RETHINKING EXTENDING REUSING

HARNESSING DIGITAL TECHNOLOGIES FOR THE CIRCULAR ECONOMY

A critical path on technologies, challenges and urgently needed enabling solutions

Metabolic Institute

One planet handle with care

Coalition for Digital Environmental Sustainability

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Suggested citation
One Planet Network (2023). Rethinking, Extending, Re-using. Harnessing Digital Technologies for the Circular Economy.

Production:
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UN Environment
Industry and Economy Division
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75015 Paris, France

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Cover photos
An artist’s illustration of artificial intelligence (AI). This image depicts how AI could be used in the field of sustainability from biodiversity to climate.

Foreword

Rapidly evolving digital innovations are influencing all sectors of society, creating unprecedented opportunities to accelerate sustainability and circularity. With the emergence of Artificial Intelligence (AI), Blockchain, Internet of Things and Big Data, we are unlocking new ways of exploring our value chains, allowing us to understand, address and communicate pressures, hotspots and impacts – in terms of environmental, social and economic issues.

However, an exponentially accelerating digital world brings new risks to our people and planet, from the digital divide to resource use and unmanaged e-waste. These risks cannot be ignored if we are to sustainably make use of digital technologies for our planet and prosperity. Now is the time to work together to harness the power of technologies to promote a circular economy, while addressing barriers and challenges, to ensure sustainability for all.

This report brings together more than 30 cross-disciplinary experts from the fields of digital technologies, circular economy, consumer behaviour and sustainable financing to define a critical path with short-term recommendations for both the public and private sector. Rethinking product use and manufacturing, extending product lifespan and reusing materials effectively are fundamental to sustainably transform our systems. For instance, in a circular economy, AI could drastically minimize the unnecessary plastic present in 30 per cent of our packaging. Moreover, as predicted by the Ellen MacArthur Foundation, if we use AI to help eliminate food waste, the global economy could benefit from up to US$127 billion per year in 2030.

With this, the One Planet Network commits to co-develop transformative initiatives with market leaders and innovators to accelerate the shift to a circular economy by means of digital technologies.

Jorge Laguna Celis,

Head of the One Planet Network

One planet
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In recent years, it has become increasingly clear that our current economic models are leading to global economic and sustainability issues, as well as climate change. Consequently, there is a push to transition towards a circular economy that is regenerative and inclusive by design, with a view to accelerating and scaling action towards climate stability. Digitalization, when intentionally leveraged through strategic action, has the potential to influence not only environmental decision-making but also economic incentives and business models, consumer behaviours, and environmental governance.

By the end of 2023, over 60 per cent of global Gross Domestic Product (GDP) will pass through digital channels, thus, urgent policy guidance is needed for both public and private sectors on how different digital technologies can be combined and leveraged to lay a progressive digital foundation for the circular economy. Opening the doors for data collaborations, promoting interoperability, increasing transparency along the value chains and ensuring accountability across sectors are necessary for changing production processes and consumer behaviours as the economic transition builds.

This report, and the continued efforts of this expert group, responds directly to the UNEP MTS 2022-2025 and the UNEP Digital Transformation Programme of Work, as well as the UN Secretary-General's Roadmap for Digital Corporation. The implementation of the critical path outlined in this report is considered of key relevance to UNEP's Digital Transformation Subprogramme and to the Coalition for Digital Environmental Sustainability (CODES).

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Introduction

Our current linear economy is contributing to global sustainability challenges, such as climate change, biodiversity loss, material scarcity and pollution. The way we produce, use and discard our materials and products causes these environmental and economic impacts, that in turn increase our vulnerability to global shocks. In the past decade, these insights about the state of our planet and its impacts on human and other life-systems have led to the development of a new economic paradigm called the circular economy (UNEP 2019). The urgency and benefits of moving towards a circular economy are clear. By shifting to such an economy we can preserve the value of materials and products, increase employment opportunities, boost innovation and safeguard the ecological systems on which we depend. This shift goes beyond simply recycling and recovery technologies, to redesigning our economic system into one that is regenerative and inclusive by design (Ellen Macarthur Foundation 2022).

60%

GDP will pass through digital channels by end of 2023

In parallel to this new paradigm shift, a combination of data, digital technologies and related innovations are sweeping the planet at an exponential rate. These digital technologies have the potential to unleash major structural economic, environmental and social transformations at a global scale. By the end of 2023, over 60 per cent of global GDP will pass through digital channels, four billion people will be influenced by social media, and two billion people will consume goods and services online (World Economic Forum 2019). Digital technologies are therefore becoming increasingly pervasive in the current economic structure. Their exponential growth shows the same problematic symptoms as the current system, contributing to unprecedented environmental and social risks related to the type of resources they demand (e.g. critical metals and energy), the consumption patterns they accelerate and the waste they produce (e.g. e-waste).

On the other hand, their capabilities can also be leveraged to accelerate the shift to a fundamental circular and sustainable economy. As a result, one of the urgent priorities is to direct the trajectory of digital transformation so that it accelerates and scales environmentally and socially sustainable products and services as well as behaviours and lifestyles. For these digital technologies to be useful tools in accelerating the transition to a circular economy, they must be combined with structural policy reforms, new financing mechanisms and new business models to be effective. For this, further research, multi-stakeholder partnerships, identification of innovative pathways and business models, investments and clear policy guidance are needed on how different digital technologies can be combined and leveraged to lay a progressive digital foundation for the circular economy (Coalition for Digital Environmental Sustainability 2022; UNEA 2022).

The One Planet Network, the Coalition for Digital Environmental Sustainability (CODES) and the United Nations Environment Programme (UNEP) are therefore working with Metabolic Institute and a new multi-stakeholder expert group to assess current and short-term opportunities brought about by digital technologies to accelerate the shift to the circular economy. Presented in this report are the results of this work, laying out a clear critical path for public and private institutions in the short term to scale and increase uptake of digital technologies and related policies. While this is quite a broad topic, this report addresses existing circular economy approaches, focusing on how digital technologies can support data collection and integration, data analysis, and data communication and dissemination along the value chain.

The three circular economy approaches, upon which this report is structured, are:

1. **Rethinking manufacturing and product design -** through practices of rethinking, redesigning, refusing and reducing.

2. **Extending the lifespan of products and their parts -** through reusing, repairing, refurbishing, remanufacturing and repurposing.

3. **The effective reuse of materials -** such as recycling by introducing secondary materials back into the earlier stages of the value chain**.**

Each section highlights the most critical function(s) of digital technologies (data collection, analysis and dissemination) required to scale the circular economy approaches in the short term. As well as describing the main barriers faced by the digital technologies to support the approaches, and presents short-term solutions to overcome these. Finally, the report provides recommendations and a critical path forward for public and private organizations to implement these solutions in the short term. The results presented in this report are based on an extensive literature review, a questionnaire sent to practitioners and insights gathered from the multi-stakeholder expert group, with practitioners and experts within circular economy, digital technologies, innovative investments and behavioural change.

> ***This report addresses existing circular economy approaches, focusing on how digital technologies can support data collection and integration, data analysis, and data communication and dissemination along the value chain.***

02

Context

The circular economy

Our current economy uses materials in a largely linear way, a ‘take-make-waste’ model where materials are extracted from the Earth to make products, and these products are disposed of as waste after their use. The linear economy has contributed to several of the largest challenges we face today including, but not limited to, climate change, material scarcity and resource depletion, global biodiversity loss, vulnerability to economic and environmental shocks and unequal distribution of benefits along globalized value chains.

A redesign of the current system to a circular economy has the potential to address these negative impacts. As the name implies, a circular economy advocates for products and materials that are designed in such a way that they can be reused, remanufactured, recycled or recovered and thus maintained in the economy for as long as possible, along with the resources of which they are made, while minimizing or eliminating waste and pollution (UNEA 2022). The objective of the circular economy is to build sustainable, equitable and resilient systems for people, businesses and the environment, and to achieve this, a holistic approach is necessary (Figure 1).

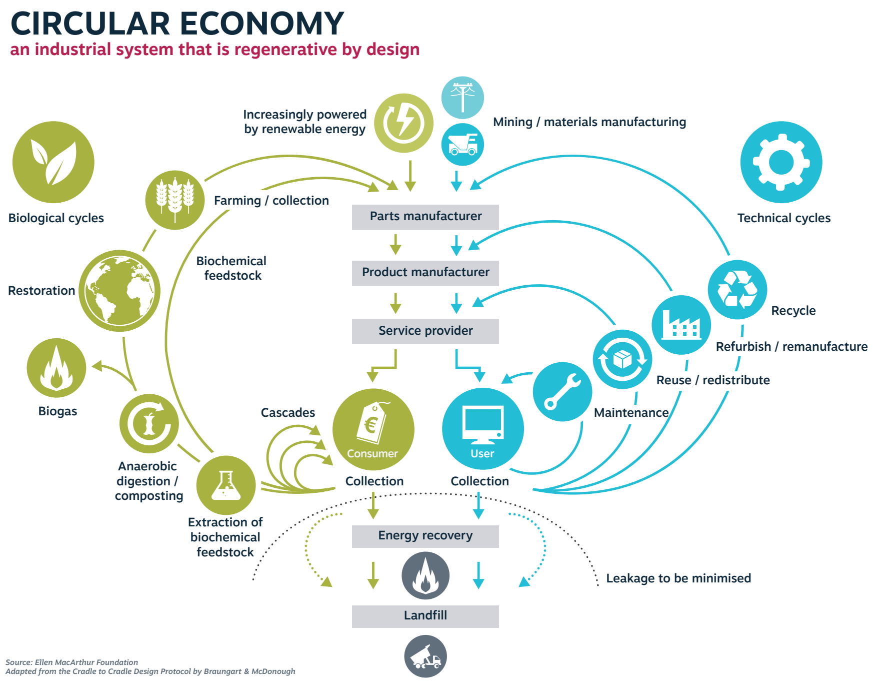


Figure 1: Circular Economy Systems Diagram

Source: Ellen MacArthur Foundation (2019). Originally adapted from the Cradle to Cradle Design Protocol by Braungart & McDonough (C2C) ©Metabolic Institute

We can reach this objective through different circular economy approaches, which can be grouped under three broad categories: rethinking product design and manufacturing, extending the lifespan of products and their parts, and the effective reuse of material. These approaches are visualized on the 'Value Hill' (Buren et al. 2016; Circle Economy 2016) which illustrates the full life cycle of any given product, from extraction and manufacturing through use and eventual disposal (Figure 2). Value is added as the product moves 'uphill' in the supply chain, and where circular strategies keep the product at its highest value (located at the top of the hill) for as long as possible. In this circular supply chain, products are designed to be long lasting and are suitable for maintenance and repair, thus slowing resource loops and prolonging the use-phase of the product. When a product starts to move 'downhill', it is done as slowly as possible so that its useful resources can still be of service to others.

The first circular approach focuses on rethinking product design and manufacture, mainly through practices of rethinking, redesigning, refusing and reducing. This approach is fundamental to the elaboration of new product ownership and product use models that are required for new circular business models. The second approach aims to extend the lifespan of products and their parts through reuse, repair, refurbish, remanufacture and repurpose. The last circular approach aims at the effective reuse of material and is essentially focused on recycling.[1] New types of business models like product-service systems are fundamental in the transition to a circular economy.

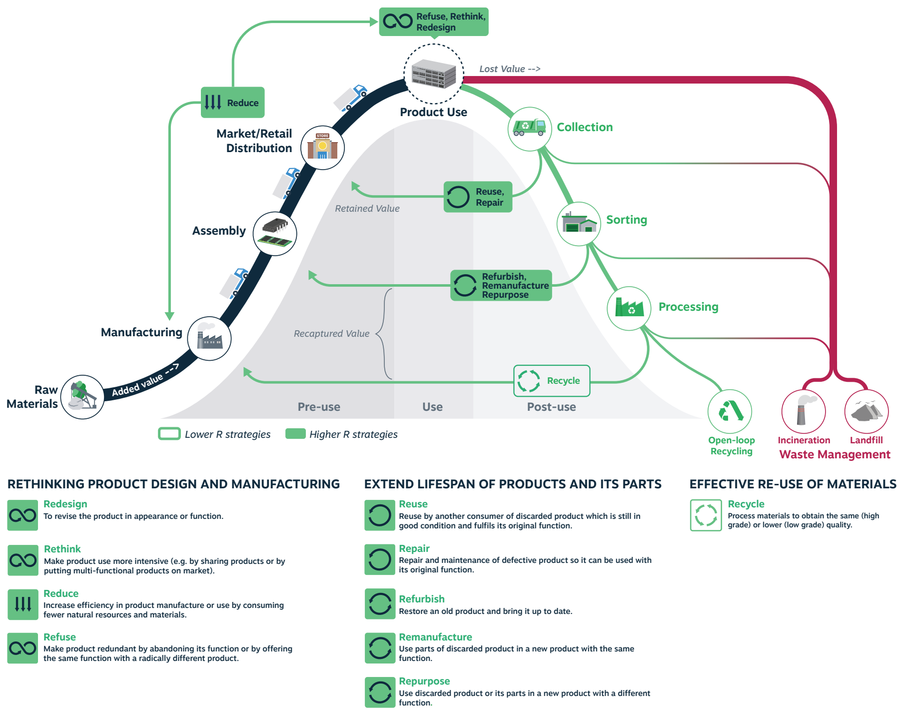


Figure 2: Adapted Value Hill Model with the 9R Framework

Source: Buren, N., Demmers, M., Heijden, R. and Witlox, F. (2016); Circle Economy (2016); Kirchherr, J., Reike, D, and Hekkert, M. (2017); Potting, J., Hekkert, M., Worrell, E. and Hanemaaijer, A. (2017) ©Metabolic Institute

1 Some strategies may also involve recovery of value through low value recovery methods like waste-to-energy. This is, however, not considered further in this case.

Three core circular economy approaches

Circular economy approach	Definition
Rethinking product design and manufacturing	This approach focuses on reducing, refusing, redesigning and rethinking processes. It aims to increase production efficiency by consuming fewer natural resources. It can also fundamentally transform how a function or value is delivered by a product and even change user behaviours, so as to reduce wasteful practices.
Extend lifespan of products and their parts	This approach focuses mostly on the use-phase of products' life cycle, extending the useful lifetime of the products' original function through repairing, refurbishing or reusing processes. Products that have passed a critical threshold can be sorted, collected and reintegrated in an alternative use-phase through remanufacturing or repurposing activities.
Effective reuse of materials	The approach focuses mostly on the end of the life cycle of products that aims to extract efficiently as much value as possible from the materials composing the products and recycle them into secondary feedstocks for the production of new products.

> ***New types of business models like product-service systems are fundamental in the transition to a circular economy.***

Industry 4.0 and digital technologies

"Circular economy approaches require scaling up sustainable practices along value chains and acknowledging that there are business models and best practices that embrace circular economy approaches, technologies that improve resource management across sectors, and "leapfrogging technologies" that generate economic savings and improve resource efficiency while still driving development, notwithstanding the need for circular innovation." (UNEA 2022)

Technology and innovation can enhance and optimize the three core circularity approaches, and as they increasingly digitize manufacturing processes and products and services they are transforming the way we produce, consume and reuse products. This phenomenon is called Industry 4.0, and there are a variety of definitions of the concept, ranging from the 'fourth industrial revolution' to 'smart value chain processes' powered by Information, Communication and Technology (ICT).

Lu *et al.* (2017) define the essence of digital technologies and Industry 4.0 as any "integrated, adapted, optimized, service-oriented, and interoperable manufacturing process which is [...][supported by] algorithms, big data, and high technologies."

The recurring theme of these definitions is the connectivity and flow of information and data across value chains and processes thanks to the application of specific digital technologies.

Purpose of this report

To effectively harness digital technologies for the circular economy, guidance for policymakers and the private sector is needed to understand:

1. How digital technologies can be combined and leveraged to lay a progressive digital foundation for the circular economy.

2. What barriers and challenges are currently limiting the integration of digital technologies.

3. Which risks are associated with digital technologies in the circular economy, including adverse environmental and social impacts, that must be mitigated within any solutions.

4. Which concrete solutions may unlock the potential of digital technologies for the circular economy.

As such, the One Planet Network and CODES, along with UNEP and Metabolic Institute, initiated the co-development of this report. By combining scientific research with practical and experiential perspectives from experts across alliances and coalitions, businesses, venture capitals, academia, international organizations and public entities within the circular economy, behaviour change, innovative investments and the digitalization space, this report sets out concrete, feasible and urgent recommendations for both the public and private sector for immediate actions needed in the short term to enable digital technologies to accelerate the shift to a circular economy.

This report is a core effort under Pillar II of the Global Strategy for Sustainable Consumption and Production (2023-2030) entitled 'Enable changes through circularity, transformative multi-stakeholder and public-private partnerships, tools and solutions across high-impact systems and sectors'.

It is also an output under Outcome 2 of the Results Framework of the 10YFP Secretariat (2023-2024) that refers to: "The transition of societal choices and markets towards sustainability is supported by common principles and standards for sustainable consumption and circularity in high-impact sectors (food, construction, tourism, e-commerce)."

The report will form the basis for a dedicated One Planet Network and CODES initiative, guiding concrete interventions and formation of communities of practice to effectively support the public and private sector in the implementation of the recommendations laid out in the critical path of this report. The report will inform ongoing preparations for the UN Summit of the Future and the Global Digital Compact, as part of the UN Secretary-General's Roadmap for Digital Cooperation.

Scope and method

Prior to expert group consultations, a systems analysis was conducted based on a literature review of articles published since 2020 (Liu *et al.* 2022; Cagno *et al.* 2022, Cwiklicki and Wojnarowska 2020; Lobo *et al.* 2022; Neligan et al. 2022; Chauhan, Parida and Dhir 2022; Khan, Piprani and Yu 2022; Bressanelli *et al.* 2022; Kristoffersen *et al.* 2022; IEA 2020). Through this analysis, major digital technologies were identified, based on their immediate potential to influence the three circular economy approaches in the near future. This scope necessitated choosing those with a certain level of maturity, possessing the critical functions needed to support the circular economy, and offering a proven application, at least at pilot scale, in one or more circular processes.

The identified digital technologies perform key functions. They enable the flow and processing of the data and information for circular business models to fulfil the complex demands of circular value chains. They can allow to track and trace materials and components of products during their life cycle. They can also execute the analysis of data to provide insights and support decision-making; which may ultimately lead to the automation of decision-making in certain circumstances. Finally, these digital technologies can communicate key information to consumers and users with the goal to shape behaviours. As such, the most critical functions (Liu *et al.* 2022), based on the analytics and knowledge hierarchy (Kristoffersen et al. 2022; Siow *et al.* 2018) that act as enablers of the circular economy, are defined below.

Critical functions of digital technologies	Definition
Data collection and integration	The first process collects data from physical and virtual sources. Information is mostly generated by descriptive analytics in the data integration process, and through tracking and tracing practices.
Data analysis	Builds on the first process to generate knowledge and wisdom. 'Knowledge' here refers to diagnostic analytics with understanding and meaning, while 'wisdom' refers to discovered, predictive or prescriptive insights which can also be used to simulate future outcomes.
Communication and dissemination	This function specifically informs and influences human behaviour and decision-making.

An important caveat to note is that these digital technologies will never be a silver bullet to the societal challenges of implementing the circular economy in practice. These technologies are tools and means that can be used to accelerate the transition, but human action and behavioural change are first required to achieve it. In the "Cautionary tale of Digital Technologies" section of this report, the limits and negative impacts of these technologies are described.

> ***Digital technologies will never be a silver bullet to the societal challenges of implementing the circular economy in practice.***

Following the literature review of the three circular economy approaches and the digital technologies that can enable their acceleration in the short term, a variety of experts from the public and private sector, academia, coalitions and civil society were engaged to prioritize, define and strengthen the recommendations. The expert group provided granular insights and further precision on the role of key digital technologies in the circular economy, their critical functions, the barriers faced by circular economy approaches and the implementation of digital technologies within these, as well as short-term solutions to overcome the latter barriers.

03

Circular economy approaches

This section elaborates on each of the three circular economy approaches. For each one, the critical functions of digital technologies (data collection, analysis and dissemination) required for their scaling in the short term are highlighted. The key digital technologies best suited to fulfil these functions are identified and illustrated with real-life examples. Finally, the most significant barriers are described and connected to the short-term solutions needed to overcome them.

Approach 1: Rethink product design and manufacturing

This approach focuses on reducing, rethinking, refusing and redesigning within product design and manufacturing processes, and would benefit significantly from harnessing digital technologies in the short term. It aims to increase production efficiency by consuming fewer natural resources, such as energy and water, and materials (Reduce). It seeks to fundamentally transform how a function or value is delivered (Rethink), leading to significant change in product and service design and production processes. Such a shift can be illustrated by the development of a circular business model called product-service systems, in which companies offer the function of a product, instead of the product itself, transforming fundamentally their ownership model. Another emerging tenet of this approach is not only to change the product or its ownership but also the user behaviour around it. This can be done by refusing the use of certain products and materials, so as to reduce wasteful behaviours (Refuse) or by redesigning the product and services surrounding it, to steer users towards a more sustainable use of a product (Redesign). An example of this is product-service systems which encourage more sustainable behaviour in consumers (Figure 3).

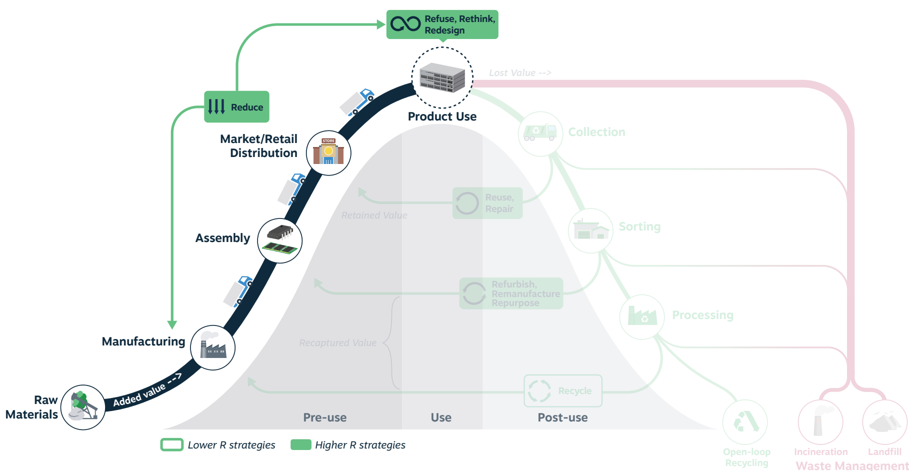


Figure 3: Adapted Value Hill Model with the 9R Framework

Source: Buren, N., Demmers, M., Heijden, R. and Witlox, F. (2016); Circle Economy (2016); Kirchherr, J., Reike, D, and Hekkert, M. (2017); Potting, J., Hekkert, M., Worrell, E. and Hanemaaijer, A. (2017) ©Metabolic Institute

Critical functions and key digital technologies

This circular economy approach was highlighted as the one that would benefit the most in the short term from digital technologies. Specific digital technologies will be considered in relation to their ability to perform such critical functions along the design and manufacturing stages of the value chain.

Data analysis has emerged as the most critical function of digital technologies in rethinking product design and manufacturing. Digital capabilities such as monitoring, optimization, forecasting and track and trace are seen as pivotal to reduce energy and material consumption during manufacturing processes, as well as test new circular business models, such as product-service systems, that necessitate different product designs.

A change of ownership model from product to service provision necessitates the integration of new digitally-enabled methods to monitor the status of products during their life cycles. This would, by and large, improve energy and resource efficiency through optimization (Cagno et al. 2021) during the manufacturing processes, but also throughout the product life cycle, thanks to improved design. Such optimization and improved design is the predominant goal of the application of Industry 4.0 technologies and processes within this circular economy approach (Oztemel and Gursev 2020).

Digital technologies can structurally support the research, development and redesign processes through the development of digital prototypes (e.g. simulated digital twin) that test suitable renewable material (raw or recycled) or embed circular design into new products at the design and manufacturing stages**.**

> ***There is a need to further explore how digital technologies, through their interactions with consumers, can influence user behaviours towards circular and sustainable consumption patterns***

Additionally, data analysis using simulation techniques can help identify novel value creation opportunities for the innovative design of future products and services (Getor, Mishra and Ramudhin 2020; Ghoreishi and Happonen 2020). The capacity of digital technologies to support innovation based on the discoveries and creations stemming from their analytical results is a key function for the circulatory integration into design and manufacturing processes.

Finally, thanks to integration of digitally-connected monitoring systems embedded within products at the design and manufacturing stages, and in the context of product-service systems, the monitoring of a products' condition and customers' activities can be ensured and used to lengthen each product's lifespan (see approach 2 on lifespan extension).

Circular and digitally-connected products are increasingly aiming to change usage behaviour by making closer connections between consumers and companies through effective communications of sustainability information.

Ultimately, an important aim of new product design could be, under certain circumstances, to change the linear consumption habits of customers and nudge them to adopt sustainable behaviours (Kurniawan et al. 2021).

This can be achieved by focusing on sustainability and circularity communication, through embedding information at the design and manufacturing stages to encourage repair or about recyclable materials, the environmental impacts of products or clear discard information for circular end-of-life solutions (Huynh 2021). There is a need to further explore how digital technologies, through their interactions with consumers, can influence user behaviours towards circular and sustainable consumption patterns.

Of critical concern is data collection and availability of information to feed data analytics, as this is a stepping stone in rethinking and redesigning products and services, and to reap the benefits of digital technologies, such as Artificial Intelligence (AI), Internet of Things (IoT) and Big Data Analytics (BDA). The collection of data during the manufacturing process generated by various heterogeneous sources is fundamental to both analysis and communication. With no or little data, there is no application possible of Big Data Analytics and most (but not all) AI methods would be very limited in their usefulness to support design and manufacturing decision-making processes.

The digital technologies most frequently cited as the most suited to successfully fulfil these functions of data collection, analysis and communications, and therefore the most promising to harness to scale this circular economy approach, are outlined below**.**

Artificial Intelligence can gather, analyse and interpret complex environmental data and information to understand issues during the design and manufacturing process and prioritize action, such as refusing the use of certain products and materials**.**

AI is different from data analysis in that it is often used to build models based on existing data to predict future outcomes or to classify objects and situations. Not every data analysis has to use AI to gather insights but many applications of AI do need data.

AI can be central in rethinking and redesigning circular strategies. For instance, catalytic upgrading of biowaste to chemicals and fuels can be aided through combining multiscale computational techniques and machine learning (Lieder et al. 2020). Embedding AI applications during the design process in equipment used in the agrifood industry includes predicting the resource and energy needs, such as greenhouse lighting, which can guide the design of new production and manufacturing lines or farming design arrangements.

AI-powered technologies also enable businesses to optimize the value chain and better predict the availability of waste materials and the demand for refined goods in the marketplace, thus, if used consciously, supporting decision-making during the design and manufacturing phases, and potentially reducing waste. For example, Google uses AI to cut down the cooling bill of their data centres by up to 40 per cent. As a result, AI has the potential to optimize and reduce energy and resource consumption in industries, such as energy, agriculture, housing or mobility.

Finally, AI technologies can be used to democratize sustainability knowledge, enabling us to drive changes in our processes and behaviours towards patterns that benefit our planet (McKinsey 2018). Since AI is capable of learning from experience, it can provide companies and others with the necessary support to implement, validate and test circular economy solutions.

Case study on Artificial Intelligence: Winnow

Winnow is using AI technology in the Foodtech branch to cut food waste in commercial kitchens in half. Its solution offers a food waste software that could also offer significant cost and sustainability benefits to organizations producing food. Daily and weekly reporting plus access to Winnow Hub identifies savings opportunities and allows food producers to reduce the procurement of certain food products and rethink the way they prepare and produce food.

Internet of Things devices give the possibility to connect products and services in real-time and monitor the performance of assets and processes, which can lead to decisions (sometimes automated) to smartly reduce their consumption of resources.

IoT technologies enable businesses to rethink their operation and focus on product-service systems, a central circular business model in this approach (Alcayaga, Wiener and Hansen 2019). By adding sensors to their products, such as Radio-Frequency Identification Devices (RFID) chips, a rising application of IoT, they facilitate the transition of companies towards a product-service system by tracking their assets in real-time (Garrido-Hidalgo *et al.* 2020). Rental service businesses, such as Swapfiets, allow customers to rent bicycles instead of purchasing them, with the option to 'swap' whenever a repair is required. This has been made possible by ensuring the security of the bicycles through RFID tagging. This prevents theft and loss, which has built the customers' trust in rent-based services, leading to behavioural change.

New ownership models are now allowing consumers to buy 'products-as-a-service', on a per-use-basis, thereby offering consumers the option to 'refuse' the purchasing of one-time products. For example, Bundles owns washing machines and leases them directly to consumers. It has established a per-use pricing system, which has the potential to reduce the number of times the washing machine is used. As the business owns the machine itself, and the consumer has simply procured a service, the ownership model encourages the business to make the washing machine last as long as possible.

Case study on Internet of Things: Algramo

Algramo uses IoT dispensing machines to offer a refill service for soap. All the packaging used through their platform is equipped with an RFID chip that links the plastic bottle present in the dispensers and the soap product one wishes to purchase. Their system allows them to track purchased goods, the expiration date and the amount of plastic waste prevented. Through their innovative IoT solutions, they are able to reduce plastic waste as customers reuse their plastic bottles.

Big Data Analytics' leading benefit is the optimization of processes to increase efficiency and reliability in the production system while reducing emissions and material and energy consumption. BDA is able to use the data gained from customers' behaviour, product usage as well as production processes to identify insights and opportunities for improved efficient resource use (Ghasemaghaei and Calic 2019). For example, supermarkets increasingly use BDA to estimate demand for their products and reduce over-ordering of food, which prevents food waste (Ovchinnikov 2022).

Big Data reduces the complexity of generating insights from the data and increases the understanding of the optimal set of actions based on descriptive, prescriptive and predictive data insights. For example, UPS, the world's largest package delivery company, uses Big Data to calculate the optimal routes for its drivers, reducing by millions the number of kilometres travelled (Discover Data Science 2021). This optimization not only reduces unnecessary environmental pollution, but it helps the company avoid unnecessary resource use such as fuel costs and wages.

Case Study on BDA: Swapfiets - Mobility

Swapfiets uses data on how their products are used and how they break to improve the design of their bikes. Swapfiets has their own repair shops and when a broken bike comes in they write down what has been broken. Based on this data they have decided to move the luggage carrier to the front of the bike and have changed to an open chain guard. As a result, their bikes break less often on average.

Barriers and short-term solutions in rethinking product design and manufacturing

Business Model Lock-In	Global Standards and Coalitions
Value proposition: linear value chains do not necessarily see the value in changing the business model towards product-service systems, and may be de-incentivized by current market distortions driven by perverse subsidies that cause extractive thinking.	Consistent global regulatory framework regarding eco-design criteria for digitally-connected product design and manufacturing.
Infrastructural lock-in: supply chains have been designed to be linear, especially manufacturing systems.	Expand coalition-building efforts, such as CIRPASS and other digital product passport initiatives, around data transparency and robust but practical security standards on data handling and data privacy.
Adoption of data collection systems	**Data Infrastructure Enabling Conditions**
Adoption of data collection systems is slow and inconsistent, leading to data gaps and poor data quality limiting data analysis activities needed for the development of smart products.	Unlocking data silos by establishing norms for sharing and collecting data through supply chain-specific agreements and protocols.
High Initial Costs and Investment Uncertainty	**Financing the Transition**
High initial costs for technological innovation to rethink smart product design and manufacturing innovation, often causes uncertainty about financial returns, which may lead to a lack of confidence and funding.	Financial instruments such as blended finance and investment guarantees, that consider social and environmental externalities, and public-private funding collaboration to de-risk and incentivize financial investments in new circular manufacturing and product-service systems.
Businesses may be reluctant to invest in digital technologies to pivot their business model towards digitally-enabled circular business models due to the fear of the quick obsolescence of these technologies that may offer only short-term competitive advantage.	Public-private innovation funds to promote the use of digital technologies to rethink product design and manufacturing, where the most promising circular economy strategies are rewarded with funding.
Lack of awareness and skills	**Education and consumer behaviour**
Limited understanding of benefits of smart products and processes by both businesses and consumers.	Educational programmes to increase the future workforce's ability to integrate digital technologies and their green skills in implementing circular design principles in their industries.
Lack of skills on circular design principles to develop novel products.	Awareness campaigns and communications around behaviour change, alternative sustainable consumption (e.g. alternative e-commerce models) and ownership models (e.g. product-service systems).
Lack of standards and cohesive policy landscape	**Incentive mechanisms and regulatory pressures**
Policy lags behind for the application of digital technologies to support the rethinking of smart product design and manufacturing.	Shifting taxes from labour to raw materials. This can incentivize the reduction in material use and allow more room for digital innovation by making work less expensive.
Lack of standards on smart circular products and processes across value chains, creating confusion and possibly greenwashing.	Digital Product Passport: global policies, similar to the mandatory European legislation, requiring product information disclosures to stimulate circularity and ensure sustainable product standards are met.

Approach 2: Extend the lifespan of products and their parts

This approach focuses primarily on the use-phase of products' life cycles, with a strong emphasis on extending the useful lifetime of the products' original function through life-extension circular processes. Products that have passed a critical threshold in their ability to deliver their original function and value can be collected, sorted and reintegrated in an alternative use-phase with either an adjusted or an altogether different function through remanufacturing or repurposing activities. Extending the lifetime of products is a critical goal of the circular economy to reduce the throughput of new products entering the economy and therefore leading to a reduction of natural resources consumption. Some types of business models like product-service systems may encourage the extension of a product's lifespan, such as through reuse and repair models. This approach was highlighted as the second approach that would benefit the most from integration of digital technologies as they perform a variety of critical functions which can scale this approach (Figure 4).

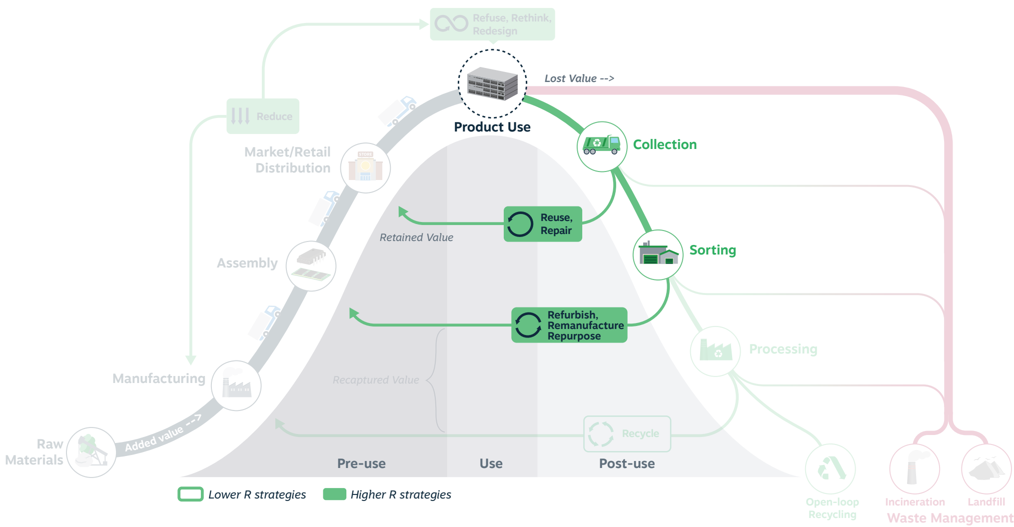


Figure 4: Adapted Value Hill Model with the 9R Framework

Source: Buren, N., Demmers, M., Heijden, R. and Witlox, F. (2016); Circle Economy (2016); Kirchherr, J., Reike, D, and Hekkert, M. (2017); Potting, J., Hekkert, M., Worrell, E. and Hanemaaijer, A. (2017) ©Metabolic Institute

Critical functions and key digital technologies

Specific digital technologies will be considered in relation to their ability to extend the lifespan of products and their parts, and how these technologies can perform such critical functions along the product use, collection and sorting stages of the value chain.

Data analysis has been highlighted as the core function required to support the scaling of the different strategies leading to the extension of a product's useful lifetime. Digital capabilities, especially detection, monitoring and forecasting, are requirements to extend the lifespan of products. Digital systems can detect failure early on, and carry out predictive, prescriptive and customized maintenance tasks on products before they actually fail or break, supporting the repair and refurbishing processes put in place by circular organizations (Akkad and Banyai 2020). Beyond supporting repair activities, digital technologies can help extend the lifespan of functioning parts that are part of non-functional products by identifying them in these products and finding suitable uses in both similar and different products. Track and Trace capabilities are therefore critical to provide in real-time the location and availability of used products and their parts (Vetrova and Ivanova 2021). Digital technologies can then build innovative solutions that support the development of industrial symbioses by finding and connecting used products with local industrial processes to repurpose them into useful parts for new (and different) products. By providing a clear and real-time view of the inventory of used products and their parts, decision-making on remanufacturing activities can be optimized, allowing these parts to be reintegrated into the value chain more efficiently, in turn minimizing waste and material consumption.

Moreover, within this circular economy approach, data collection and integration plays an important role in fostering industrial collaboration by collecting and sharing the data and information required to perform remanufacturing, refurbishing and repair activities. For example, data is collected on the type, quantity of input materials and waste, and location, and shared between industries in the same area that are not usually in contact, to support real-time waste-to-resource matching and reducing uncertainty of used parts and products' availability (Zeiss *et al.* 2020). Finally, through reselling and sharing used products (on for instance second-hand markets) through digital platforms and marketplaces, the lifespan of used products in good condition can be extended through reuse. Data collection and integration is necessary to support relocating reusable products through providing their geographic location and detailed information about their state (collecting and sharing data), to provide transparent information on the items purchased to second-hand customers (Rocca *et al.* 2020).

Communicating and disseminating sustainability and circularity information is seen as an equally critical function as that of data collection. Digital technologies can *connect* customers with companies, providing to both parties information on wear and tear and maintenance status of products to help arrange personalized repair, refurbishing and remanufacturing options (Moreno *et al.* 2018). Furthermore, it can nudge customers to start maintaining their products thanks to technical digital assistance from companies. Finally, the communication and dissemination of data is critical to connect potential second-hand buyers to used products by accelerating the information exchange process, therefore facilitating the reuse of assets and material resources.

The digital technologies most frequently cited to fulfil the critical functions of data collection, analysis and communications were BDA, IoT and AI. Blockchain, usually ranked after these three technologies in terms of importance, still appeared to be a (re)emergent technology, specifically useful for its capabilities of secure data sharing and transfer.

Big Data Analytics plays an increasingly critical role for the entire emerging reverse logistics industry by generating insights from large amounts of data and increasing the understanding of the optimal set of actions. This, in turn, enables remanufacturing, and reuse of parts or components at the end of the product's life (Awan *et al.* 2021).

Through the use of Big Data (often in combination with IoTs), unexpected insights about user behaviours can be revealed, leading to providing customers with customized products, specialized maintenance, and repair and refurbishment services through remote online diagnostics services, and the provision of key spare parts, extending the lifespan of the product. Core to these post-sales and reverse logistics processes is the ability of BDA to provide reliable time estimates of maintenance and repair activities for companies, enabling them to optimize their overall process.

Finally, Big Data can strengthen business-to-business relationships to establish a circular value chain, with increased insights into their production and manufacturing processes to spare part suppliers and raw material suppliers.

Case study on Big Data Analytics: Madaster - Built Environment material passport

The Madaster foundation is a platform that provides openly available material passports for buildings. Their objective is to stimulate the circular economy by providing methods on reusing and remanufacturing building parts and data on the materials used in buildings. By making information available on what materials are stored in buildings, it should make the reuse of these materials easier. The platform can automatically generate a materials passport, a circularity report and an emissions report based on the analysis of the large amounts of data it is given.

Internet of Things (embedded sensors) can be used by companies to reduce uncertainties faced during remanufacturing to monitor and track their assets, and help achieve efficient planning of operations, which is critical to reduce costs. Practically, real-time information of manufacturing resources is sensed and captured by a network of sensors. When abnormal events occur, they can be sensed and the maintenance, remanufacture or repair plan is scheduled automatically (in real-time scheduling).

Additionally, sensors can help prevent damage during product dismantling, and optimize value creation during remanufacturing. For instance, General Electric's transportation division gathers performance data from sensors attached to locomotive engines while they are in use to determine whether parts and products need a full or partial makeover. This automation process has reduced costs during locomotive rebuild (Alcayaga *et al.* 2019).

Finally, the ability of IoT to track products and their parts in the supply chain is key to enable circular value chains and support the development of industrial symbiosis. This is because remanufacturers are able to track the product status, and estimate through environmental sensors the expected residual life of each smart component, leading to efficient decisions on prolonging products' lifetimes.

Case study on IoT: BOTTO - IoT solution for food waste

Botto is an IoT technology product-service that facilitates the flow of communication between food wholesalers, local producers, a donation association (RECUP) and the Italian Red Cross for tracking surplus fruit and vegetables. The device is similar to a remote control designed to provide wholesalers and local producers in Milan with a quick and easy way to communicate what and how much of their surpluses can become a donation, simply by pressing a button. Botto sends the message to a digital platform monitored by a Telegram Bot, which reports the new donations, and facilitates the redistribution (and reuse) of selected goods in less than 30 minutes.

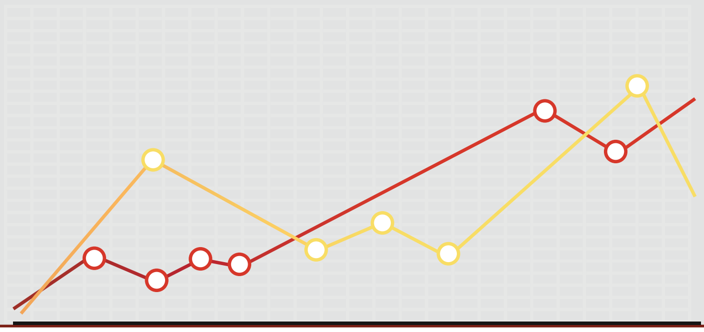
Artificial Intelligence allows computers to recognize patterns in data and apply the knowledge of these patterns to other data sets. AI can be used to support repair activities by extending machines and products' lifespan through predictive and prescriptive maintenance models built by machine learning. This leads to customized maintenance tasks being carried out on devices before any actual failure happens.

AI has the potential to capture and model urban data, forming digital twins of buildings. For instance, a digital twin combines IoT and AI with spatial network diagrams to create real-time digital simulation models of urban landscapes. These models are then used to specify how construction elements could be reused, remanufactured or repurposed for other buildings (Chen and Huang 2020).

Within reverse logistics systems, AI can identify and recognize old parts of machinery or vehicles based on their appearance and features such as weight, volume, shape, size and colour characteristics, and also customer data, such as use frequency and usage wear-and-tear patterns. By speeding up the process of identification and reducing risks of misidentifying components, this technology can facilitate the remanufacturing of these elements into new products.

Case study on AI: Éxxita Be Circular - AI-powered marketplace

Éxxita Be Circular uses AI to predict recoverability and repairability of electronic products with a material passport. Éxxita Be Circular uses data on previously tracked products to estimate these characteristics. This system allows for more product reuse by estimating what the product needs.



Blockchain is an immutable, tamper-proof distributed ledger technology (DLT), which is utilized in a shared and synchronized environment where all transactions are validated by users and that enables material and product tracing throughout their life cycle. While the hype of the technology has dwindled, and concerns about its high energy consumption remain, Blockchain still appears as a useful tool in the digital infrastructure required for the circular economy.

Due to its record-keeping and anti-tampering capabilities, the technology can support full traceability, combined with reliable and verifiable information of both products that can enter the second-hand market for reuse and used components that can enter remanufacturing processes. The products and components can safely be reintegrated in the value chain since each action along the value chain can be registered, and stamped and validated by a third-party.

The integration of Blockchain is increasingly visible in high-end secondary markets for luxury clothes (Bloomberg 2021) or items such as diamonds, avoiding counterfeiting and facilitating the reuse of products. Finally, Blockchain has been increasingly establishing itself in the construction industry. Through the establishment of a material passport describing the characteristics of the components of a building, it provides the key data and information needed for reusability and recycling programmes and circularity performance management.

Case study on Blockchain: Telefónica Tech - Building trust in the second-hand market

Telefónica Tech uses Blockchain to create a digital product passport for electronic equipment. Individual products can be traced through the system. One of the goals of the platform is to encourage reuse of these products by building trust in the state of the products, for instance by describing the repair and refurbishing history. Buyers also have access to this information so the product's origin is fully transparent. Blockchain technology allows the organizations to recover more than half a million devices per year.

Barriers and short-term solutions for extending the lifespan of products and their parts

Revenue Model Disruption	International initiatives to build both business and consumer trust
Increasing the lifespan of a product through repair or remanufacturing may lead to a reduction in sales of new items, a primary revenue generator.	Gold-standard framework, built on existing initiatives, such as GAIA-X and Digital Product Passports, to set binding standards for data collection and sharing across value chains to specifically allow for repair, repurpose, refurbishing and remanufacturing activities.
Business scepticism due to a lack of awareness of existing successful examples of using digital technologies to support lifespan extension processes.	Public awareness campaign on how the lifespan of products can be extended and aimed at changing consumers' perceptions of second-hand products.
Data collection bottlenecks and interoperability challenges	Support future technological integration
Poor data quality and availability due to the slow roll-out of data collection and data storage technologies (e.g. IoT, Blockchain) are hampering the development of analytics by digital technologies (e.g. BDA, AI).	Technological standards for Research & Development in technologies to ensure the physical and digital interoperability of new technologies, and anti-obsolescence practices.
A lack of data collection and safe information-sharing infrastructure limits reuse, repair and remanufacturing activities since without key information, these activities cannot safely or efficiently take place.	Beyond the hype, research Blockchain as key digital technology to support upcoming initiatives, such as Digital Product Passports.
Lack of 'physical' interoperability between technologies limits their repairability and remanufacturing potential. The lack of 'digital' interoperability limits synergies between multiple technologies such as IoT, AI and BDA, hampering data flow and analytics-based decision-making for repair and remanufacturing actions.	
Reverse Logistics upfront costs	Reducing risks through financial support and incentivizing circular purchasing
High initial costs of setting up reverse logistics for remanufacturing activities reduces the speed of adoption of reverse logistics systems.	Proposals for subsidies and tax reduction schemes incentivizing the establishment of reverse logistics.
	Proposals for the reduction or removal of the VAT for second-hand products that have been repaired, refurbished or remanufactured.
Contradicting skills trends and consumer perception	Empowering an emerging workforce
A decline in 'traditional' repair and refurbishing skills limits the expansion of these activities.	Public awareness campaigns to revalorize trade and circular labour skills such as repair, remanufacturing and refurbishing.
Lack of trained personnel to match the emerging skills needed within an organization to implement digital technologies in repurpose, remanufacturing and refurbishing activities.	Fund new educational programmes targeted as skills for the emerging reverse logistics industry.

Public perception of second-hand, repaired or remanufactured products is often negative as they are seen as substandard products compared to new products.	Tools to support the development and financing of professional digital upskilling programmes in the repair, refurbishing and (re)manufacturing industry.
Lack of standards and cohesive policy landscape	Advancing policies to influence business behaviours
Stringent policies and fragmented global guidelines on waste management render difficult the use of used products in reuse, remanufacturing or refurbishing processes since they are often considered as 'waste' as soon as they exit the linear value chain.	Proposals beyond Extended Producer Responsibility, to make companies responsible (beyond voluntary standards) for providing maintenance, repair, remanufacturing and refurbishing services.
	Review and update waste management policies to strengthen lifespan extension pathways by removing some barriers on waste utilization.

Glass bootles sorted for recycling. Photo Credits: Furkanvari, Pexels.com

Approach 3: Effective reuse of material

This circular economy approach focuses on the post-use phase of a product's lifecycle. There is a strong focus on maintaining the value of the materials within a product and this is often achieved by recycling a product. When the lifespan of a product can no longer be extended, the value of the materials making up the product should be maintained as much as possible. This is done through collecting, sorting and processing further the material of the products into new feedstock for the same or an alternative industry. This approach increases the longevity of materials, increases the value they bring to society and reduces the economy's dependence on new raw materials. It is important to note that recycling should be the last resort in an ideal circular economy (Figure 5).

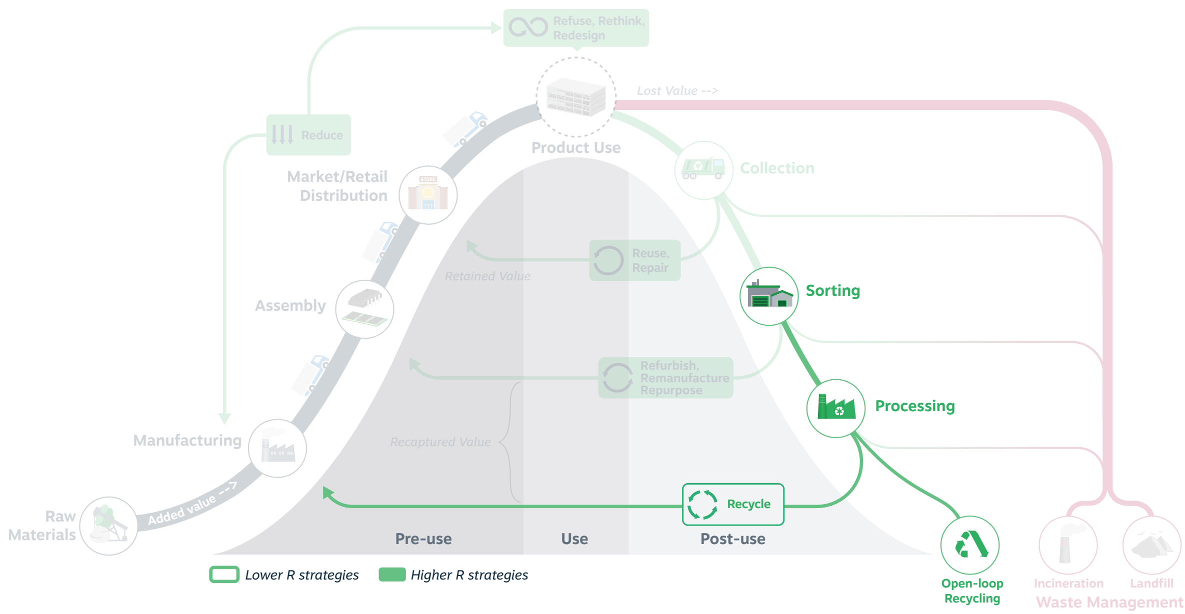


Figure 5: Adapted Value Hill Model with the 9R Framework

Source: Buren, N., Demmers, M., Heijden, R. and Witlox, F. (2016); Circle Economy (2016); Kirchherr, J., Reike, D, and Hekkert, M. (2017); Potting, J., Hekkert, M., Worrell, E. and Hanemaaijer, A. (2017) ©Metabolic Institute

Critical functions and key digital technologies

Specific digital technologies will be considered in relation to their ability to perform such critical functions along the waste management stages of the value chain (sorting, processing, re-introduction into the value chain and end-of-life).

Data collection and analysis are critical functions for, in particular, sorting and classification, which are essential in identifying materials and directing them towards adequate recycling processes (Wilts *et al.* 2021). Data can be used in effectively helping to separate waste, deciding whether an item should be reused, repaired, refurbished, remanufactured, recycled or disposed, and as such should be considered as critical in increasing the efficiency of these processes. This also includes detecting the types of materials present in products by using analytical digital technologies, especially when the bill-of-material of the products is not present (Laskurain-Iturbe *et al.* 2021).

By and large, digital technologies' ability to increase the flow of data along value chains can support the overall efficiency of the reverse logistics supply chain. By tracking and tracing wastes, the locations and conditions of used products and wastes can be monitored in real-time, accelerating decision-making through better planning, reducing waste and therefore increasing material recovery.

For instance, an increasing number of waste collectors and managers are using planning routes, scheduling waste collection and transport, based on both IoT sensors placed directly on the bins, or by analysing large amounts of waste collection data and user behaviours (Dev, Shankar and Qaiser 2020).

> ***Digital technologies' ability to increase the flow of data along value chains can support the overall efficiency of the reverse logistics supply chain.***

Through data analytics, waste streams may be *forecasted* with increasing precision and innovative end-of-life options can be derived based on material types and rate of collection. This allows for more effective waste collection and waste management which in turn could be used by decision-makers to change their policy based on the expected waste generation.

Additionally, data analytics can help by automating waste collection processes, such as using self-driving vehicles or by automatically sorting incoming waste through automated robotics assistance, which can increase the effectiveness of material retrieval (Gordon 2021). Instant data analytics, through technologies such as AI, can support the use of recycled feedstock into new applications and products by supporting new manufacturing processes for re-introduction of materials into value chains, such as additive manufacturing.

Finally, communication and dissemination of sustainability and circularity information is gaining importance in increasing general awareness of the public on why and how the effective reuse of materials should be increased.

The digital technologies described as most apt to fulfil these digital functions of data collection, analysis and communications successfully were BDA, Additive Manufacturing and AI.

Big Data Analytics, with its collection of analytical methods, tools and applications, can increase the overall effectiveness of the reverse logistics and recycling processes. By analysing the origin, amounts and frequency of waste generation, BDA can support the planning of waste collector truck fleets and help forecast the collection and processing capacity required to perform waste management activities.

Finally, BDA can analyse waste feedstocks and the patterns surrounding their recyclability to inform product design and future manufacturing activities to increase overall recyclability performance (Part 1).

Case study on Big Data Analytics: Saint-Gobain - Built Environment recycling

Saint-Gobain uses automated measurements and their models to estimate the amount of materials needed for a construction project. Their service called Material@Hand allows for combining the Saint-Gobain material offering with a service that enables assessment of material needs, customized production and scheduled delivery. By rethinking their production design, they are able to save up to 50 per cent of waste according to their own estimates. The gathered data for the initial construction of a building could also be used to more easily recycle used materials when a building is demolished.

Artificial Intelligence applications like computer vision can be used to automatically identify objects. This capability is especially useful during the sorting process of different waste streams and can direct used materials towards the appropriate recycling processes (Wilts *et al.* 2021).

As a specific example, AI can further refine and improve processes of additive manufacturing. This entails manufacturing an object through the successive addition of material. This is opposite to the more common 'subtractive' manufacturing process that starts with a mass of material and removes material until the intended form is created.

This technology, while still in its early stages, provides an avenue for the efficient use of recycled material feedstock, especially plastics, into new products, components and even building parts (Sanchez *et al.* 2020). As such, it significantly enlarges the application of recycled feedstock into a variety of industries, strengthening the value creation and proposition of the recycling industry. AI may be specifically used in the sorting and quality control of waste materials for additive manufacturing purposes (Isi 2023).

Case study on AI: KeyMakr - Waste sorting

Keymakr offers data-creation technology and annotation tools for computer vision-based AI. One of their services uses computer vision to automatically identify and classify waste, which makes it easier to sort the waste into the right bins after it has been thrown away. Robots can use this information to sort the waste appropriately. This vital technology can increase the efficiency of waste management, keep workers safe from harmful materials and protect the environment. Keymakr can, among other waste sectors, be employed in the electronics sector, where electronic waste can be sorted using AI so it can be recycled appropriately.

Barriers and short-term solutions for effectively reusing materials

Uncertain demand for recycled materials	International standards and coalitions
The demand for recycled materials is highly fluctuating leading to uncertain revenue streams.	International standards on data transparency and reporting on recycled materials and their origins.
The return-on-investment and cost-benefits analysis of integrating digital technologies in the collection, sorting and recycling activities is unclear.	
Adoption of data collection systems	**Maturity of promising technologies**
The lack of data collection, data sharing and clear material classification among value chain actors leads to products with unknown material content limiting the potential recycling opportunities.	Develop further Research & Development trajectories of additive manufacturing to ensure practical feasibility at scale.
	Perform clear return-on-investment studies on technologies, such as AI, IoT and BDA in the waste logistics and waste management industry.
Low margins	**Financial incentives and deterrences**
Investing in digital technologies is difficult due to the low profit margins in the recycling industry.	Proposals to reduce VAT on products that use a minimum content of recycled material feedstock.
	Proposals to increase customs tariffs and taxes on virgin feedstocks while providing tax break on recycled feedstocks.
Digital gap in the recycling industry	**Digital upskilling**
The workforce in the recycling industry is often very manual. They therefore need to be upskilled to integrate digital tools in their daily activities.	Develop and finance digital upskilling programmes in the recycling industry - from waste sorters to logistics planners, and waste management decision-makers.
Organizations in the recycling industry have limited access (network-wise and financially) to people with the required digital expertise to implement these changes.	Develop match-making programmes to ensure that the waste logistics and recycling industries are connected with the emerging digital workforce.
Volatile policy environment	**Policies for the effective use of material**
Global policies on waste and recycling (e.g. ban on waste imports) evolve swiftly, making the supply chain brittle and discouraging long-term investment.	Customs requirements and regulatory tools such as Digital Product Passports increasingly set ambitious thresholds of recycled content for products and components, based on industry-per-industry agreements.
Stringent policies on the use of recycled feedstock for health and safety concerns may discourage their innovative application in new products.	Proposals to evolve policies and regulations to recognize waste materials - especially e-waste as commodities.

Transmitter tower. Photo Credits: William Carvalho, Pexels.com

04

Cautionary tale of digital technologies

While digitalization provides the solution to many of the barriers in accelerating the shift to a circular economy, a holistic perspective must be taken when implementing digital solutions to avoid adverse effects and burden shifting.

Below we pose a few examples of sustainability challenges as they pertain to the current state of digital technologies. The clear recommendation of this report is that emphasis is placed on the sustainability of the digital technologies themselves when harnessed in accelerating the circular economy. As such, to be truly sustainable, any innovative solutions for digitally-enabled circular approaches and business models must critically address and improve the sustainability and circularity of the proposed technology itself.

The variety of environmental risks that are the consequence of an increase in production of electronic and electric equipment, as well as their use to facilitate digitalization, must be considered. An increase in hardware for digitalization and technological innovation requires increased input of natural resources and critical materials from an ever-shrinking pool. A lack of circular procurement will pose a risk to resource availability. While the pool of resources is shrinking, it is also affected by a variety of other factors such as geopolitics and unforeseen events like supply chain disruptions due to COVID-19, increasing demands for minerals of the renewable energy sector and natural disasters (Babbitt 2021).

20%

Projected increase in global electricty use on ICT by 2030

As the move towards cloud computing, Blockchain and other energy-intensive technologies increases, the demand for energy to power data centres and ICT will also increase, as well as water to cool such systems. ICT currently accounts for approximately 5–9 per cent of global electricity use but this is projected to increase to approximately 20 per cent by 2030. ICT also emits around 1.8–3.9 per cent of global greenhouse gases (GHG), depending on the scope of estimations of various sources, and is largely attributed to the consumption of energy at data centres and the use-phase (EPC 2020; Freitag et al. 2021). Meanwhile, water cooling of data centres consumes the equivalent of 120,000 Olympic-sized swimming pools per year (0.2–0.8 L per kWh), contributing to global water stress (Andrews *et al.* 2021).

E-waste is the fastest growing waste stream in the world. In 2019 an estimated 53.6 million metric tons of e-waste was generated globally, of which only 17.4 per cent was collected for recycling. Since 2014, the global generation of e-waste has grown by 9.2 million metric tons (Mt) (21 per cent) (Global e-waste monitor 2020). Landfilling also results in the leakage of hazardous substances into the environment and pollutes the soil and water (EPC 2020). Increasing e-waste brings with it challenges around its transboundary movement. E-waste is shipped to low-income countries for waste management due to high costs of end-of-life waste management practices. Transboundary flow of e-waste has a variety of serious environmental and health implications in the destination countries (Thapa *et al.* 2022).

Apart from the environmental risks posed by digital technologies, there are also social challenges that need to be de-risked. Access to the benefits of digitalization is not felt equally across and within all populations. It is estimated that about 3.6 billion people, or 47 per cent of the world's population, remain totally unconnected to the Internet (UN's Broadband Commission for Sustainable Development 2020), and they are often located in low-density or low-income areas that are not as profitable for digital businesses to provide services and build infrastructure (Internet Society 2022). As a result, this has led to a slower rate of growth of new people connecting to the Internet and an overall stagnation of the digital divide. The digital divide means that wealthy nations have better access to the benefits of digitalization. Digital technology is susceptible to other risks associated with information security and may also pose health risks to users such as radiation exposure (EPC 2020).

With the increase in the use of digital technologies, such as the use of AI for targeted advertising and nudging, comes the risk of hyper- and overconsumption, putting further pressure on our natural resources and environmental systems (Kingaby 2021). While this risk is becoming increasingly evident, more scientific research is needed to further understand the concrete effects of AI and other digital technologies on hyper- and overconsumption patterns, and how these technologies may be used instead to reverse current negative trends in this regard towards more conscious and sustainable consumption.

05

Critical path

This report has highlighted the key functions of digital technologies that are critical for the scaling of the three main circular economy approaches. A set of digital technologies were illustrated as the most suited to deliver these functions, and therefore will be key to integrate further in the short term. Nevertheless, there are barriers that both affect the use of these digital technologies in the circular economy and the development of the circular approaches themselves, beyond technological bottlenecks, that first must be addressed to unlock the full potential of the digitalization of the circular economy. Solutions have been identified based on evidence from the literature and insights from the expert group.

This concluding section outlines an urgent critical path synthesizing solutions across the three approaches into practical recommendations for both the private and public sector to be addressed in the short term. With these, this critical path paves an enabling environment for harnessing digital technologies to unleash the full potential of the circular economy.

Private sector

Recommendation 1: Set data collection and data management standards to strengthen circular value chains
Circular value chains are inherently more information-intensive than traditional value chains. They require data to function well and produce more data across each life stage. To meet these new requirements, organizations must build value-chain specific coalitions and standards around data collection and sharing agreements, and practical security standards on data handling and data privacy. This can be done in collaboration with intergovernmental organizations, such as the United Nations, and using existing public and private initiatives such as Digital Product Passports and GAIA X as blueprints.

Recommendation 2: Further enhance technological interoperability and capabilities to support circular economy approaches and business models
Interoperability of data and technology across value chains is a necessity to allow circular models to flourish. Organizations must ensure communication between different digital technologies applied across life stages and sectors. This will require further development in the application models of digital technologies for each circular economy approach. Building an integrated technological system truly tailored to circular needs will be critical.

Recommendation 3a: Invest in digital innovation for the circular economy
Create innovation and impact funds and programmes with public-private partnerships and industry leaders across the value chains within high-impact sectors such as food, mobility, textiles, electronics and the built environment. The aim for such funds should be to promote the use of digital technologies for the circular economy, through (i) rethinking product design and manufacturing, (ii) the extension of products' lifespans, and (iii) the effective reuse of materials. The most promising initiatives may be rewarded with innovative funding mechanisms, such as blended finance, impact-based finance, outcome-based finance and investment guarantees.

Recommendation 3b: Design business models for a digital circular economy
Organizations should perform clear return-on-investment assessments on the use of digital technologies to support their shift towards reverse logistics, product-service system operations and digitized circular strategies - inclusive of forward-thinking policy trends that will affect their business in the short to medium term. The development of new business models should be grounded in these assessments to most efficiently deploy digital technologies to support their circular transition.

Recommendation 3c: Pilot test digitally enabled circular business models
Organizations should develop private sector-led pilot programmes on digitally enabled circular business models. Business models could include switching from products to services, sharing economies, virgin-to-secondary materials and right to repair models, such as Extended Producer Responsibility for products with the added services of maintenance, repair and refurbishing during the full life cycle of their products.

Recommendation 4a: Upskill current workforce and future digital talent acquisition
Organizations should invest in digital upskilling programmes for their existing workforce in the repair, remanufacturing and recycling industries, at all levels in the organization to avoid labour shortages in the short term. In parallel, companies should develop pipelines of talents to accelerate the inflow of a digitally-trained workforce in the design, manufacturing, reverse logistics industry, second-hand and waste industries.

Recommendation 4b: Support behavioural change through digital technologies

In collaboration with public and research entities, organizations should explore how current digital techniques can be used to spur behaviour change at the consumer level towards sustainable and circular consumption. Different digital methods of providing supply chain transparency and sustainability information for e-commerce platforms or digital labelling should be tested and assessed based on their effects on consumers' purchasing and use behaviours. The One Planet Network's guidelines for providing product sustainability information in e-commerce should be considered a key resource (One Planet Network 2022).

Recommendation 5: Standardize product information disclosure practices
Based on market research, companies and industry associations should form proposals for standardized product information disclosure practices (such as Digital Product Passports) to stimulate circular practices in their respective industries.

Public sector

Recommendation 1: Position data transparency as a global common good
With intergovernmental organizations, and in collaboration with industry leaders, develop a proposal for a global regulatory framework on data transparency, specifically tailored to address data requirements for repair, repurpose, refurbishing and remanufacturing activities and to build transparency on eco-design claims and recycled material use and origins.

Recommendation 2: Set standards for digital interoperability and physical interchangeability
With technological leaders, develop standards for Research & Development (R&D) in technologies to ensure digital interoperability to support upcoming initiatives (e.g. Digital Product Passports in the EU) and the physical interchangeability of new hardware technologies (e.g. the EU's common charger directive) to limit the unnecessary generation of e-waste. These standards should ensure that the digital technologies that are increasingly integrated into circular value chains do not generate additional waste.

Recommendation 3a: Develop a new financial toolkit to fundamentally accelerate the circular economy transition
Develop a future-proof financial toolkit to evolve the taxation and subsidies systems to accelerate the transition. The spectrum of new tools should encompass proposals that include (i) a shift from taxes from labour to raw material consumption for producers and manufacturers; (ii) a reduction in VAT for retailers and service providers of circular products and services; (iii) subsidies to encourage reverse logistics; and (iv) customs tariffs that favour the import of products made of recycled materials over virgin feedstocks.

Recommendation 3b: Reinforce the value proposition of circular models with policy levers
To support businesses in operationalizing circular and regeneration-based business models, national governments and pan-governmental organizations should develop specific policy instruments in collaboration with local civil societies. These should reinforce the value proposition of localized circular models and position them in the regional and national circular strategies. This effort should include outreach activities targeting companies to raise their awareness on how existing and upcoming policy levers can help them shift their value proposition towards circularity.

Recommendation 4a: Educate the new generation of digital workers

Public organizations should develop secondary-education and continued education programmes, especially in STEM education and social and humanities programmes, to increase the future and current workforce's ability to integrate digital technologies and adopt circular design principles in their respective industries. Digital sustainability should be embedded in these curriculums.

Recommendation 4b: Consumer awareness of circular economy in practice

Intergovernmental organizations should create an international campaign to raise awareness on (i) alternative circular consumption models (e.g. alternative sustainable e-commerce models); (ii) ownership models (e.g. product-service systems); and (iii) lifespan extension pathways (e.g. repair and remanufacture).

Recommendation 5: Align policies and technologies' development for the digital circular economy

Regulatory public bodies should develop proposals to evolve policies and regulations to (i) extend the definition of Extended Producer Responsibility to include responsibilities for providing maintenance, repair, remanufacturing and refurbishing services; (ii) recognize waste materials (e.g. e-waste) as commodities; (iii) strengthen lifespan extension pathways by removing barriers on waste utilization; and (iv) promote standardized product information disclosures, for example Digital Product Passports.

06

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