental costs are for the most part not reflected in product and raw material costs**. They are largely invisible not only to end consumers but also to stakeholders within the value chain. Even if the Circular Economy makes economic sense when external costs are taken into account, circular services and products are currently more expensive than linear ones – there is a market distortion to the detriment of circular practices and products. Environmental costs are largely borne by the general public, with the added complication that they are often incurred across borders.[191]

While digital solutions can help to reduce the costs of circular services and products, they are generally unable to compensate for the disadvantage suffered by the Circular Economy due to environmental costs not being taken into account. If environmental costs are not only to be priced but also taken into account as a selection criterion in public procurement or (voluntarily) in purchasing and investment decisions, they must first be determined and made transparent. This requires indicators that can be implemented by inspection bodies and companies, with there being a need to strike a careful balance between accuracy, completeness and data collection costs.

**Digital technologies can play an important role in determining environmental costs:** for example, planning software with a digital twin makes it possible to compare the life cycle assessment and recyclability of different product design alternatives. Distributed ledger technologies and digital product passports in turn allow information on environmental costs to be tracked along the entire value chain and also facilitate market surveillance. Statutory obligations to present environmental costs in standardised formats make this information transparent and more easily accessible for various stakeholders. The EU Ecodesign Regulation, which came into force in 2024, provides such a framework for many products with the introduction of the digital product passport, which is planned for 2027. Practical implementation is currently being worked out and trialled.

## 6.2 Standardisation, approval and certification

**The development and use of standardised and interoperable data formats and interfaces** must be driven forward to facilitate the exchange of product information and enable the creation of a data ecosystem. Appropriate measures form the basis for a consistent and efficient flow of information along the entire value chain, which is essential for establishing a Circular

191 | See Ockenfels/Schmidt 2019.

Economy. The creation of interoperability in data formats and interfaces is already being driven forward by various initiatives and is in some cases already being standardised. Standardisation work should be driven further forward, particularly at European level, in order to establish circular ecosystems across the entire European single market. Global connectivity of the corresponding standards and acceptance by relevant stakeholders is also of great importance if they are to be willing to share their data.

Digital applications based on standards and specifications, such as the digital product passport and data spaces, provide the necessary tools for establishing circular value creation systems. For example, the standards for the technical design of the digital product passport are currently being developed on behalf of the EU by the European standardisation organisations CEN and CENELEC[192]. It is crucial in this context for these organisations to work closely with active industry initiatives that are developing standards and interoperable interfaces for their respective sectors so that sector-specific requirements can be identified and corresponding specifications interoperably incorporated into the digital product passport.

In addition, data space initiatives, in the mobility sector for example the *Mobility Data Space* (MDS), in the automotive sector *Catena-X* and, in an Industrie 4.0 context, *Datenraum Industrie 4.0/Manufacturing-X*, can also drive the development of standardised data formats and interoperable interfaces. The *Gaia-X* ecosystem is already building data infrastructure based on the digital sovereignty of data owners, interoperability and the open source concept. Data spaces for different sectors can be developed on this basis. Further development of the technical components of *Gaia-X* is just as important as the development of specific use cases that demonstrate the benefits of data spaces in the respective sectors and can so contribute to the emergence and growth of data ecosystems.

Another major obstacle to the development of circular value creation models in Germany and the EU is a product and waste regulatory system which is still largely geared towards a linear economy. This currently further complicates the use of recycled products and should be simplified. For example, waste, i.e. a product at the end of its life cycle, can to date only be processed by authorised waste management operators. Manufacturing companies must acquire their own licence as a waste management operator at considerable expense in terms of time and money in order to gain access to the corresponding product streams. A revised, circular definition of waste in the regulations should therefore make recyclable materials streams more readily accessible to more market participants.

In addition, greater consideration should in future be given to the **properties of recycled material when granting approval** for production. To date, recycled materials must meet criteria comparable to those for new materials in order to be approved for use, regardless of whether these criteria are achievable in the reprocessing process or are even necessary for the intended use. Materials regulations and regulations to promote the Circular Economy must therefore be coordinated in order to enable long-term closed-loop materials management by companies. Digital technologies can provide the necessary information for characterising materials, for example by AI-assisted image data analysis. Data spaces and online platforms also make it possible to interconnect all stakeholders and to trade recycled materials between suppliers and buyers.

The EU Ecodesign for Sustainable Products Regulation issued in 2024 states that products should be durable, easy to disassemble and recyclable. The corresponding product information must in future be made available in digital product passports and, in combination with digital identification technologies (e.g. RFID tag, QR code), will enable the information to be clearly assigned to the physical product. The information should furthermore be used to particularly emphasise aspects relevant to the Circular Economy, such as recyclability or durability, to the end customer by means of (existing) labels and certificates for materials and products. This would create a database for pricing environmental costs that would counteract the current market distortion. In addition, such labels could be the basis for providing more information and building trust within a value creation network and among the population.

## 6.3 Incentives on existing markets and design of new markets

A further necessary prerequisite for the development of a Circular Economy is the establishment and scaling of markets for circular products and corresponding services. Possible measures



192 | CEN: European Committee for Standardization, CENELEC: European Committee for Electrotechnical Standardization.

should be based around incentive systems that promote circularity. Moreover, matching platforms should be set up or improved to bring stakeholders together and support the conclusion of transactions. A Circular Economy does not correspond to the logic of today's markets and geopolitical trends are not enough to bring about change. This is why there is a need for incentive systems and support for the development of circular markets. However, the regulatory framework should strike a balance between mandatory requirements and freedom for entrepreneurs to shape the transformation in order to promote creativity and innovation.

Once they have been made visible (see section 6.1), **environmental costs should also be actively priced** in the next step as an incentive for developing circular products. With carbon pricing in European emissions trading, some of the resulting greenhouse gas emissions are already taken into account as a cost factor, and circular economy products and services, which often have significantly lower emissions, are supported to a certain extent in this way. However, in order to create a truly level playing field for circular and linear products or corresponding services, other environmental costs, such as the impact of raw material extraction and waste disposal on soil, water and ecosystems, would have to be included in the pricing. A product's entire life cycle, including production, use phase and disposal, should be considered when creating incentives for extending product life and using recycled and sustainable raw materials. A fundamental challenge in this context is implementing suitable mechanisms for non-European imports and exports so that European manufacturers are not put at a pricing disadvantage. The Carbon Border Adjustment Mechanism (CBAM), which prices certain imports on the basis of their carbon footprint, is set to be introduced by 2026 and is at least a first step towards achieving this.

In addition to the above incentive systems, the successful development and expansion of circular markets is above all based on **creating stronger connections between market stakeholders**, for instance in reuse and continued use and in the establishment of new business models. Better connections between stakeholders, for example through the provision of public information platforms and data spaces as already outlined in the draft NKWS or through industry initiatives, help to consolidate material and product streams at the end of a product's life. In this way, economically viable and predictable markets for secondary raw materials and component recycling can be established. Industry initiatives and collaborative projects could promote such connections, although possibilities are currently still severely restricted by competition legislation and especially antitrust legislation. Current circular business models are therefore largely limited to small value creation networks with small materials streams, which reduces their economic viability.

In the interests of a sustainable Circular Economy, materials and product streams should also be logistically coordinated and thus consolidated for recycling and closed-loop management. In this way, new business models can be created and recycling by type accelerated. The resulting scaling effects can make it economically viable also to recycle waste streams from low-value or low-volume products/materials. If secondary raw materials are already being used in production, it is largely in the context of "open-loop" approaches, such as using secondary raw materials from the packaging sector for textiles based on recycled materials. When it comes to the type of recycling, open-loop and closed-loop approaches must be weighed up on a case-by-case basis. [193]

Here too, connections based on digital technologies, for example via appropriate matchmaking platforms, form the basis for joint recycling and consolidation of materials streams within a sector or across manufacturers for a class of products. Digital technologies for automating management and reprocessing and for designing return logistics improve economic efficiency in circular markets, for example by reducing transaction costs and improving the scalability of reconditioning or recycling processes. Especially in a high-wage country like Germany, recycling processes should be automated as fully as possible not only to minimise costs but also to enable scaling of recycling which is currently limited due to manual process steps.

Thanks to stronger connections between market participants, digital technologies also make it possible to model and anticipate the complex relationship between supply and demand for secondary raw materials and thus enhance the predictability and viability of new business models. These stronger connections additionally create incentives to develop circular products in terms of simpler recycling of products and materials, provided these can be put to use in a larger ecosystem.



193 | Closed-loop-approaches minimise intersectoral dependency as no materials streams from other sectors are "cannibalized". Open-loop approaches in contrast can help to build new value creation networks; in addition, they also offer comparatively greater opportunities for upcycling and reduce the risk of downcycling.

## 6.4 Transfer-oriented, interdisciplinary funding strategy

However, some obstacles still remain on the road to a comprehensive Circular Economy that cannot be overcome by legal frameworks and economic incentive systems alone. For instance, significant investment is often necessary before circular strategies pay off for companies. In addition, developing circular products and business models requires a three-fold skill set that includes not only an in-depth understanding of the Circular Economy and digital technologies but also their application to a specific sector and product. An interdisciplinary funding strategy is therefore required that is geared towards applying circular strategies and the corresponding digital technologies.

The pricing of environmental costs could be trialled as a Circular Economy driver by initially giving them greater consideration as a selection criterion for public procurement. The resulting value chains, business models and experience could ultimately be of value to the private sector and contribute to both the expansion and the economic viability of circular approaches and business models.

At present, there are still too few examples of good practice in the successful implementation of circular business models. Financial support for transfer-oriented flagship projects serving as role models for their particular sector could make a significant contribution to the development of a Circular Economy by creating connections between stakeholders and strengthening circular business models. The projects should have a strong multi-stakeholder focus and involve not only academics from various areas of research but also stakeholders from the value chain in question. New technologies and business models could be trialled by the resultant sectoral projects. Concepts such as digital data spaces, some of which remain abstract, could thus be translated into concrete corporate roles and business models. In particular, projects aiming to create value networks and circular business models based on them could be economically viable after the end of the funding period.

In addition to developing flagship projects, it is also crucial to support projects with a high level of technological maturity. The feasibility of circularity strategies and circular business models should be tested and proven in an operational environment involving (global) value chains. Real-world laboratories provide a suitable format for test environments in which the innovative implementation of R strategies is possible and solutions for regulatory obstacles are tested. For example, recycled construction materials could be tested in real-world laboratories in the construction sector on a regionally limited basis prior to their being statutorily approved if there are no concerns regarding harmful substances and safety.

Such real-world laboratories are very complex to implement because many stakeholders such as different authorities and waste management companies need to be involved in order to create a suitable test environment. In the case of projects with strong international links, the complexity of implementation processes often exceeds the possibilities of a real-world laboratory and this is where a digital twin of a real-world laboratory could be a promising approach. For example, circular value networks could be simulated in such a virtual real-world laboratory and the effects of differing international legislation and multinational market incentives could be tested. Data definitions and infrastructure that are important for the Circular Economy could also be tested in such virtual real-world laboratories on an industry-specific basis.

The German quality infrastructure initiative *QI-Digital*, funded by BMWK, is a good example of such a cross-sectoral, highly transfer-oriented funding project. This initiative, which is supported by the German Institute for Standardization (DIN), the German Commission for Electrical, Electronic, and Information Technologies (DKE), the German Accreditation Body (DAkkS), Germany's National Metrology Institute (PTB) and the Federal Institute for Materials Research and Testing (BAM), brings together relevant stakeholders from politics, industry and public administration with the aim of digitalising quality infrastructure (QI) processes. Digital quality assurance solutions are indispensable, for example, for the development of product passports, which are a crucial tool for establishing a Circular Economy. Concrete solutions for new methods, processes and tools for digital quality assurance are in turn developed in real-world laboratories. Finally, the laboratory processes are accompanied by studies on the necessary business and regulatory environment and transfer measures.

## 6.5 Involve society

Since the circular transformation requires far-reaching economic and social change, it is essential for the public to be involved in shaping the process. In view of the necessary business and regulatory environment and the role played by consumers, implementing the Circular Economy means that political and socio-cultural dimensions must be debated in addition to technical and economic issues. Tapping the full potential of the Circular Economy requires a **holistic systems approach** with the aim of enabling society to live and operate within planetary boundaries.[194] However, this requires the development of new cultural practices and narratives.

German society's knowledge of the Circular Economy is still very poorly developed. However, a deeper understanding is an important prerequisite for establishing a Circular Economy, and key policy decisions such as the pricing of environmental costs must be supported by society. In addition, people must be empowered to implement and drive forward circular approaches in their current or future profession. Societal dialogue about this complex issue should therefore be encouraged at various levels, including at school, during training and at university.

In order to embed the Circular Economy more deeply in society, support should be provided for initiatives at the local authority level which actively involve citizens in decisions about the design of their own living environment. For instance, the public can decisively contribute to the success of circular approaches by making behavioural changes in terms of dealing with waste and sharing products. Upskilling, for example by supporting repair cafés, also empowers people to participate in the implementation of circular economy strategies, and creates a better practical understanding of circular concepts.

Citizens can also make a decisive contribution to supporting the Circular Economy when it comes to consumption. Transparent communication is therefore important – information about product sustainability and circularity must be made available to the public in a way that is appropriate for the target group. Digital product passports can act as a format for storing product information and making it accessible, for example via QR codes. On this basis, traceable trustmarks and certificates can build trust and support informed consumer decisions but it is important to avoid a profusion of such marks and labels causing confusion among consumers. Furthermore, greenwashing should be prevented by clear guidelines on product advertising and description and by consistent monitoring. A current EU Directive on reducing greenwashing in consumer products already partially addresses these issues by providing consumers with better information to support them in adopting more sustainable consumption behaviour.[195]

Digital applications can help to make such information more easily accessible and allow manufacturers to provide attractive product-service offers. And finally, digital technologies can be used to create incentive systems for sustainable consumption behaviour. For example, gamification, i. e. transferring gaming concepts to non-gaming contexts, can convey content in an entertaining way and help change established behavioural patterns in consumption.

194 | See Kara et al. 2022.
195 | See Directive (EU) 2024/825.

# Conclusion and outlook

This acatech STUDY outlines a variety of possible applications for digital technologies in the context of the Circular Economy and underlines the central role of these technologies in the transformation towards circularity. The analysis of the three application examples also shows that a Circular Economy requires significantly more information exchange between all the stakeholders involved than a linear economy. Digital technologies and applications such as the digital product passport and data spaces, which can store and pass on standardised information about products and materials, are tools that can offer cross-sectoral assistance in implementing the Circular Economy.

The central importance of digitalisation to the development and expansion of a Circular Economy is therefore being taken into account by the federal government in the National Circular Economy Strategy (NKWS) and at EU level in the new Ecodesign Regulation. In this context in particular, however, this STUDY reveals a number of aspects that should be considered when it comes to promoting digital technologies in the Circular Economy in future:

1. It is particularly important to use digital tools to create connections between the stakeholders within the value chain and cross-sectorally if circular value creation models are to gain a foothold and if a cross-sectoral business and regulatory environment is to replace the silo mentality that is often still prevalent within industries. This is also apparent from the policy options for establishing a Circular Economy described in section 6.
2. It is just as important to take an integrated approach to digitalisation. This is because greater synergies will also be created as technologies and applications such as artificial intelligence, digital twins, automation, data spaces and product passports become increasingly intertwined. For instance, AI-assisted evaluation of data from the digital product passport or from data spaces can make a significant contribution to more efficiently and automatically reusing, reprocessing or recycling materials and products.
3. Digital solutions must be tailored to the particular intended purpose and the sector- or product-specific circumstances. This is clear from the differing roles various R strategies play in each sector, the specific suitability of digital technologies and the derived policy options (see sections 3-5). For example, differences in the lifespans of products and the materials used as well as the structure, complexity and geographical distribution of the respective value chains must be taken into account.
4. Projects relating to digital enablers in the Circular Economy should pursue an interdisciplinary approach and involve international partners in value chains. These aspects often already constitute parameters applied in funding initiatives, but greater attention should be paid in general to internationalisation as a factor to ensure targeted implementation of the Circular Economy.
5. Finally, the focus in future should also be on making a nuanced analysis of the sustainability aspects of using digital technologies for the Circular Economy. Overall, digital technologies and applications should be designed in such a way that not only economic, but also environmental and social aspects are taken into account.

However, all the challenges mentioned here can only be tackled effectively if there is political support for the implementation of existing and future initiatives and financial resources are available to kick-start them. This is particularly true for small and medium-sized enterprises which, being a major pillar of the transformation, are crucial to the success of the entire project but, when it comes to digitalisation and the goal of sustainability, are faced with major tasks which often overtax their existing capabilities.

**Examples of particularly relevant digital technologies and applications**

This STUDY suggests that the digital product passport and data spaces are particularly important for successful implementation of the Circular Economy. For this reason, these two digital enablers are briefly examined below in the context of relevant funding projects.

**Digital product passport**

Analysis of the application examples has revealed across all sectors that comprehensively sharing data along the entire value chain in the digital product passport format is advantageous. The federal government has already identified a need for such sharing and plans to support eight relevant flagship projects for the plastics, textiles, electronics, food, water and nutrients, packaging, batteries and vehicles, and construction and buildings sectors by 2028 as part of the *Digital Product Passport* initiative which is jointly funded by the Federal Ministry for Economic Affairs and Climate Action (BMWK) and the Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV).

The *Battery Pass* project takes batteries as an example to reveal the complexity (data definitions, analysis of technical standards, transfer of liability, auditability, etc.) that arises when implementing the digital product passport for a specific product group. It thus demonstrates the necessity and challenges of a concrete design that makes the added value of digital technologies for promoting the Circular Economy feasible in the first place. Additionally, the EU-funded Cirpass2 project is analysing use cases for the digital product passport for a range of other products and value chains, for instance from the textile and electronics sectors.

**Data spaces**

Digital data spaces have been identified as an important technology for all three of the economic sectors considered as examples. Data spaces make it possible to create connections between value chain stakeholders and make use of data securely and confidentially while maintaining the stakeholders' data sovereignty. For example, data spaces can be used to exchange information about the availability of materials and products on digital marketplaces, or they can facilitate the flow of information in complex (construction) projects between a large number of stakeholders. The draft *National Circular Economy Strategy* has already taken account of the relevance of data spaces and provides for strategic pilot projects (*Circular Economy Use Cases*) as part of the *Manufacturing-X* initiative in exemplary sectors and value creation networks in order to develop and test structures for shared data use.

The European *Gaia-X* initiative, the reference architecture of which is also used as the basis for *DataSpace Industrie 4.0*, also offers the possibility of interlinking a number of data spaces via compatible interfaces, so promoting the cross-sector exchange that is important for implementing the Circular Economy. In order to establish the use of data spaces on a broad scale, many companies and sectors still need support with introducing them, something which should be achieved with suitable funding projects.

# Appendix

## List of abbreviations

| | |
|---|---|
| B2B | Business-to-business |
| B2C | Business-to-consumer |
| BAM | Federal Institute for Materials Research and Testing |
| BIM | Building Information Model |
| BMBF | Federal Ministry of Education and Research |
| BMUV | Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection |
| BMWK | Federal Ministry for Economic Affairs and Climate Action |
| CBAM | Carbon Border Adjustment Mechanism |
| CE | Circular Economy |
| CEID | Circular Economy Initiative Deutschland |
| CEN | European Committee for Standardization |
| CENELEC | European Committee for Electrotechnical Standardization |
| CPS | Cyber-physical system |
| CSRD | Corporate Sustainability Reporting Directive |
| DAkkS | German Accreditation Body |
| DERA | German Mineral Resources Agency |
| DIN | German Institute for Standardization |
| DKE | German Commission for Electrical, Electronic & Information Technologies |
| DLT | Distributed ledger technology |
| DPP | Digital product passport |
| ESRS | European Sustainability Reporting Standards |
| EU | European Union |
| GOTS | Global Organic Textile Standards |
| IoT | Internet of things |
| AI | Artificial intelligence |
| SME | Small and medium-sized enterprises |
| NFC | Near-field communication |
| NKWS | German National Circular Economy Strategy |
| PTB | German National Metrology Institute |
| RFID | Radio-frequency identification |

# Glossary

This glossary is intended to provide readers with guidance and is an attempt to clarify the digital technologies and applications mentioned in the expert interviews. Sources for the glossary include the *Technologie- und Trendradar 2022*[196] published by the Federal Ministry for Economic Affairs and Climate Action and the *Gabler Wirtschaftslexikon*[197]. It makes no claim to general validity or completeness of the definitions.

**Digital technologies**

**3D printing**
3D printing, also known as additive manufacturing, is a method in which material is applied layer by layer to create a three-dimensional object. 3D printing is used in many areas, including industry, medicine, construction and arts and crafts and can produce complex, custom parts. Typical materials for 3D printing are plastics, metals, ceramics and certain biological materials.

**Cloud computing/edge computing**
Cloud computing and edge computing are approaches to data processing and storage. While cloud computing involves data being stored and processed in centralised data centres, edge computing enables data to be processed closer to where they are generated, for example on devices or local servers. Both technologies enable scalable, flexible IT infrastructure and are essential for the internet of things (IoT) and data-intensive applications. Applications of cloud computing and edge computing include optimising production processes in industry, providing rapid diagnostics in healthcare, assisting autonomous vehicles in the automotive sector and providing 5G applications in telecommunications.

**Distributed ledger technology (DLT)**
Distributed ledger technology is often used synonymously with blockchain, although blockchain is just the best-known example of DLT. DLT is a decentralised database technology that documents transactions securely, transparently and unmodifiably. Each transaction is stored in a network of computers (nodes) and validated by consensus mechanisms. DLT is applied in cryptocurrencies, supply chain management and digital identities.

**Internet of things (IoT)**
The internet of things relates to a network of physical objects that are equipped with sensors, software and other technologies for collecting and exchanging data. Such "smart" devices communicate with each other and with central systems in order to automate processes, increase efficiency and enable new services. Applications of this technology include networked household appliances, autonomous vehicles and industrial machinery.

**Communication technologies**
Communication technologies encompass systems and processes that enable the exchange of information. These include technologies for mobile internet services such as enhanced data rates for GSM evolution (EDGE), as well as radio and satellite technology. The latest 5G and 6G mobile radio generations enable higher data rates, lower latency times and the networking of a larger number of devices. 5G is already in widespread use and supports applications such as IoT or autonomous driving. 6G is in development and will probably enable still higher speeds and innovative applications such as holographic communication.

**Artificial intelligence (AI)**
Artificial intelligence is the field of computer science that deals with the development of systems that can perform tasks that normally require human intelligence. This intelligence can, for example, be based on defined program sequences or developed through machine learning. AI is used in a wide range of applications, from voice assistants and medical diagnostic tools to autonomous vehicles.

**Simulation**
Simulation refers to the virtualisation of a process or product to create a digital model based on defined characteristics of the real process or product. Changes in the model can be predicted in the simulation under defined conditions. In this way, changes to the process or product can be tested and optimised in the virtual world. Simulation provides reliable predictions under reproducible conditions.

196 | See Stich et al. 2022.
197 | See Gabler Wirtschaftslexikon 2024.

## Digital applications

### Autonomous robots

Autonomous robots are machines that are capable of carrying out tasks without human intervention. They use sensors, cameras and algorithms to perceive their surroundings, make decisions and adapt. These robots are used in various areas, including logistics, agriculture and manufacturing, to automate processes and increase efficiency.

### Image analysis

Image analysis using artificial intelligence enables computers to analyse images and videos and extract relevant information from them. It is used in many applications, such as medical diagnostics, object identification in industry or in surveillance technology. The term also includes scanning technologies that are used to generate the images.

### Cyber-physical system (CPS)

In a cyber-physical system, physical processes are linked to digital networks and computing power. This integration enables real-time monitoring and control of physical systems, such as in Industry 4.0 or in smart transport systems.

### Data spaces

Data spaces are digital infrastructure systems that enable the secure exchange and sharing of data between different stakeholders. They provide a structured environment in which data providers and users can trust each other and collaborate while maintaining data sovereignty. Data spaces play a key role in data-driven business models and in creating connections between companies in the digital economy. They are therefore a key technology in *Europe's Digital Strategy*.

### Digital identity

A digital identity is the representation of a person or object in the digital world. It enables access to digital services and the performance of online transactions. Digital identities are essential for security and data protection on the internet and play a central role in authentication and authorisation in the most varied digital applications.

### Digital product passport (DPP)

A structured collection of product-related data with a predefined scope and differentiated data ownership and access rights, transmitted via a unique identifier. Data are stored decentrally and, while maintaining data sovereignty, shared by the product's distributor with other stakeholders. Product passports are being introduced in the European Union by the new Ecodesign Regulation and other regulations for a large number of different products. Among other things, they contain information about carbon footprint, due diligence and technical parameters of the product such as performance, durability and chemical composition.

### Digital twin

A digital twin is a virtual replica of a physical object, system or process in a single or over multiple life cycle phases. Digital twins enable real-time monitoring and analysis as well as the simulation of scenarios to optimise performance and perform predictive maintenance. Digital twins are used in manufacturing, construction, urban planning and healthcare.

### Online platforms

Online platforms are digital environments that enable different stakeholders to interact with one another, exchange data and implement joint business processes. They provide a basis for the development and provision of software, services and products. Platforms are the basis for various digital business models.

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**Editors:**
**Prof. Dr. Dr. h. c. Christoph M. Schmidt**
**Prof. Dr.-Ing. Thomas Weber**
acatech – National Academy of Science and Engineering
Munich Office
Karolinenplatz 4
80333 Munich, Germany

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Munich Office
Karolinenplatz 4
80333 Munich | Germany
T +49 (0)89/52 03 09-0
F +49 (0)89/52 03 09-900

Berlin Office
Georgenstraße 25
10117 Berlin | Germany
T +49 (0)30/2 06 30 96-0
F +49 (0)30/2 06 30 96-11

Brussels Office
Rue d'Egmont/Egmontstraat 13
1000 Brussels | Belgium
T +32 (0)2/2 13 81-80
F +32 (0)2/2 13 81-89

info@acatech.de
www.acatech.de
acatech @ X | LinkedIn | Instagram



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The restructuring of the economic system towards a Circular Economy that is necessary for the purpose of sustainability goes hand in hand with the digital transformation, as digital technologies hold great potential as enablers for the successful implementation of circularity strategies. This acatech STUDY analyses the role of digital technologies in the Circular Economy on the basis of application examples from three different sectors of the economy and shows that the digital toolbox required to establish a Circular Economy is largely already available. However, it will only be possible to realise the full potential of digital technologies in the future if both the sector-specific and cross-sectoral business and regulatory environment is made more conducive to a Circular Economy.