VTT Technical Research Centre of Finland

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Digital technologies for circular manufacturing

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Summary

The manufacturing industry is undergoing some significant transformations. One example is the shift from exclusive to shared ownership of products and services. Furthermore, the scarcity of natural resources is leading to more circular approaches to manufacturing. The manufacturing industry needs to become greener and more digital while remaining competitive on the global stage. Intelligent use of production assets, resources and materials lies at the core of a circular economy. Circular manufacturing is providing the means for increasing resource efficiency and reducing the use of natural resources. A circular economy mainly contributes to overcoming environmental challenges via implementing various R-cycles, such as reduce, repair, recycle, remanufacture, to mention a few.

The purpose of this white paper is to provide an overview of circular manufacturing, especially the opportunities for utilising digital technologies in circular manufacturing's nine R-cycles (9Rs). Additionally, it presents the integration of digital technologies and 9Rs from four different perspectives – risk and safety, waste hierarchy, additive manufacturing and life cycle assessment – as well as in two different proof-of-concepts (PoCs) related to data sharing for the purpose of achieving sustainability goals.

This white paper is written by researchers from three complementary research areas (Cognitive Production Industry, Safe and Connected Society and Foresight-driven Business Strategies) at the Technical Research Centre of Finland Ltd. (VTT).

Contents

I. Introduction

It is imperative for the manufacturing industry to contribute to the UN sustainability development goals (SDGs) (United Nations, 2015) by reducing its waste and emissions and usage of water, energy and virgin materials. For example, one-fifth of the total greenhouse gas emissions worldwide is generated by manufacturing and construction (World Bank, 2017). There should be a drastic change towards sustainability, as pointed out

Raw materials currently represent the largest individual cost incurred by manufacturing companies in the European Union (EU), accounting for up to 40% of their total expenditure. Inefficiencies in raw material use account for up to €630bn in annual economic losses[1]. At the same time, global crises, such as the COVID-19 pandemic and the Ukrainian conflict, are driving the shift to more resilient operations within company supply chains, including securing critical raw material sourcing. Considering these two related drivers, it is crucial for the EU to develop sociotechnical frameworks and methods for facilitating resource circularity.

The green and digital transition (twin transition), which is transforming Europe towards a green, digital and resilient economy, is creating the basis for this work. We especially perceive a circular economy (CE) as a vehicle towards sustainability, by providing frameworks and methods for resource reuse (Schroeder et al., 2019). Normally circularity aims to improve sustainability. In practice, the impact of circular solutions on sustainability is not implicit but must always be ensured. The Finnish Ministry of Economic Affairs and Employment (2022) conducted an extensive study on the digitalisation and ecosystems of a CE. However, the study "was not able to discover any existing, effective ways to collect, manage, share and utilise circular economy data to support decision-making" (Työ- ja elinkeinoministeriö et al., 2022). Still, Finland aims to play the leader role in implementing twin transition in Europe (Työ- ja elinkeinoministeriö, 2022). In this white paper, we present potential digital technologies for supporting circular manufacturing at a more practical level by providing examples and use cases.

The goals of the project behind this white paper are as follows:

1. to understand the relations among sustainable manufacturing, a CE and R-cycles;
2. to identify the digital technologies that help achieve sustainability goals; and
3. to identify the topics and opportunities for future research.

First, we aim to build a framework for understanding the relations between sustainable manufacturing and circular manufacturing, as well as digital technologies better. Second, we aim to create an understanding of digital technology opportunities while implementing 9Rs for circular manufacturing. Additionally, the most relevant potential digital technology building blocks are described as means for achieving sustainable solutions. Third, we conduct a more in-depth study of digital technologies and their applicability to 9Rs from four different perspectives: risk and safety, waste hierarchy, additive manufacturing (AM) and life-cycle assessment (LCA). Fourth, we develop two different proof-of-concepts (PoCs) for testing the suitability of digital technologies for selected Rs.

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[1] https://rmis.jrc.ec.europa.eu/uploads/CRMs_for_Strategic_Technologies_and_Sectors_in_the_EU_2020.pdf

Circular manufacturing

Although the UN SDGs have three pillars (economic, environmental and social) (United Nations, 2015), the majority of the activities considered in the manufacturing industry still pay attention purely to the economic goals. The ongoing climate change has put the environmental aspects on the agenda. Unfortunately, the social aspects are hardly considered. The common actions of sustainable manufacturing involve decreasing material usage, energy consumption, greenhouse gas emissions and the creation of unwanted by-products, while maintaining or improving the value of products.

A CE mainly contributes to overcoming the environmental challenges via implementing various R-cycles, such as reduce, repair, recycle, remanufacture, to mention a few. Kauppila et al. (2022) classify the R-cycles into three categories, where the weakest level focuses on useful applications of materials (recycle and recover). At the next level, the R-cycles focus on the extension of the product life cycle (repurpose, remanufacture, refurbish, reborn, repair and reuse). At the highest level, the objective includes both smart manufacturing and product usage (reduce, rethink and refuse).

The twin transition combines digitalisation and green transition and creates a green, digital and resilient economy as digital technologies enable the circular strategies of the manufacturing industry (Kristoffersen et al., 2020). According to Orko et al. (2022), the positive impacts on the sustainability of manufacturing can be achieved by

- increasing data sharing and the use of artificial intelligence (AI),
- using digital products and services, instead of physical products, as much as possible (digital twins, simulations, etc.),
- exploiting information and communication technology (ICT) solutions for energy and material consumption optimisation, and
- developing (and applying) sustainability tools and methods.

R-cycles

R-cycles started with recycle, followed by reuse and reduce (3Rs). Table 1 summarises most of the R-cycles found in the literature (Kauppila et al., 2022). The circularity increases, starting from the bottom of this table, that is, useful applications of materials. At the second level, the R-cycles focus on the extension of the product life cycle. At the highest level, the objective includes both smart manufacturing and product usage. Furthermore, it is reasonable to assume that some new R-cycles will appear.

Different R-cycles implement circularity at different product life cycle phases. The CE aims to retain the value of a product and its materials as long as possible. This sets the general preference of different R-cycles (Table 1). First, it should be considered whether the product could be replaced with another more sustainable solution. Next, the production and use of the product should be made as sustainable as possible. Then, the life of the product should be extended as long as possible with reuse, repair, refurbish, remanufacture and repurpose (in this order). Finally, at the end-of-life phase of the product, the recyclable materials should be recycled, and the energy content of non-recyclable materials should be recovered.

Table 1. 9R framework (adopted from Kauppila et al., 2022).

Goal	R-cycle	Description
Smarter product use and manufacturing	R0 Refuse	Make a product redundant by abandoning its function or by offering the same function with a radically different product.
	R1 Rethink	Make product use more intensive (e.g., by sharing the product).
	R2 Reduce	Increase efficiency in product manufacturing or use by consuming fewer natural resources and materials.
Extended lifespan of product and its parts	R3 Reuse	Allow another consumer to reuse a discarded product, which is still in good condition and fulfils its original function.
	R4 Repair	Repair and maintain a defective product, so it can be used according to its original function.
	R5 Refurbish / Reborn	Restore an old product and bring it up to date.
	R6 Remanufacture	Use parts of a discarded product in a new product with the same function.
	R7 Repurpose	Use a discarded product or its parts in a new product with a different function.
Useful application of materials	R8 Recycle	Return a used material to obtain the same (high grade) or lower (low grade) quality of the product.
	R9 Recover	Incinerate a used material, with energy recovery.

Digital technologies as enablers of circular manufacturing

Digital technologies, such as the Industrial Internet of Things (IIoT), big data and data analytics, are considered essential enablers of the CE in the manufacturing industry (Kristoffersen et al., 2020). Additionally, Traficom and Deloitte (2022) list five technologies that will contribute to the SDGs: i) AI, algorithms and machine learning; ii) blockchains; iii) robotics and autonomous systems; iv) quantum technology; and v) augmented reality (AR) and virtual reality (VR). The most relevant ICTs, such as AI, AM, AR or VR, blockchain and web3, data spaces, digital twin (DT), IIoT and metaverse, are briefly described next.

Artificial intelligence

AI refers to the algorithms that simulate human intelligence in decision-making situations. The fields of AI include expert systems, fuzzy logic, robotics, genetic programming and neural networks.

Machine learning (ML) denotes the algorithms where the programmer does not have to define the rules. Instead, the programmer presents the algorithm with a large number of examples (e.g., here are 1000 examples of cat photos; here are 1000 photos without cats; learn to distinguish the cat photos from the other photos), and the algorithm “learns” the correct decisions from the examples. Thus, the human programmer does not have to know or define the “catness” in the cat photos; the ML algorithm learns this from the data (= cat photos).

Lately, using the neural network ML algorithms has turned out to be the most fruitful approach in many applications. They have started to dominate the AI field because much more teaching data (social media, cheap sensors), more computing power (graphic processors can be used) and better algorithms are available now than previously.

Additive manufacturing

AM involves technologies that build three-dimensional (3D) objects layer by layer by using data from computer-aided design (CAD) software or a 3D object. The software creates still files that slice the object into thin layers. The process is carried out in a powder bed by recoating and bonding each powder layer to the previous layer through selective melting or adding a binder, which will subsequently be removed, and the object will be sintered to form a solid structure. Another way is to directly deposit each layer, using a feeder and a nozzle, on the substrate to create a 3D object. In the case of deposition techniques, both the powder and the wire can be used as raw materials. Concerning circular manufacturing and especially repairing, the deposition technique is more suitable for gaining the needed advantages.

Augmented reality or virtual reality

AR and VR are related but offer different kinds of advantages. The advantage of VR is that information can be presented in the relevant context. For instance, instead of reading from a table that the temperature in pipe ABC123 is 55° C, the temperature can be printed on top of that pipe model in VR. Currently, almost all design is done in 3D anyway, so the additional effort of creating such VR models is relatively minimal.

In AR, the viewpoint on the VR model is set to be the same as the user’s viewpoint in the real world. So, when a technician looks at pipe ABC123, the temperature value (55° C) can be printed on top of the real pipe. Usually, this requires advanced information filtering (e.g., based on the user role), or there will be too much information to present clearly. However, in our example, the AR view can provide much help to a pipe engineer, who can see not only the visible pipes but also has a kind of X-ray vision that enables him/her to see the pipes inside the walls, too.

For the user (e.g., a maintenance technician in a factory environment), the best approach is to combine VR and AR. In AR, the user can look around to see what is going on in the machines around him/her, whereas in VR, the user can teleport to other locations in the factory, without having to walk there. The easy and seamless switch between these two modes is essential.

VR can especially be used to train people, for example, to learn using machinery in the most efficient way to minimise resource usage. In contrast, AR is often used to help maintenance personnel in their tasks; for example, the part to be removed next is highlighted in AR, with animations showing the bolts that must be opened.

Blockchain and Web3

Web3 can be perceived as the next step in the evolution of the World Wide Web. It incorporates a vast array of technologies, of which blockchain technology is the most prominent. Additionally, smart contracts, tokens, decentralised autonomous applications and organisations, as well as decentralised identities (DIDs) and metaverse, are covered by the Web3 umbrella. Blockchain provides immutable shared data records and well-documented data management processes.

In the CE, these capabilities are useful in ensuring the origins of materials and components, adding to the transparency of supply chains and verifying companies' responsibility reporting data. Besides the blockchain, other Web3 technologies also assist in increasing trust and self-sovereignty in a digital environment. Combined with token-based economics, Web3 reinforces trusted decentralised business ecosystems and novel grassroot-level incentivisation, which can be very valuable, especially in the CE context. DIDs[2] are already well under way in their standardisation process and can constitute a crucial part of product identifiers in the future.

Data spaces

Introduced in 2020, the European strategy for data presents the idea of a single market for data to ensure competitiveness and data sovereignty. For the purpose of materialising the idea, the concept of European dataspaces was presented. After three years, there are already nine data spaces (e.g., industrial, mobility, health, energy, agriculture), whose interoperability will be guaranteed with several coordination actions and standardised data sharing. The key principle of data spaces involves keeping users in control of their data, which encourages companies to share data more in diverse business networks. International Data Spaces (IDS)[3] and the federated data infrastructure Gaia-X[4] are significant European initiatives, which produce tools and services for trusted data sharing (Otto, 2022). Especially, Gaia-X has decentralised architecture, which utilises many Web3-based mechanisms.

For the CE, data spaces provide data interoperability and an environment for more secure data sharing. The Green Deal Data Space also aims to support environmental actions related to climate change, pollution, biodiversity and deforestation, as well as to the CE. The Green Deal Data Space still seems to be at the emergent phase, but the The Green Deal Data Space Foundation and its Community of Practice (GREAT) project[5] targets delivering the roadmap for implementing and deploying the Green Deal Data Space.

Digital twin

A DT means that all the available information held by a device or a plant (throughout its lifetime) is attached to the VR model of the device or the plant (using Microsoft's old slogan: "Information at your fingertips"). Thus, besides design–time information (as designed vs. as built), maintenance information, user notes, and so on, are also attached and available through a single portal. When all this information is available to decision makers, maintenance engineers, and so on, the decision making will be much easier. It is also possible to make the DT of each product, thus simulating even minor differences in each of the products manufactured in the production line.

DTs range from comprehensive models to limited digital simulations of their physical counterparts. Currently, there are aims to provide more comprehensive DTs, utilising physics and human behaviour. In some European roadmaps, DTs are expected to be comprehensive, even single sources of truth, but in reality, a lot of research and development (R&D) has to be done before DTs can fulfil this role.

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[2] https://www.w3.org/TR/did-core/

[3] https://internationaldataspaces.org/

[4] https://gaia-x.eu/

[5] https://www.egi.eu/project/great-project/

Industrial Internet of Things (and sensor networks)

The IIoT refers to a system of interconnected sensors, instruments and other devices, networked together with computers' industrial applications, including manufacturing and energy management. This connectivity allows real-time data collection, exchange and analysis, potentially facilitating improvements in productivity and efficiency, as well as other economic benefits. These benefits may be obtained by means of improved product or service delivery, a productivity boost, reduced labour costs, decreased energy consumption and a shorter build-to-order cycle (Boyes et al., 2018).

The IIoT is enabled by technologies, such as cybersecurity, cloud computing, edge computing, mobile technologies, machine-to-machine interfaces, 3D printing, advanced robotics, big data, internet of things, radio frequency identification (RFID) technology and cognitive computing (Brauner et al., 2022).

Metaverse

When the idea of combining VR and AR is taken to the extreme, metaverse is the outcome. We have a 3D model of the whole world, updated in real time. If privacy issues are resolved, individual people can be there as avatars, too. All people can wear goggles, which can switch from AR to VR to real-world modes. In the AR mode, the user can view all digital information on top of the real world. In the VR mode, the user can "teleport" to any location in the world (and meet one's friends as avatars). In the real-world mode, people see the world like we do now. In the VR mode, historical information can also be available, so people can move across time if they wish. Currently, the best 3D models of many historical locations are in the computer game Assassin's Creed.

The metaverse of the whole world can take a long time to arrive, but AR/VR/metaverse techniques can already be applied to factory environments now. Valmet and VTT have already published some industrial PoCs[6] (in Finnish).

Circularity of manufacturing companies

Companies' present CE activities were collected through qualitative interviews and analysed through the CE maturity matrix, comprising five maturity levels mapped with seven linear manufacturing value-chain phases (Saari et al., 2021). The matrix was piloted with nine manufacturing companies, of which four were based in Finland, one in Italy, one in Germany and three in Ireland. The interview results are summarised in Table 2. The majority of the hits (25) are at the systemic resource management level, as resource efficiency has long been a recognised goal of the manufacturing industry.

In **product design,** material and energy efficiency are important design parameters for every company. Two companies at systemic level are also considering disassembly and thus already tapping the CE thinking level. Another two companies have already reached CE thinking since i) their metallic products can be repaired, remanufactured, refurbished and reborn, and ii) the environmental impact assessment is a driving force. The only company at the circular level is a textile manufacturing start-up, born to be circular. It follows eco-design principles by using 3D design software and precise client-like avatars.

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[6] https://yle.fi/a/74-20015271?utm_source=social-media-share&utm_medium=social&utm_campaign=ylefiapp

Table 2. Summary of nine companies' circular economy (CE) matrix results.

	Linearity	Industrial CE piloting	Systemic resource management	CE thinking	Circularity
Product design		2	3	2	1
Sourcing		3	3	3	
Production		3	4	2	
Logistics		2	2	4	1
Marketing and sales			6	2	1
Product use		3	1	4	1
End of life		1	5		2
	0	**14**	**25**	**17**	**6**

In **sourcing,** the three middle levels catch three companies each. One company has selected the piloting level, although its mineral sourcing is already systemic, and the social impact is caught via the environmental programmes of its suppliers. Another company sources long-life lithium batteries from products that have reached the end of their first life. Three companies have selected the systemic resource management as their amount of waste is minimised. The CE thinking level is explained by i) a transparent and traceable supply chain and ii) careful monitoring of the partners to whom production is outsourced or by iii) reverse logistics.

In **production,** most of the companies were assessed at the systemic resource management level. Three companies have selected the piloting level because of process improvements, for example, recycling processed water and chemicals in a closed loop, minimising energy consumption or performing the LCA. Usually, the losses in the production process are monitored at the systemic level. Furthermore, energy consumption, emissions and other environmental impacts are on the development agenda. The CE thinking level indicates implemented R-cycles, such as reconfigure, reuse and recycle, in a closed loop.

In **logistics,** one company has chosen the piloting level as it does not trust the data and forecasts provided by its logistics partners. The CE piloting level has been chosen because of the ongoing pilot experiment focusing on developing a long-life lithium battery management system that enables secure removal, collection, sorting and discharging of waste batteries. The systemic resource management level is explained via i) the most sustainable packaging, ii) minimal transportation of raw materials and waste or iii) optimal shipping with lower emissions. At the CE thinking level, the traceability of products is implemented. The highest level, circularity, is reached because the value chains are local (three companies), the transparency of products and of production characteristics is enabled (one company), and product-as-a-service business models (another company) are employed.

Marketing and sales remain at the systemic level or above. One company confesses that the origins of the materials, the workforce and production sites are followed mainly for quality reasons. Furthermore, the reason for the CE pilots is the company's brand image. In four companies, the CE thinking level is within reach because of i) customer-specific carbon footprint calculations, ii) sustainability demonstrations implemented or considered together with LCAs, and because iii) transparency is explored among their supply chain partners. One company is positioned at the circularity level since it offers transparency to its clients. Two companies have reached the circularity level because of their handprint goal. The handprint indicates focus on positive impacts together with partners instead of decreasing negative impacts (footprint).

Product usage is at the CE thinking level in four companies as the extended life cycle of their products is realised by updating and repairing these products during their usage and by producing high-quality long-lasting products. Two companies are chasing the circularity level because their maintenance contract business models based on the usage of a product are either offered or considered. Three companies still occupy the industrial piloting level. One company has reached the circularity level as the development of its food manufacturing components is prompting business model innovations.

The end-of-life (EoL) phase remains at the systemic resource management level in over half of the companies (five) as their products, by-products and waste are reused, but the zero defect is not their driving target. One company has totally skipped this phase, considering it inapplicable to subcontractors. One textile company and a food manufacturing company are positioned at the circularity level since their business models are based on circularity and on minimising environmental, social and economic impacts.

The good news is that according to our study, none of the companies remains at the linearity level. There are several phases (sourcing, production, logistics, use and EoL) where pilots are ongoing instead of systemic resource management. Furthermore, there are already several hits at the circularity level, in phases such as product design, logistics, marketing and sales, product use and EoL. Still, the most popular level is systemic resource management, followed by CE thinking.

II. Value loops of circular manufacturing

Circular manufacturing has often been studied from the economic perspective, identifying new business models, novel business approaches and opportunities when moving from traditional manufacturing to manufacturing that utilises circular approaches. The CE is therefore closely related to the platform economy that allows multiple actors to operate with different abilities. In this paper, we focus on identifying the digital technologies perceived as essential when moving towards circular manufacturing. We have defined a simple value loop describing the positions of the R-cycles, as illustrated in Figure 1.

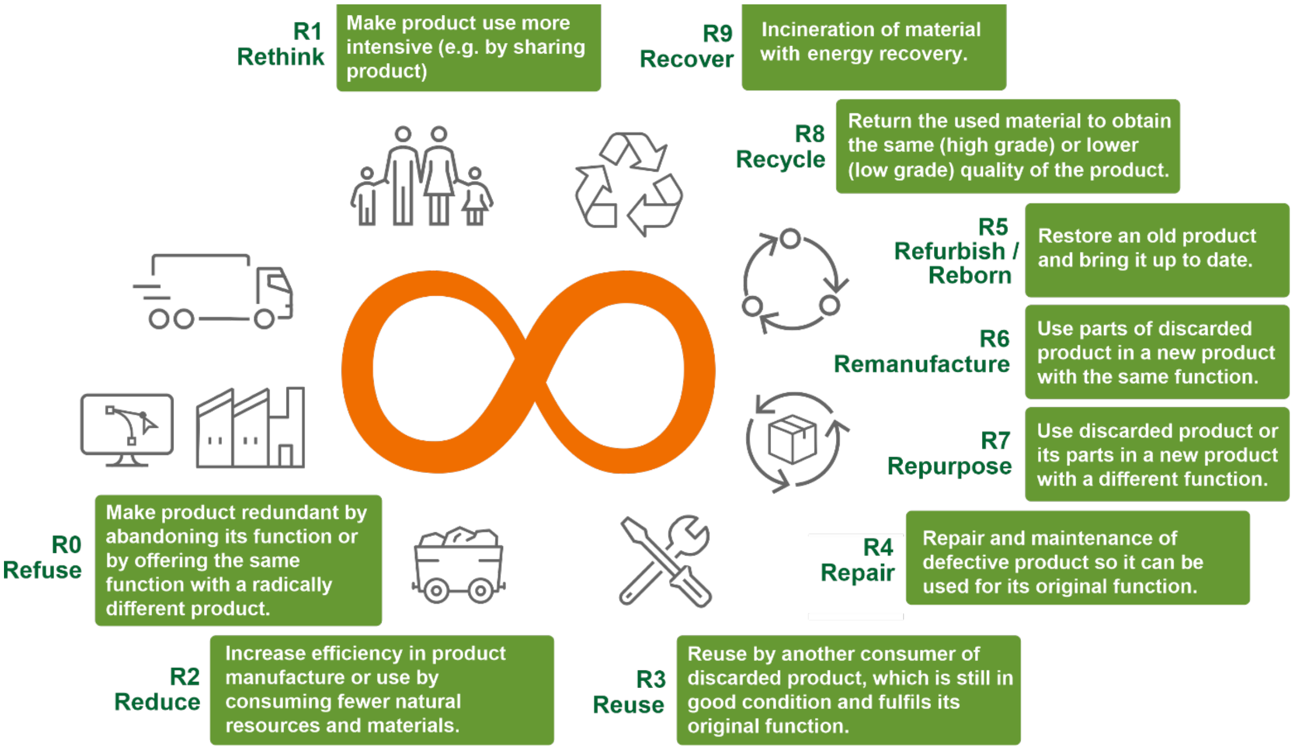


Figure 1. Simple value loop with the Rs (inspired by VEOLIA, 2020).

The left side of Figure 1 shows the typical manufacturing process, consisting of the supply chain of raw materials, manufacturing and R&D and logistics for the user. In this part of the loop, the typical R-cycles of circular manufacturing consist of developing a completely new product that replaces the old one, increasing efficiency in material and resource utilisation and supporting product use via sharing or multifunctionality.

On the right side of the value loop, we have several means of extending the lifespan of the product and dissolving it to reuse the materials obtained. These include reuse, repair and refurbishing of the product, remanufacturing and repurposing it, and at the end of the product life cycle, recycling and recovery.

The CE maturity matrix offers the means to understanding where a company is on its CE path. As the CE is a complex issue, often dealing with inter-organisational operators, the value loop aims to create a link between selected technologies and their impacts on the R-cycles and the level or research needed. For example, some of the technologies may support a large set of Rs, whereas others focus on specific Rs, which in turn may be essential for a specific company moving on the CE path, as defined in the CE maturity matrix. Furthermore, some technologies may be mature enough that the research is focused more on adding value to already existing solutions, while sometimes, technologies are only approaching markets; thus, more research is needed. Some potential technologies for three selected R-cycles are described next.

Digital enablers of three R-cycles

Circular manufacturing is dependent on several key enabling technologies (KETs). However, the selection of technologies within different R-cycles is not trivial, as different technology combinations have varying synergies, based on the objectives of each R-cycle. In this work, we first set out to collect a raw data table between KETs and R-cycles. VTT researchers involved in three different research areas contributed to the table, based on their technological backgrounds. Based on the table, a simple heatmap analysis in terms of the technology appearance in relation to a certain R-cycle was performed to find which technology groupings would appear relevant. Finally, three sample scenarios were derived to better describe the R-cycle–technology relation and to represent a higher level of abstraction compared with the raw data table. The main objectives of the scenario work were to illustrate and concretise the synergies between R-cycles and KETs and to identify future research themes. The selected three scenarios, that is, sharing (rethinking), repairing and recycling, are connected to several product life cycle phases – not only to manufacturing. However, the link to manufacturing is also strong. The potential KETs are highlighted in **bold** for each scenario – sharing, repairing and recycling.

Smarter use and manufacturing of the product: Sharing scenario

Sharing means the temporary use of the same product by different users. The shared product may be owned by one or more users (e.g., car sharing), the sharing organiser (e.g., online forums for electric scooter drivers, libraries) or a third party. One form of sharing applies the product-as-a-service concept. For manufacturing, sharing activities provide the following:

- opportunity to collect data and feedback about product use, user experiences and durability in several use cases;
- natural long-term contact point for users;
- need and opportunity to produce high-quality and higher-value products, since in sharing, the focus is inherently on life cycle costs; and
- decreased need to manufacture new products, which will be compensated by higher-value products, thus saving materials and avoiding negative environmental impacts.

Sharing utilises **digital platforms,** especially digital marketplaces for reservation, payment, locating products, user identification, delivering instructions or information about repair or other services, collecting and sharing user feedback and data about product use, and so on. The **digital product passport (DPP)** is a means to manage all product-related information. The manufacturer will produce the basic product information, but the collected user experience information may also be managed with the DPP. **Optimised logistics is** essential for the environmentally and economically effective use of the shared product. **Positioning technology** may be used to locate the current position of the product. This is essential for sharing mobile devices. It is also useful for security reasons when sharing any product. **Security solutions** are required for user identification, product locking and release, information security and ensuring the General Data Protection Regulation (GDPR) compliance. The management of the sharing service requires **product and service (production) management systems.** The sharing service and its marketing may be developed with **data analysis and ML,** based on the product use and user experience information.

Extending the product life: Repairing scenario

Repairing is the process in which the condition of a defective product is restored (returned) so that it can be (sufficiently) used for its original purpose. Repairing a product includes several challenging phases, including cleaning, fault diagnostics, dismantling, actual repairing, reassembly and testing. As a service and a circular operation, repair also includes some logistics and customer contacts. Remanufacturing is a specific combination of repair and manufacturing, producing new products by using used and repaired components.

Repairing is an essential activity for a manufacturer. For manufacturing, a repair service provides the following:

- information related to product weaknesses for supporting product development;
- natural contact point for users of the product to maintain customership; and
- additional business, decreasing the need to manufacture new products, thus saving materials and avoiding negative environmental impacts.

The information related to all phases of the repair process may be managed with a **DPP.** This includes product design documentation, spare part information, repairer information, repair guidance, safety information, fault and repair history, and so on. A **data-sharing platform** utilising the federated data space principles can be used for collecting and sharing DPP information. In this regard, it is essential to ensure that the information is relevant, sufficient, accurate and verified, thus also applying **security solutions***.* **AR** solutions can be used to provide guidance for the repairers, and **cobots or exoskeletons** may be employed to aid them physically. The components' state of health may be **diagnosed with different sensing technologies**, providing information about the need for repair before the actual failure.

Fault diagnostic technologies may be used to support repair. Continuously complementing a fault diagnostic database could be managed via a DPP, for example. The database would include the original guidance by the manufacturer and information about the actual faults, their symptoms and the fixing provided by repairers of the product. A learning AI solution using the database could provide support in the diagnostics. **DT solutions** could be applied for fault diagnosis, too.

Dismantling of the product for repairing without causing any harm requires knowledge about what should and should not be done. Continuously complementing the database with guidelines, experiences, hints and warnings concerning dismantling may be managed with a **DPP**. **AR solutions** could provide online guidance for dismantling, and dismantling may also be automated with **robot or cobot solutions***.*

Information about spare parts, spare part providers, part manufacturers and repairers may be managed with a **DPP***.* Information about (among others) the materials and dimensions needed for repairing components may be managed with a DPP**. AM, for example, 3D printing,** may be used for repairing as well as for manufacturing new parts, instead of or in addition to other manufacturing technologies.

The production line for new products may be used for reassembling repaired products if the **production management system** is sophisticated enough.

Useful application of the materials: Recycling scenario

Recycling is the process in which discarded products are collected and processed to obtain the materials to be used in new products. For manufacturing, recycling provides materials to replace virgin materials. Compared with virgin materials, recycled materials, in many cases,

- are environmentally better options,
- are socially more sustainable because of the unethical production of many virgin materials and
- at first hand, ensure the availability of rare materials and eventually, the availability of all materials.

Different discarded products are separately collected, for example, paper, glass, electronics, textiles, plastics, biowaste, and so on. Identification of materials, sorting products according to their materials and recovery of materials are essential phases of recycling. Different technologies, such as **machine vision, near infrared (NIR) and hyperspectral imaging, combined with data analytics and ML,** can be used to identify and sort different products and materials. Sorting and recovery processes apply **solutions for automatic material handling,** as well as **process and chemical technology** solutions. Product and material identification can also be based on a **DPP**.

Optimised logistics is important for minimising both the costs and environmental impacts of recycling material transfers. **Digital marketplaces** are used for dealing in recycled materials. Residual materials may be used with **AM techniques** instead of the traditional material recycling.

III. Mapping digital technologies with 9Rs

Several aspects need to be considered when mapping digital technologies and the 9Rs, as well as determining which technologies could support the deployment of an R-cycle. Although circularity is a key driver in achieving economic goals, there might be conflicts among circular activities. Reverse supply chains might not be given much notice from circularity perspectives. From the digital technology development perspectives, AM can create advantages in remanufacturing and repairing. Additionally, an overall sustainability evaluation of the 9Rs would be beneficial. These vantage points are discussed in more detail in the next section.

Conflicts among circular activities

Circularity is mostly presented as a solution for sustainability, highlighting its opportunities and advantages. The challenges and risks of circularity have been rarely studied, but we have found some studies and reviews of challenges in circularity (e.g., Corvellec et al., 2022; Sehnem et al., 2019).

In real circularity solutions, it should be remembered that **the most sustainable options in design and production and the question of whether to extend a product's life or recycle it depends on the specific arrangements, situation and context,** not on the circularity strategy as such. There can be certain conflicts among different sustainability and circularity targets or on whether extending the product's life is more sustainable than recycling it. Figure 2 presents examples of possible conflicts among different circular activities.

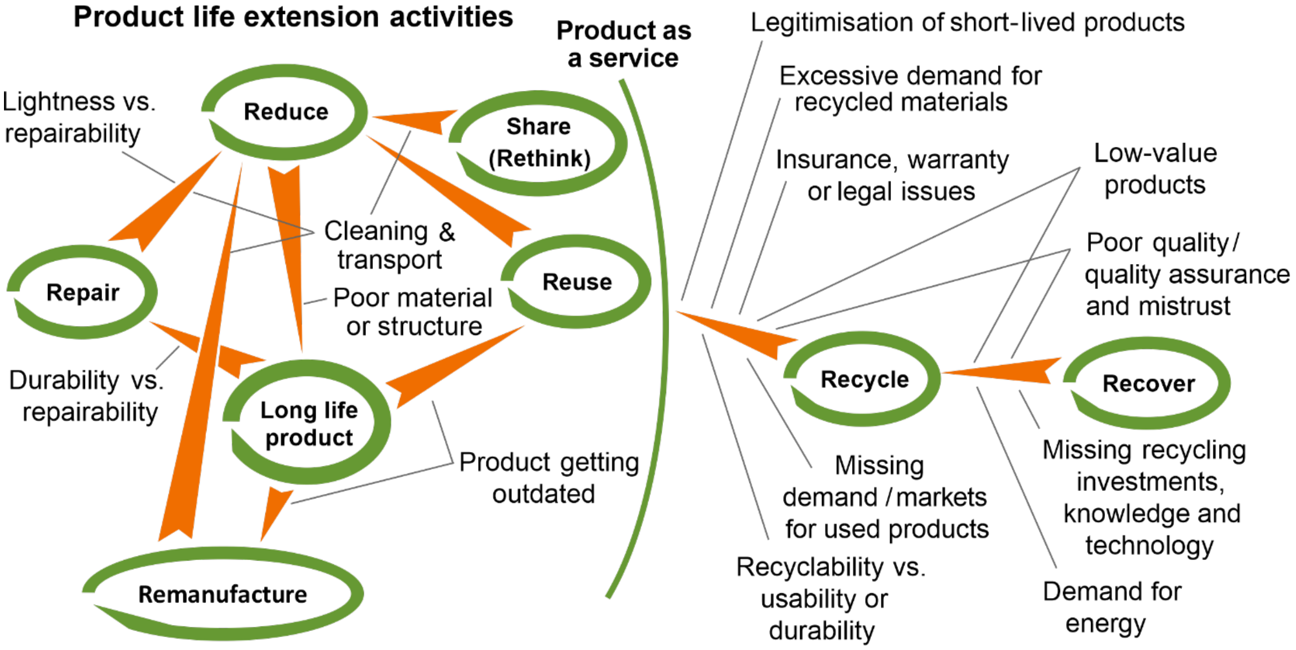


Figure 2. Potential conflicts among different circular activities.

The examples about conflicts and problems leading to fewer outcomes are as follows:

- **Reduction** in product material amount or lighter structure may lead to a **less durable, ineffective or unrepairable** product, shortening its **life**.

- **Repair, reuse, sharing and remanufacturing** may have a positive effect on sustainability because of **reduced** production. However, the positive effect may be overridden by the needs for (additional) cleaning and transportation.
- Durable materials and structures that extend a product's life may be difficult to **repair** (e.g., a component attached by welding).
- Old **long-life** products may be less sustainable in their **use** than new products, more difficult to repair, and so on. However, remanufacturing may enable updating the product.
- The aim of **recycling** is not to extend a product's (or a component's) life but to reuse the materials obtained from discarded products for the production of new products. A conflict may emerge if recycling is perceived as a sufficient solution for sustainability, thus legitimising the growing consumption of **short-lived** products.
- An excessive demand for **recycled** materials may lead to a situation that exerts a pressure to recycle reusable or repairable products – or even new products.
- Due to insurance, warranty or legal issues, a product may not be **reused or remanufactured** but be recycled or **recovered as energy.**
- Low-value products pose challenges to all product **life-extension** activities because of the additional efforts they require. They are easily discarded to be **recycled**, **recovered** or just thrown away.
- Poor quality and poor quality assurance or mistrust in their quality may cause the lack of demand for **used, repaired or remanufactured** products, which may lead to **discarding** even usable products. The same is true for **recycling**, leading to **incineration** of discarded products or already recycled materials.
- Missing demand and market mechanisms for **used** products may result in **discarding** products.
- Easily **recyclable** materials or product structures are not necessarily the most **usable or durable** (e.g., monomaterial products vs. multimaterial products).
- Missing the required **recycling** investments, knowledge and technology leads to **discarding** the EoL products (or by-products) – to be burned or even dumped into a landfill.
- **The demand for energy** may put pressure on manufacturers and users to incinerate (or develop fuels from) materials, which could be recycled. This may also hinder the development of recycling processes (e.g., existing waste burning vs. new recycling investments).

Reuse and recycling in a reverse supply chain

In this section, we outline how reverse logistics and supply chains in two Rs – reuse and recycling – have been studied to support moving the waste up the waste hierarchy. The waste hierarchy forms the basis of EU legislation, whose purpose is to treat waste as high up the hierarchy as possible, and where at the top of the hierarchy, the material has not yet become waste. The different steps of the waste hierarchy are prevention, reuse, recycling, recovery and disposal.

In the CE context, reverse logistics includes the activities set-up by the reverse supply chain to connect the forward flow and allow the circulation of the materials by the Rs. The activities usually include collection, transportation and sorting, followed by recycling processes.

Currently, recycling as an EoL solution for single use, especially in packaging and other municipal solid waste, has received much attention. In other sectors, such as waste electrical and electronic equipment, the research focus is not only on recycling but also on distribution to the different Rs through reverse logistics solutions. Most research concentrates on only one of the Rs, but depending on the context, other studies examine reverse logistics and supply chain solutions for several Rs. This is the case especially in remanufacturing, where the parts can be either reused or recycled, depending on the conditions of the different parts. Figure 3 summarises our main findings.

Reuse

- Reverse logistics and reuse are studied significantly less than recycling; however, there is also more variety in terms describing reuse (e.g., refillable and returnable packaging).
- Reuse is not possible in all contexts, but the contexts in which it should be identified as the process required to reuse a product is usually more simpler than recycling (among others), as long as the logistics works well.
- Examples of reuse contexts studied from reverse logistics perspective: online retail packaging, textiles & clothing, end-of-life electronic products.

Recycling

- Reverse logistics and recycling are mostly studied in a specific context, but depending on the context, several Rs can be included; thus, there is no need to form the reverse supply chain separately for each R.
- R studied separately or combination of Rs, possibly depending on context.
- Examples of recycling contexts studied from reverse logistics perspective: household waste, plastic bottles, electrical and electronic equipment, municipal solid waste, grocery retail, refrigerators, batteries, phones, textured glass, end-of-life vehicles, wind turbine blades, textiles.

Higher waste hierarchy levels

- How could reverse logistics solutions maximise ending up in high waste hierarchy levels?
- In both reuse and recycling, research often addresses implementation of reverse logistics practices to achieve circulation in contexts where there is a lack of solutions.
- For most contexts, reverse supply needs to be designed for each R, also to increase sorting at the source (e.g., packaging, textiles); however, studying several Rs at once, depending on the context, could allow maximisation of ending up in higher waste hierarchy levels.
- Logistics solutions can support steering the materials to higher waste hierarchy levels, but it requires established logistics solutions for those routes.

Figure 3. Summary of reverse logistics and supply chain research related to reuse and recycling.

Additive manufacturing

The most typical AM techniques are directed energy deposition (DED), powder bed fusion (PBF) and binder jetting (BJ). DED is one of the most used processes in remanufacturing and repairing damaged components, due to lower heat input, less warpage and distortion, and higher precision compared with traditional techniques, such as welding. The repaired parts also have good mechanical properties. DED also enables utilising multimaterials and functionally graded materials to achieve the best efficiency by using the repaired parts, combined with several dissimilar materials, that fully realise the economic and performance advantages of each material.

The damaged components are usually replaced by new parts; however, in some cases, it is more useful to repair them. This is the case when the repaired components have high economic value. The high value originates from the numerous manufacturing steps required to produce the component and from the expensive material used. Consequently, repairing these parts means remarkable cost savings. The most important industrial sectors' shares in AM applications for remanufacturing purposes are presented in Figure 4 (Shrivastava et al., 2021).

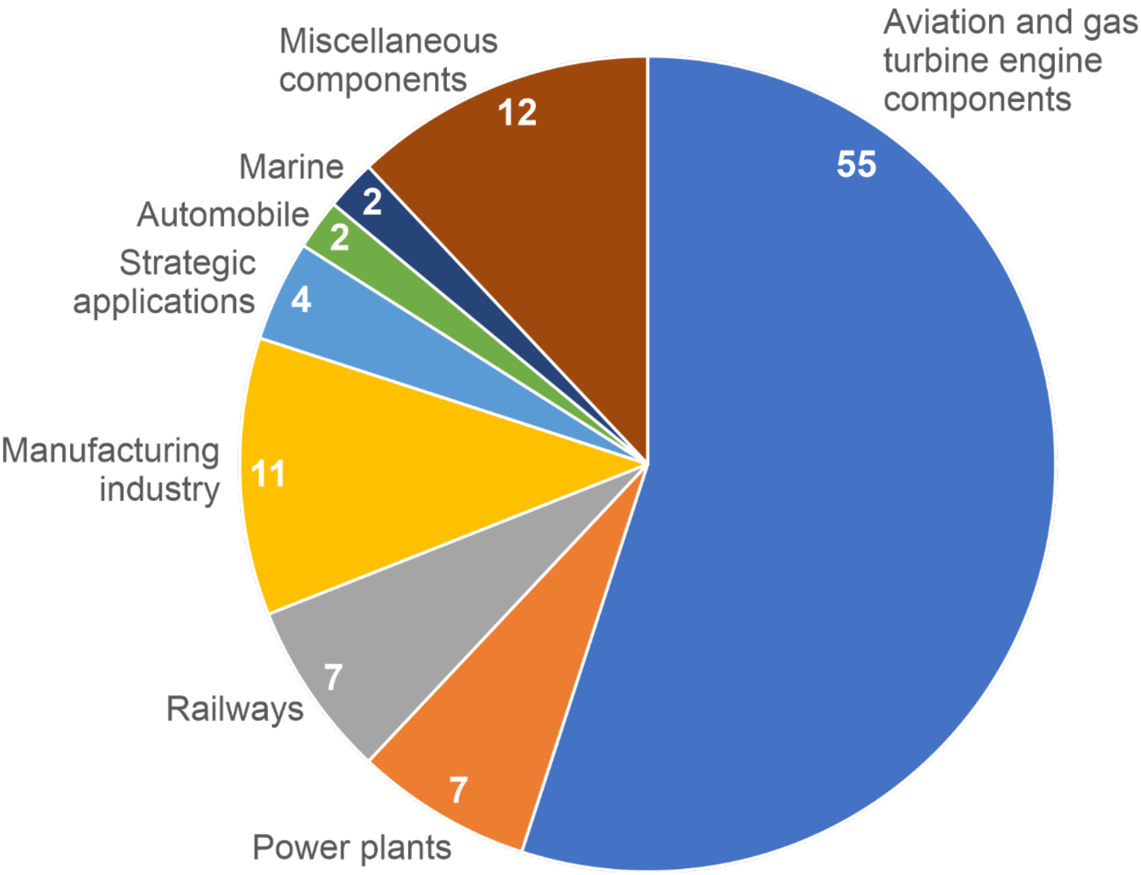


Figure 4. The shares of the main industrial sectors' AM applications (adopted from Shrivastava et al., 2021).

Concerning R-cycles, the conflict/risk mainly lies in the possibility of recycling remanufactured and repaired components. This is especially the case if bimetal or functionally graded materials are used in the repairing process.

The outlook for VTT concerning additive remanufacturing means that investment in DED is needed to gain the prime circular manufacturing advantages because DED is the main technology used for repairing and remanufacturing. Focusing on demanding components and expensive materials leads to major benefits. Remanufacturing and repairing costs can be lower than the cost of creating new components, especially in the case of demanding shapes and expensive materials.

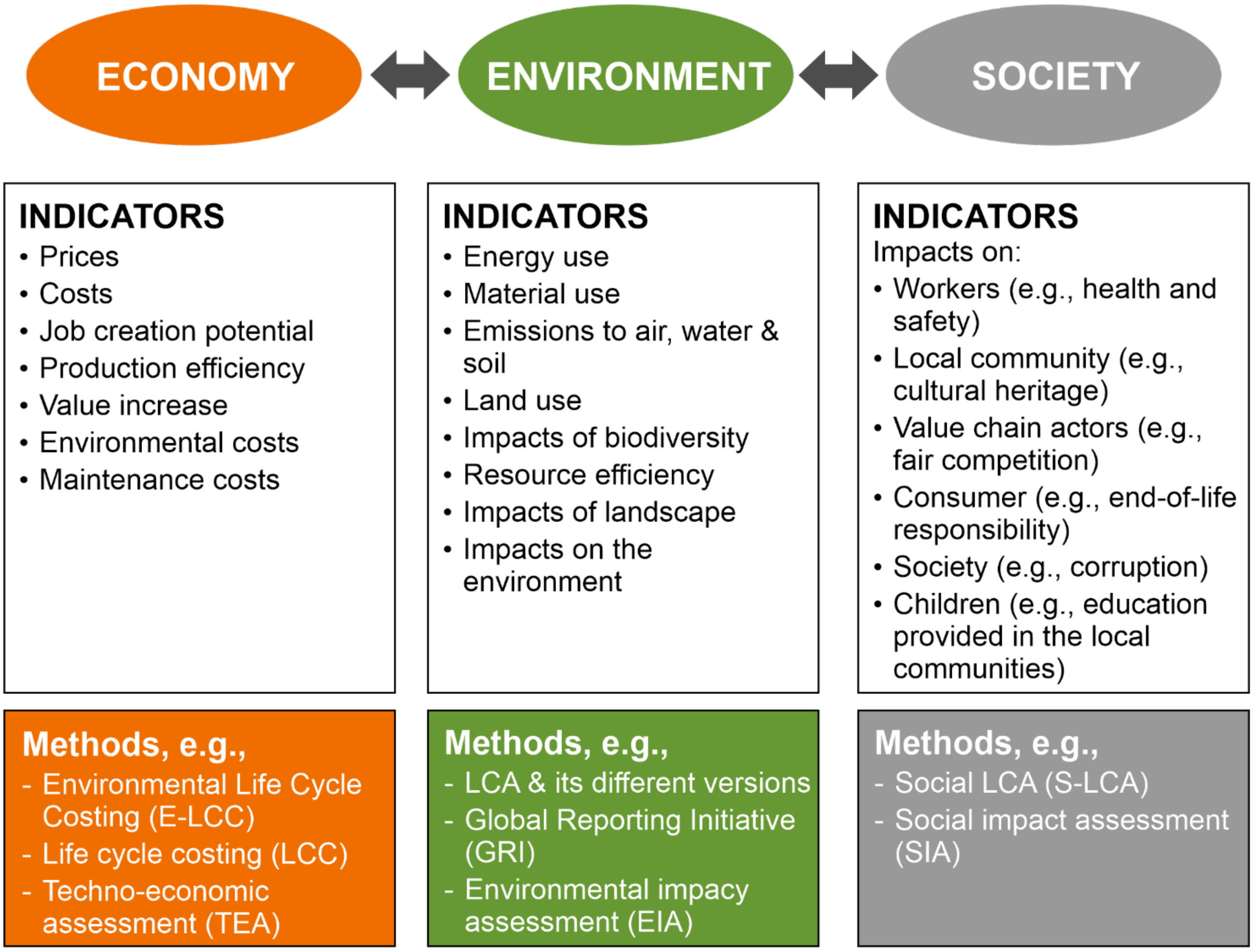
VTT has excellent knowledge and facilities for powder technology (manufacturing, handling and characterisation), including powder bed techniques for AM. However, DED technology is a new area for VTT, and facilities and knowledge are already available in many institutes in Finland and abroad. Thus, differentiating and focusing are important in order to find target market segment for the research. Potential research areas could be the exploitation of the circulated/recycled raw materials from different processes and the investigation of the multimaterials and functionally graded materials used in the repairing process to acquire even better properties compared with those of the original components.

Sustainability indicators and 9Rs

In this section, we present the requirements and prerequisites of the 9Rs for improving sustainability (environmental, economic and social), based on a literature review, and introduce the indicators that are typically used in sustainability assessment. The latter is directed especially to companies that are not very experienced in sustainability assessment.

The 9Rs have prerequisites to be more sustainable than linear solutions (e.g., recycling may not consume more energy or chemical resources than primary production does). From our preliminary literature review related to the 9Rs, we mainly observe the lack of research articles that systemically evaluate the sustainability aspects of the 9Rs. The articles that include all 9Rs focus more on discussing the definitions and goals of the 9Rs and describe how they serve as circularity indicators. Therefore, it would be beneficial to carry out such an overall sustainability evaluation of the 9Rs.

The second part of this study consists of listing the typical indicators and methods used by companies and organisations when conducting sustainability assessments. Figure 5 shows examples of the common sustainability metrics. It should be noted that the list is not comprehensive. Longer versions of the social LCA (S-LCA) indicators are available in two publications (Goedkoop et al., 2020; UNEP, 2020). Sustainability consists of the three dimensions (environmental, economic and social), each of which can have various indicators. All of them do not need to be addressed at once, and starting with the most relevant ones is recommended. For example, materiality assessment is useful for identifying the most important indicators.



INDICATORS
- Prices
- Costs
- Job creation potential
- Production efficiency
- Value increase
- Environmental costs
- Maintenance costs

Methods, e.g.,
- Environmental Life Cycle Costing (E-LCC)
- Life cycle costing (LCC)
- Techno-economic assessment (TEA)

INDICATORS
- Energy use
- Material use
- Emissions to air, water & soil
- Land use
- Impacts of biodiversity
- Resource efficiency
- Impacts of landscape
- Impacts on the environment

Methods, e.g.,
- LCA & its different versions
- Global Reporting Initiative (GRI)
- Environmental impacy assessment (EIA)

INDICATORS

Impacts on:
- Workers (e.g., health and safety)
- Local community (e.g., cultural heritage)
- Value chain actors (e.g., fair competition)
- Consumer (e.g., end-of-life responsibility)
- Society (e.g., corruption)
- Children (e.g., education provided in the local communities)

Methods, e.g.,
- Social LCA (S-LCA)
- Social impact assessment (SIA)

Figure 5. List of most common indicators in sustainability assessments.

IV. Data sharing for sustainability goals

For the technology validation, two data-sharing PoCs are selected. The first one carries the requirements and technical solutions needed for a DPP. A DPP shall enable data sharing among the actors involved and thus also allow and boost circularity in the manufacturing value chain. In the future, the EU will request a DPP for each product that will enter the European markets.

The second PoC describes the technical solution for data sharing in a supply chain, based on the international data spaces reference architecture model (IDS RAM). For example, transparency in the supply chain both decreases waste and the value of inventory. Therefore, the input-output ratio of the manufacturing value chain improves, which further contributes to the economic pillar of sustainability.

The digital product passport provides the means for a data-enabled circular economy

The DPP is one of the key tools of the EU Green Deal and the Circular Economy Action Plan (CEAP) in the pursuit of sustainability and climate neutrality. The DPP is intended to support both more sustainable politics and businesses by providing visibility of the product information for the entire value chain and other authorised stakeholders. The product information may contain data on materials, components and chemicals, as well as instructions related to the repair, recycling, dismantling and disposal of the product. These data should help consumers and investors make more informed purchasing decisions and serve as a basis for public procurement (Saari et al., 2022).

The DPP can support the implementation of R9 strategies in many ways (Figure 6). From both the holistic and individual stakeholders’ perspectives, measuring the performance and progress of sustainability is facilitated by utilising the DPP with suitable indicators and corresponding verifiable data. Thus, better-informed policy actions and business decisions can be made. Circular design processes also benefit from the data-enabled approach. Harmonised and verifiable product data increase market transparency and efficiency (better and faster data transmission, decreased transaction costs). Increased transparency and well-functioning markets nourish the discovery of new circular value streams and the development of novel circular businesses.

At the moment, the DPP is at the pre-conceptual phase but maturing rapidly. The EU's Battery Regulation mandates the introduction of the DPP by 2026, and batteries as a product group are at the forefront of DPP development. However, the Sustainable Products Initiative (SPI) and the EU Ecodesign Directive strive to considerably expand the number of product groups with appropriate sustainability information. Other potential product groups for DPP implementation include textiles, furniture, electronics and construction industry products.

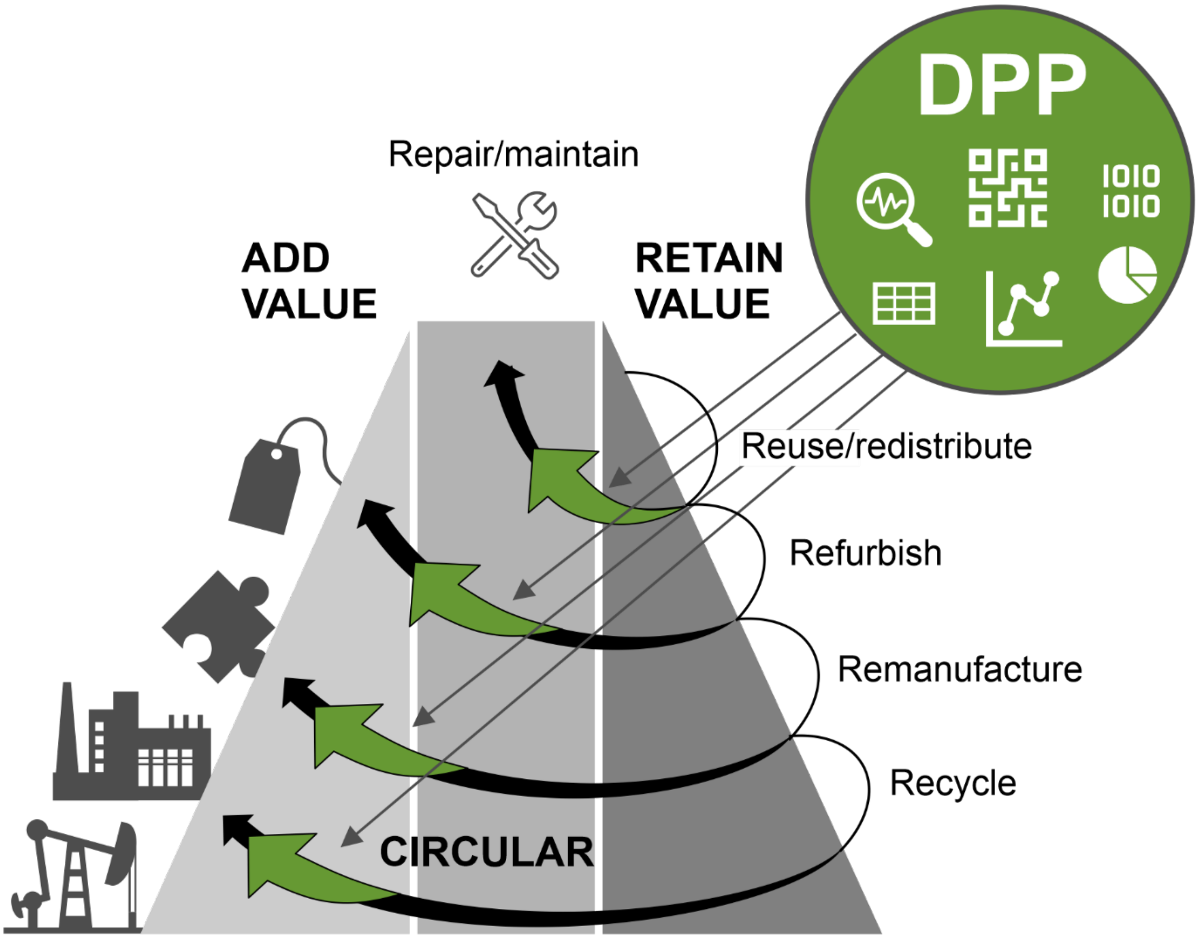


Figure 6. DPPs can facilitate the implementation of circular strategies
(modified from Achterberg et al., 2016).

The successful implementation of the DPP concept will first require factoring in circularity and right-to-repair widely in the regulation. This way, circular business models become more attractive, creating a viable business case for the DPP. The EU Ecodesign for Sustainable Products Regulation (ESPR) especially considers this relation. In addition to the regulation supporting circularity, broad interoperability and compliance with the principles of a fair data economy will be needed for the DPP. The EU's data regulation is undergoing significant changes towards "digital sovereignty", and this revolution should be taken into account. To guarantee technical interoperability, the development of data-sharing technologies should be based on open international standards (e.g., W3C[7], ISO[8], OASIS[9], etc.). Many of these standards are already well-established and widely used in other contexts.

At the time of this writing, there are dozens of on-going projects and initiatives related to the DPP. Although there is no clear consolidation of the approaches yet, the prominent ones are mainly based on decentralised architectures, in which product information is compiled from different parties. This kind of approach would speed up the advent of the DPP because much of the data already exist. However, it also underlines the importance of a unified and harmonised data solution and information confidentiality. As a result,

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[7] https://www.w3.org

[8] www.iso.org

[9] www.oasis-open.org

many DPP initiatives (e.g., Catena-X[10], Spherity[11], IOTA[12]) propose representing the DPP in the format of W3C-verifiable credentials, which can embed several data scheme standards. To gain a collective understanding of the data and their semantics, shared vocabularies will also be needed.

The European data infrastructure Gaia-X (as well as the previously mentioned initiatives) follows the principles of the EU data strategy, forming interoperable data spaces for different sectors. As the DPP concept, and especially the CE built on top of it, extremely require cross-sectoral data sharing, Gaia-X's reference architecture could act as a potential technical enabler for the DPP. The Gaia-X trust framework also provides a coherent foundation for DIDs and digital signatures, which are used to cryptographically sign the pieces of product information in a DPP. This way, the reliability of the DPP data is improved. One of the practical ways to enhance the level of trust in the DPP and its claims is to use what W3C did – a web method that builds on a trusted web domain's reputation by providing the means to securely manage the DPP using the domain's X.509 public key infrastructure. Furthermore, various tools for creating access control mechanisms will be available in Gaia-X. Access control is a crucial prerequisite for viable DPPs because it provides the means to protect confidentiality and trade secrets.

The readiness level for many technologies proposed for the DPP is already quite high, but there are still many development topics for the overall DPP solution. The formation of the appropriate governance frameworks needed for DIDs and verifiable claims is at its early phase. Vocabularies and semantics for different CE use cases and product groups need standardisation. The usability of the DPP is also one of the crucial aspects so that the DPP's benefit for the CE can be maximised. For example, what is the efficient level of product information for each stakeholder, how can privacy be guaranteed, and how can product usage information be efficiently fed into the DPP? Numerous parties are currently working on these themes.

Federated data sharing supports sustainability in a supply chain

In this section, we briefly describe a data-sharing PoC from an innovation ecosystem called the Open Smart Manufacturing Ecosystem (OSME)[13]. In this ecosystem, the original equipment manufacturer (OEM) and its selected suppliers and technology partners seek new ways to achieve sustainability and service-based business logic in their operations. One part of this development is to study and pilot new methods for secure data sharing within the ecosystem. In practice, the IDS-RAM is chosen as a technical framework.

The EU aims to create a single market for data with a concept called data spaces. This is not only for companies or organisations but also for individuals. The goal is to enable ethical data sharing and exchanging and make this mainstream. Data sharing ecosystems (DSEs) are essential for business, as well as for enabling sustainability (environmental, economic and social). DSEs enable the following: i) for material sciences, sharing material information throughout the product lifecycle, ii) for energy, sharing process data for asset maintenance, and iii) for manufacturing and logistics, sharing event data across the supply chain. The IDS[14] of the European Data Strategy aims towards trust,

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[10] https://catena-x.net/

[11] https://www.spherity.com

[12] https://www.iota.org/

[13] https://cris.vtt.fi/en/projects/open-smart-manufacturing-ecosystem

[14] https://internationaldataspaces.org/

security and data sovereignty, DSEs, standardised interoperability, value-adding apps and data markets (Otto, 2022). Figure 7 presents an overview of the IDS architecture. The core component that both the data provider and the data consumer utilise is the IDS connector, which i) provides communication between and among participants and ii) determines the data access policy.

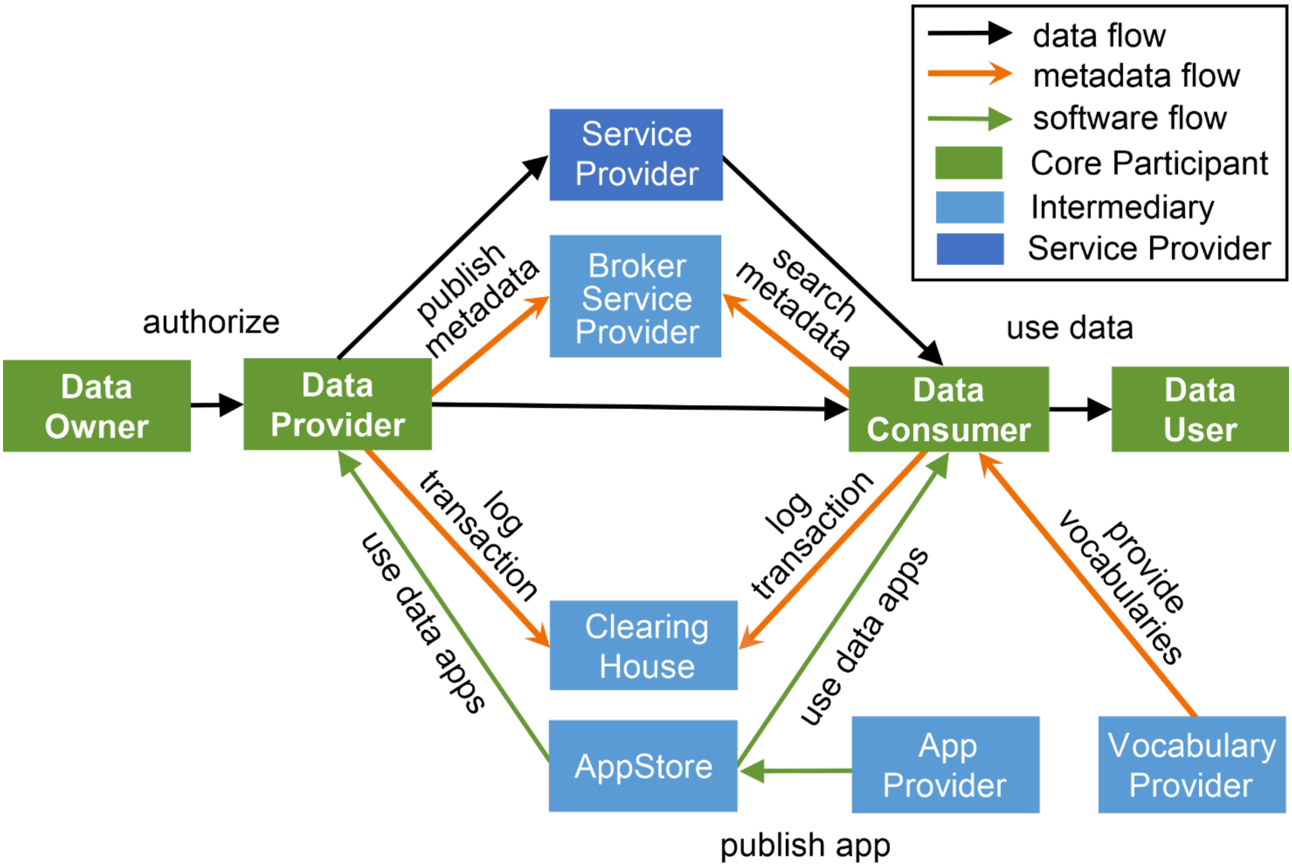

Figure 7. IDS architecture overview (based on Nagel & Lycklama, 2021).

Figure 8 outlines our solution for data sharing between the OEM and the suppliers as a PoC with the IDS. The PoC replaces the former solution, where the same data from the OEM were delivered to all suppliers. One crucial problem with the former solution was that suppliers could access even the data that were not meant for them. The outline of the PoC is as follows: The OEM declares individual artefacts, based on the application programming interface (API) for each supplier on a need-to-know basis. The OEM acts as the data provider, and the suppliers act as the data consumers. The data provider controls who utilises the data, and the data consumers receive the data that they need. Although in Figure 8, the data flow is shown as coming from the OEM to the suppliers, the data also flow from the suppliers to the OEM (i.e., the OEM acts as the data consumer, and the suppliers serve as the data providers). The suppliers may also have their own suppliers.

The IDS-RAM enables the creation of DSEs that make possible standardised means for fluent data flow and transparency. Furthermore, enabling monitoring through the supply chain and within the manufacturing value chain creates awareness and early detection of potential new Rs.

Data sharing increases transparency in the operation of a supply chain. Moreover, the sustainability of the supply chain and production can be better assessed, and concrete ways to reduce the amount of raw materials and waste, decrease energy consumption, optimise logistics, and so on, can be planned and implemented.

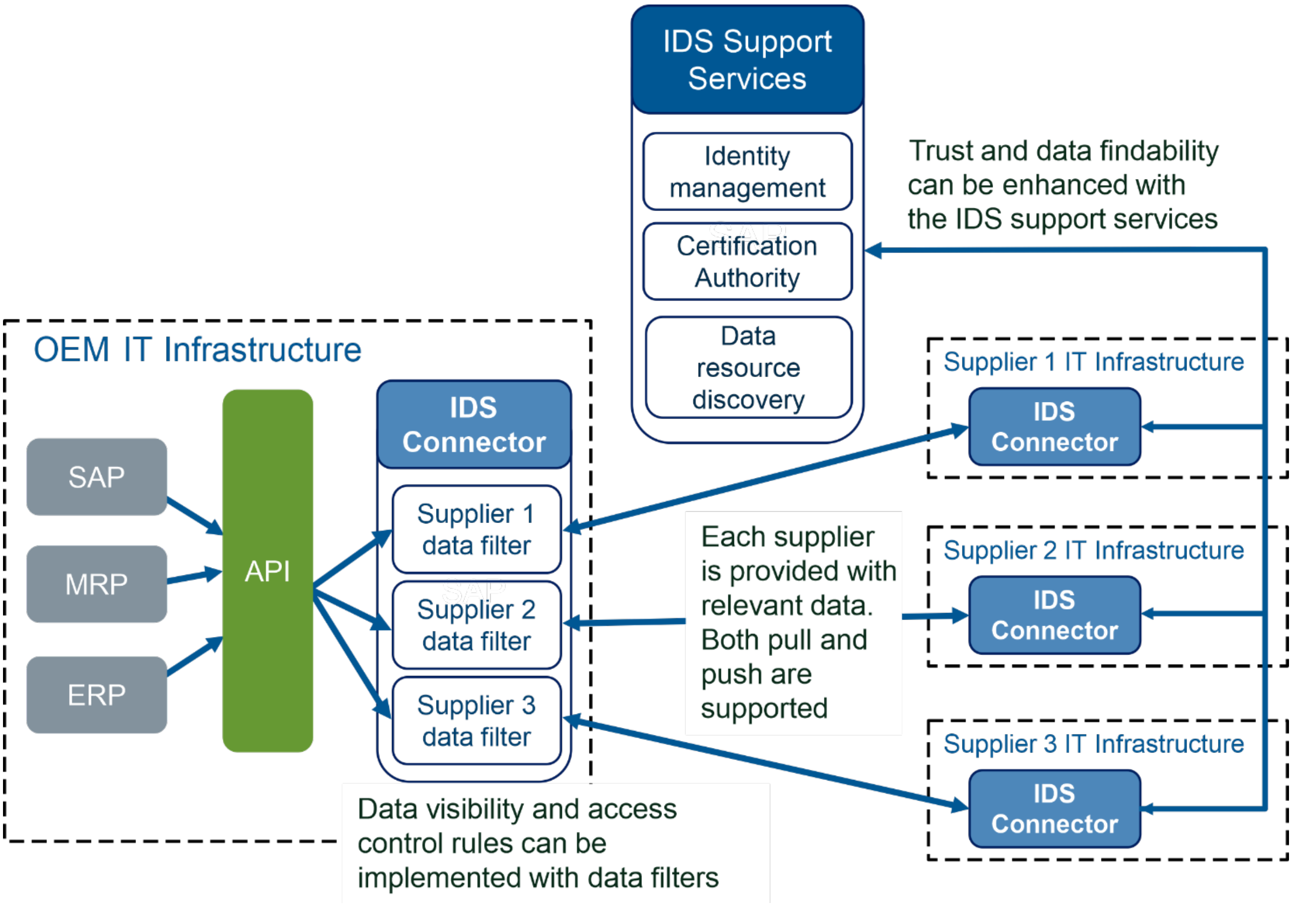

Figure 8. Manufacturing supply-chain data space enabled by International Data Spaces (IDS).

V. Future research topics

Many ICTs are suitable for different purposes. Therefore, instead of presenting a large set of different technologies, we will focus on technology-based challenges that will help us in supporting the manufacturing industry to be more sustainable and then evolve into a circular one.

These challenges include advanced data sharing and interactions among different operators, often functioning through **joint data platforms**. There are many promising approaches; at VTT, we regard IDS as a key European-level initiative to further push data sharing between the companies and other operators.

A DPP offers a means to follow a manufactured product's life cycle, from the material build-up to the final EoL of the product. This kind of interaction also requires the means to collect information from different operators and provides important abilities for the traceability of product sustainability.

DTs typically present simulations and physics-based models of the selected products or their parts. **Sustainability DTs** would broaden their range to encompass ecological and human-related aspects, thus supporting sustainability-based decision making.

LCA is a largely established method that offers a means to measure environmental impacts (e.g., the carbon footprint of the analysed product) efficiently and throughout the product life cycle. Some aspects of environmental impacts, such as land use and biodiversity, still require methodology development to be fully applicable in LCA. Future research interests in this topic also include real-time aspects and digitalisation/automation of the assessment (e.g., in the form of the so-called online LCA). Additionally, the possible lack of data in the value chains due to confidentiality issues might be overcome with an LCA network, where all actors in the value chain would provide the data related to their processes/products in a confidential way to obtain a joint result.

Additive remanufacturing requires investments in the main technology for repairing and remanufacturing, as well as DED, to gain the prime circular manufacturing advantages. Focusing on demanding components and expensive materials may lead to significant benefits, as remanufacturing and repairing costs can be lower than the cost of creating a new component.

Risk management in the circularity context includes the specific aspect of ensuring the aimed positive impact on sustainable development. The intended positive overall sustainability impact may be endangered by conflicting interests within and among different circular systems and various sustainability aspects if they are not considered in the development of practical solutions. Future R&D needs include an improved understanding of these conflicts and the tools for managing them when developing new circular solutions.

Table 3 summarises the potential research topics, mapped to the relevant R-cycles and technological readiness levels (TRLs)[15].

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[15] The NASA's TRLs have also been adopted for less critical terrestrial software development (Armstrong, 2010). These levels are listed in Appendix A.

Table 3. Topics and potential research interests.

Topic	Main Rs	TRLs at VTT	Potential research interests
International Data Spaces	all	3–6	Data Space Innovation Lab with open access components, services and certificates
Digital product passport	R2–R9	3	Identity of digital product, accessed online Data needed to deploy R-cycles, tokens for incentivisation *In DaCapo[16] project started in 1/2023, the goal is a minimum viable DPP solution based on IDS RAM.*
Sustainability digital twin	all	3	Cognitive support tools (user interfaces on top of digital twins) for sustainable decision making *To be developed and piloted in DaCapo*
Life cycle assessment (LCA)	all	9	LCA utilising digital data, operating online and in real time
Additive manufacturing	R2, R4, R8	3–4	Directed Energy Deposition (DED)
Risk management in sustainable development	all	3–5	Identification and management of dependencies and conflicts within and among circular systems aiming for sustainable development Supporting balanced future choices

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[16] https://cris.vtt.fi/en/projects/digital-assets-and-tools-for-circular-value-chains-and-manufactur

VI. Conclusions

Digital technologies may perform a potential role in developing a resource-efficient industrial base (Demartini et al., 2019). To achieve long-term impacts, sustainability needs to be integrated into many other thematic areas and implemented simultaneously as digital solutions. Data are enablers of sustainability and CE models. Furthermore, they can be perceived as vehicles for more sustainable production through data-driven decisions at different phases of the life cycle. Data play a significant role in increasing material and energy efficiency in manufacturing, and data should be considered an integral part of all production processes.

Manufacturing companies must take into account not only economic objectives, but also the need to achieve environmental and social objectives in their businesses, as well as to understand their impacts at different stages of the value network. **Sustainable manufacturing** refers to the ability to use resources intelligently in manufacturing and creating products and solutions that can meet economic, environmental and social objectives, thereby protecting the environment while further improving people's quality of life.

Circular manufacturing offers ways to increase resource efficiency and reduce the use of natural resources. The CE mainly contributes to overcoming environmental challenges by implementing various R-cycles, for example, reduction, repair, recycling and remanufacturing.

Digital technologies as essential enablers of circular manufacturing include IIoT, AI, algorithms, ML, blockchains, AM, robotics, AR and VR.

The purpose of this white paper is to provide an **overview of circular manufacturing** and in particular, **the potential to utilise digital technologies in the 9Rs of circular manufacturing**. Additionally, the digital technologies supporting and enabling the 9Rs are studied from four different perspectives – risk and safety, waste hierarchy, AM and LCA – and exploring two different PoCs.

The CE maturity matrix offers a means to understand the point reached by a company along its CE path. According to our interview results, none of the manufacturing companies remains at the lowest level – linearity. Some companies have already reached the top level – circularity. However, most companies are at the middle CE maturity levels, either at the systemic resource management or the CE thinking levels.

Circular manufacturing is dependent on several KETs. However, the selection of technologies within different R-cycles is not trivial, as different technology combinations have varying synergies with the objectives of each R-cycle. In this paper, we study **three different scenarios for integrating circularity and potential technologies**:

- Sharing scenario – smarter use and manufacturing of the product,
- Repairing scenario – extending the product life, and
- Recycling scenario – useful application of the materials.

In reality, the most sustainable options for design, production and life extension or recycling depend on specific arrangements, situations and contexts, not on the circularity strategy as such. There may be certain **discrepancies among different sustainability and CE goals** or the issue of whether extending the life of a product is more sustainable than recycling it.

Two PoCs are used to study data sharing in circular manufacturing. The readiness level of DPP technologies is already quite high. However, there are still several development topics. Additionally, federated data sharing in supply chains increases transparency and promotes sustainability data sharing as well.

Future circular manufacturing-related research topics include joint data platforms, the DPP, sustainability DTs, online LCA, AM and risk management in the circularity contexts.

For example, VTT's outlook for additive remanufacturing involves **investing in DED** to gain the most important circular manufacturing benefits, as DED is the most important repair and remanufacturing technology.

According to our study, there is a lack of research that systematically assesses the sustainability aspects of the 9Rs as a whole. It would therefore be useful to carry out such a **general sustainability assessment of the 9Rs**.

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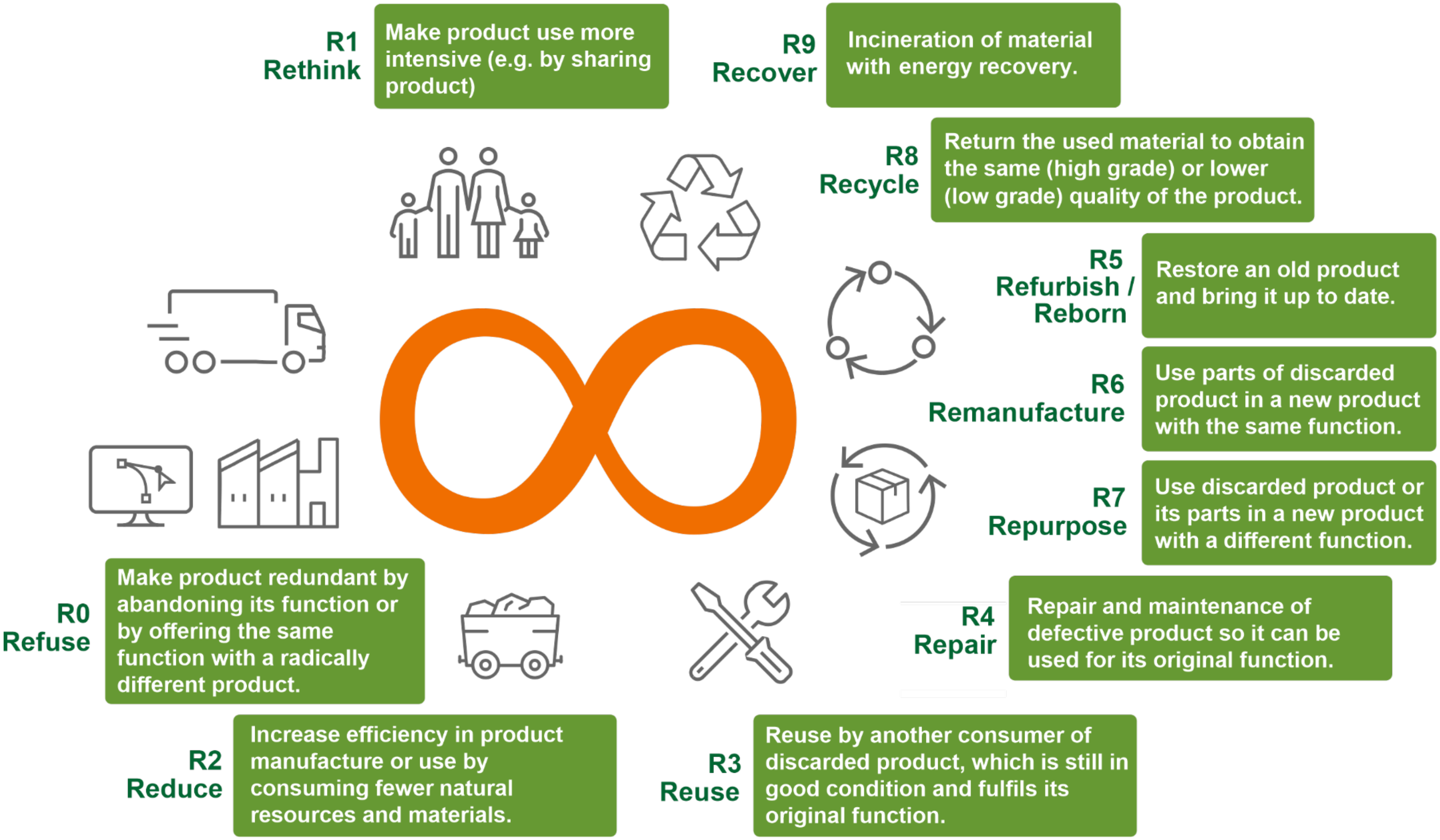
Appendices

Appendix A: Technological readiness levels for software

The NASA created the original technological readiness levels (TRLs) for the quality assurance of its space applications. Currently, the TRLs have also been adopted for less critical terrestrial software development (Armstrong, 2010). Starting from the lowest, the levels are as follows:

1. Basic principles observed and reported
2. Technology concept and/or application formulated
3. Analytical and experimental critical function and/or characteristic proof-of-concept
4. Module and/or subsystem validation in a laboratory environment (i.e., software prototype development environment)
5. Module and/or subsystem validation in a relevant environment
6. Module and/or subsystem validation in a relevant end-to-end environment
7. System prototype demonstration in an operational high-fidelity environment
8. Actual system completed and mission qualified through test and demonstration in an operational environment
9. Actual system proven through successful mission-proven operational capabilities

Appendix B: Simple value loop with the Rs



R0 Refuse Make product redundant by abandoning its function or by offering the same function with a radically different product.

R1 Rethink Make product use more intensive (e.g. by sharing product)

R2 Reduce Increase efficiency in product manufacture or use by consuming fewer natural resources and materials.

R3 Reuse Reuse by another consumer of discarded product, which is still in good condition and fulfils its original function.

R4 Repair Repair and maintenance of defective product so it can be used for its original function.

R5 Refurbish / Reborn Restore an old product and bring it up to date.

R6 Remanufacture Use parts of discarded product in a new product with the same function.

R7 Repurpose Use discarded product or its parts in a new product with a different function.

R8 Recycle Return the used material to obtain the same (high grade) or lower (low grade) quality of the product.

R9 Recover Incineration of material with energy recovery.

Figure 1. Simple value loop with the Rs (inspired by VEOLIA, 2020).

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