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Digital assets and tools for Circular value chains and manufacturing products

Deliverable D1.2

Circular business models for EU manufacturing value chains

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LIST OF ABBRIVIATIONS

CE	Circular Economy
CE-DSS	Circular Economy Decision Support System
R&D&I	Research & Development & Innovation
SME	Small and medium-sized enterprises
CEAP	Circular Economy Action Plan
ICT	Information and Communications Technology
ERP	Enterprise Resource Planning
API	Application Programming Interface
DPP	Digital Product Passport
PSS	Product Service System
OEM	Original Equipment Manufacturer
AI	Artificial Intelligence
VAE	Variational Autoencoder (deep learning based generative model)
IoT	Internet of Things
AAS	Asset Administration Shell (an implementation of a digital twin)
PET	Privacy Enhancing Technologies
LCA	Life Cycle Assessment

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EXECUTIVE SUMMARY/ ABSTRACT

This deliverable discusses the concept of a circular economy transition and the promising opportunities for manufacturing innovations. These opportunities are expected to overcome growing frustrations resulting from tenacious barriers experienced by businesses looking to implement circular strategies. The document is part of the DaCapo project (GA 101091780), which aims to create digital tools and services for enhancing the adoption of Circular Economy (CE) strategies in manufacturing value chains and product lifecycles. The project focuses on technologies such as connectivity, digitization, and new production techniques that are driving Smart Industry or Industry 4.0.

The three main trends identified are increased connectivity between manufacturers, digitization of manufacturing processes, and ongoing innovation in production techniques. These trends enable the sharing of product data throughout a product's lifecycle, leading to the development of Digital Product Passports (DPPs) that track manufacturing, materials, and emissions data. This data can support circular strategies, sustainable manufacturing, and more efficient resource utilization.

The text emphasizes the importance of circular business models in enhancing circularity and sustainability. It introduces servitisation business models that focus on offering value through services alongside products. The different archetypes of servitisation models are product-oriented, use-oriented, and result-oriented, each with implications for retaining value and promoting circularity.

The DaCapo project aims to facilitate circular business model adoption by providing tools like the Circular Economy Decision Support System (CE-DSS) and the Modular Digital Thread concept. These tools help manufacturers to apply technologies (features), creating results (benefits) that eventually lead to a number of concise set of impacts such as attracting talent, reducing environmental impacts or increasing profitability over time. The application of technology can be enabled by decisions based on the CE-DSS.

The text concludes that barriers to implement circular strategies can't be overcome easily. Even for efficiency of value effectiveness measures, many enterprises do not see a reason to invest in new (digital) technologies with the aim to deploy circular strategies. The uncertainties and other barriers of investment are too sizeable compared to the positive business-case in case new technologies would be in place. An even more significant barrier arises when looking to deploy novel circular strategies or pursue societal goals. Persistent market failures prevent most companies for investing in R&D&I activities that need legal or societal change in order to create a positive business-case. Especially SME's can't afford to invest in complex R&D&I activities that have no assured return on investment.

The focus of R&D&I should therefore be on developing technologies that have both a use-case and a positive business-case. This means that technologies need to be deployed within one year, can be financed within (regional) peer-groups, clusters or branch organization and do not require a major (over 50% of exiting accounting value) change in corporate software, machinery or company staff. More ambitious R&D&I will follow as soon as either a new technology has proven itself on TRL 9, legal requirements are put in place or disruptive new business-cases are launched backed by significant financial investment.

1. Introduction

The circular economy transition is a long, strenuous, oftentimes frustrating but inevitable process that the current global economy has to undergo to maintain stable societies, at a comfort level that people in materially advanced economies have grown accustomed to. It is therefore the transition that combines relatively weak but undeniable policy drivers and a continuous search for business models that will make a circular economy transition a reality. And when it comes to realizing the circular transition, manufacturing will lead and services can subsequently anticipate.

Manufacturing value chains encompass a wide variety of stakeholders connected through a diverse and complex economic, data and material flows framework. The promotion of a paradigm change towards CE principles established by the 2020 Circular Economy Action Plan (European Commission 2020) has major implications in this industrial ecosystem, requiring the creation of new tools and methodologies aligned with stakeholders and user requirements for each stage of the industrial products lifecycle. That is the objective of the DaCapo project.

The DaCapo project aims to establish a systematic approach enabling the creation of human-centric digital tools and services for improving the adoption of Circular Economy (CE) strategies along both manufacturing value chains and product lifecycles. These tools and services – focused on the creation of new digital assets, AI-based systems, and the application of process and product Digital Twins (comprising Digital Product Passports) – can increase the value retention opportunities within manufacturing chains and product use-cycles. As such, the DaCapo project is pushing towards a new paradigm of digital-enabled industrial sustainability and resilience within the EU. **It provides the input to business decision making that, in case of circular strategies, too often had to rely on failing data and information.**

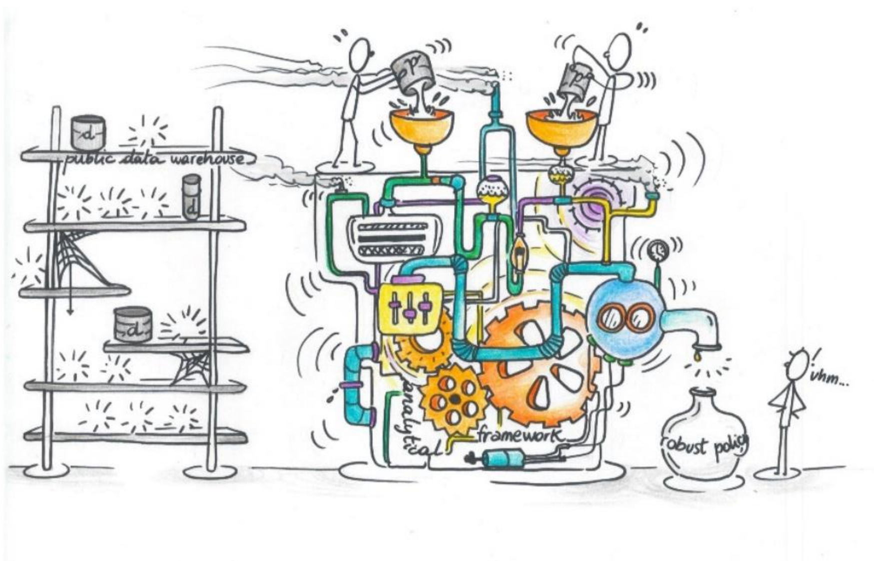

Figure 1: DaCapo providing the necessary input for business decision frameworks (Rietveld et al. 2019)

The **main thesis** of this deliverable is that digital tools and services will play a key role in terms of enhancing circular business models and thus moving towards a circular economy[1], provided that these tools are affordable and accessible for most of the manufacturing sector.

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[1] The underlying assumption here is that business perspectives of companies that want to strategize a circular economy action are sustainable in environmental, social and economic sense.

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This deliverable is organised as follows: first, part 2 provides the context of the circular economy transition, part 3 aim to discuss key technologies, demystifying and relating them to the transition, part 4 discussion about business models. Finally, part 5 offers a synthesis of technologies looking forward to the coming decade. Throughout the deliverable, we will seek to related business models, technologies and innovations to the three DaCapo case studies.

1.1. Case study introduction: the companies in the DaCapo case studies

In the DaCapo project the consortium focuses on three main use cases with different potentials for circular economy developments[2], which all are subject to European policy drivers.

Fairphone, a Dutch social enterprise building a market for ethical smartphones, develops modular smartphones. They focus on circularity in the sense that their modular phones allow for increased reuse and recycle of modules and critical raw materials. In their journey towards further circularization, they focus on two major elements within the DaCapo project: (1) creation of a product digital twin supporting the implementation of advanced digital tools to boost circularity along lifecycle (eco-design, design-for-repairability, disassembly, etc.); (2) adopting the Digital Product Passport to be assigned to each mobile phone tracing key materials and components data and tracking performance through new digital diagnosis tools, enhancing R-strategies implementation coordinated under the CE-DSS for selecting the most adequate circularity strategy.

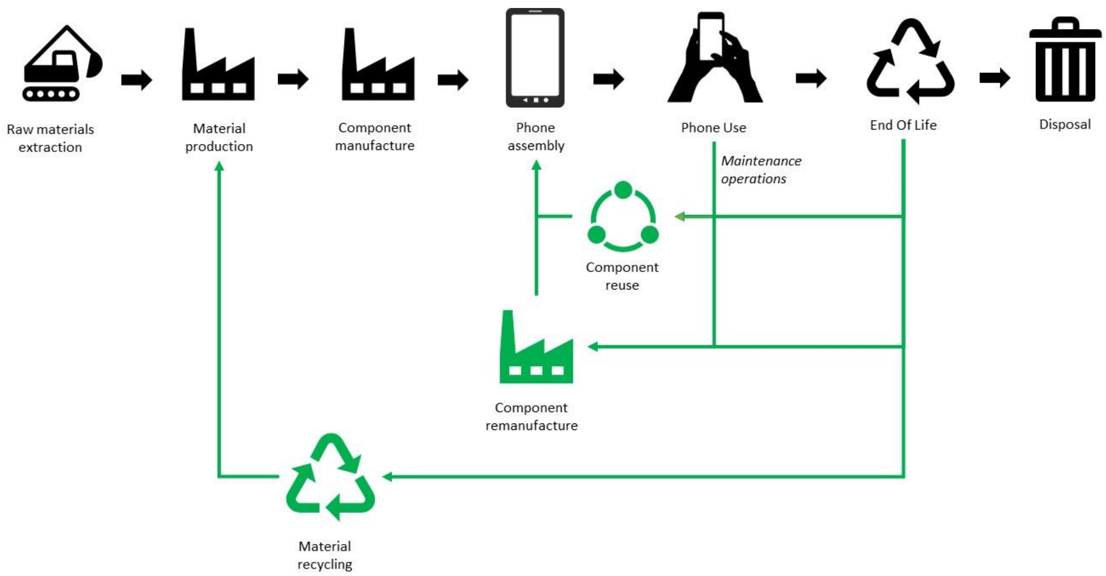

Figure 2: R-cycle strategies for Fairphone use case.

Second is GKN Aerospace, a supplier of advanced aerospace systems, components, and technologies. The focus of the production relies on engine components, airframe structures or fuselage structures. GKN Engine Systems designs, develops, manufactures, assembles and maintains engine and rocket components for both commercial and military applications. Through the DaCapo project GKN recognizes opportunities for example in re-engineering for repairability and resilience, but also extending sustainable-oriented manufacturing strategies towards zero-waste by implementing process digital twins, advanced monitoring and feedback loops from NDT/inspection.

[2] Use Cases — DaCapo (dacapo-project.eu)

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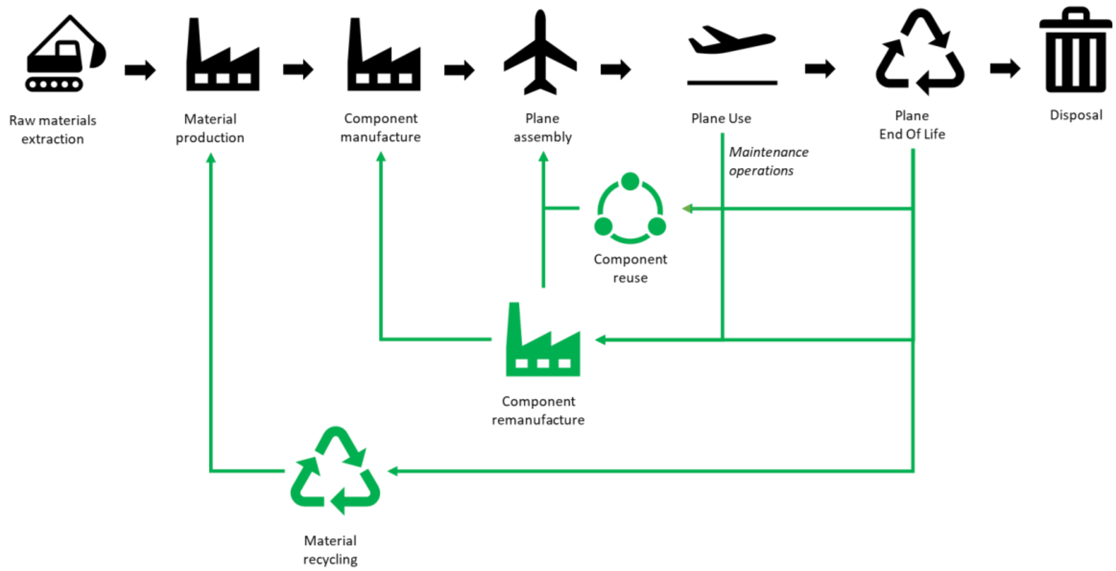

Figure 3: R-cycle strategies for GKN use case.

The third use case is owned by PESMEL, a Finnish company. The services and engineering of PESMEL are aimed at automation and material handling solutions. Their core strategy revolves around providing tailored, cutting-edge systems for various industries, including metal, paper, and logistics. PESMEL leverages its expertise in robotics, conveyors, and intelligent software to optimize productivity and enhance operational efficiency. By offering end-to-end solutions, encompassing design, manufacturing, installation, and service, PESMEL aspires to maintain long-term relations with its clients. PESMEL's business model features a regular investment in innovation, trying to maintain their position in advanced material handling solutions.

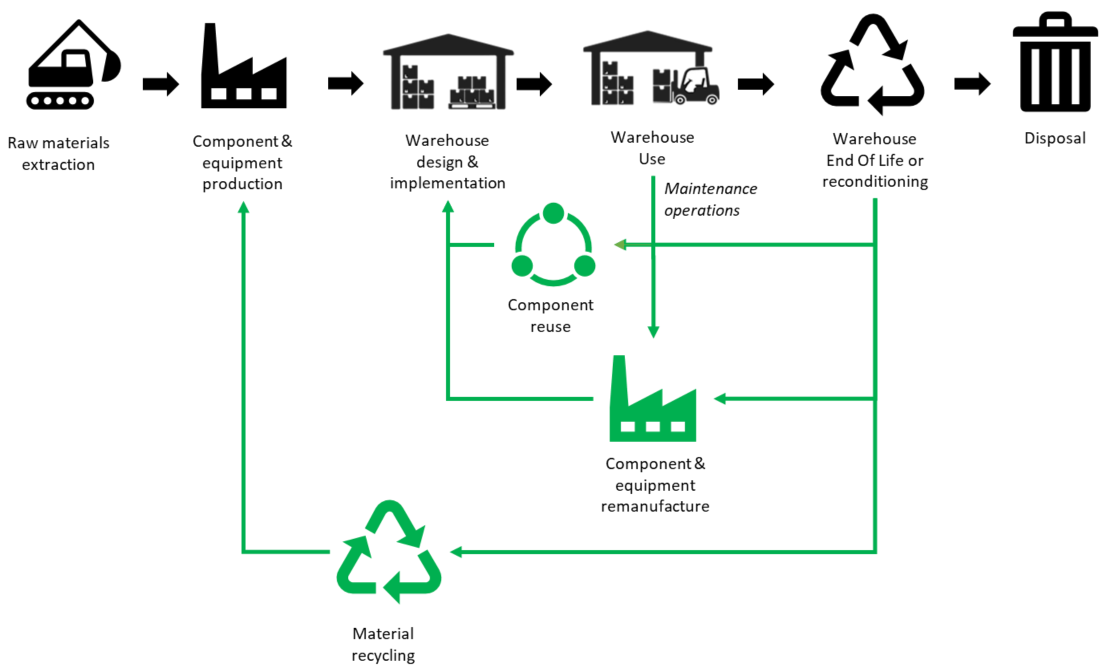

Figure 4: R-cycle strategies for PESMEL use case.

2. The context of moving towards the circular economy

Moving towards a circular economy is important to reduce the impact of manufacturing and consumption on the environment and to decouple material use from value creation. This section describes part of the context in which the transition towards a circular economy is taking place. First, the need for a circular economy due to market failures in the neoclassical economy is discussed. Second, a brief discussion of theoretical frameworks that describe the CE and give context on how the CE is commonly approached follows. Some policies and regulations are included to indicate that there is also political awareness on the topic. Lastly, the increasing importance of digitalisation in society is discussed; specifically the potential of digitalisation for enhancing the circular economy.

2.1. Market failures are real

Standard neoclassical economic theory can describe demand, supply and resulting prices in markets as a perfect reflection of human needs, with actual humans as "homo economicus": perfectly informed, moved by invisible forces and poised to make individual decisions that lead to an optimal societal outcome. This is the ideal model-exercise representation. But markets normally operate in a less than perfect way, and invisible forces are sometimes merely absent forces. The ways in which markets can fail this perfect image are extensively described in the economic literature and are very relevant for the circular economy. Market failures can be of a primary nature, such as negative externalities (e.g., "the polluter does not pay"), an imperfect market clearing (e.g., a monopoly or a situation where many suppliers can only serve a few customers) or a lack of information (e.g., "the one that tells me to repair my car is the one that benefits from that advice"). The secondary nature of market failures can come from the benefit of being a "free rider" ("over-consuming as a result of absent checks/feedbacks on consumption"), taking advantage of different tax regimes or suffering from lock-in/path dependency ("too late to change now"). These market failures indicate the relevance of a circular economy and a different approach on the economy (Raworth 2018).

2.2. Strong but static: The theoretical framework of CE strategies

The Circular Economy concept was revamped in Europe in 2012 by the first report of the EMF (Ellen MacArthur Foundation 2012). Various organizations have since then added their five-, seven-, or other multi-legged framework to the fray. The number of strategies that are most prevalent are defined by the "R-ladder" framework (Cramer 2015). The ladder offers a hierarchy of Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose and Recycle (heat recovery being the first undesirable option).

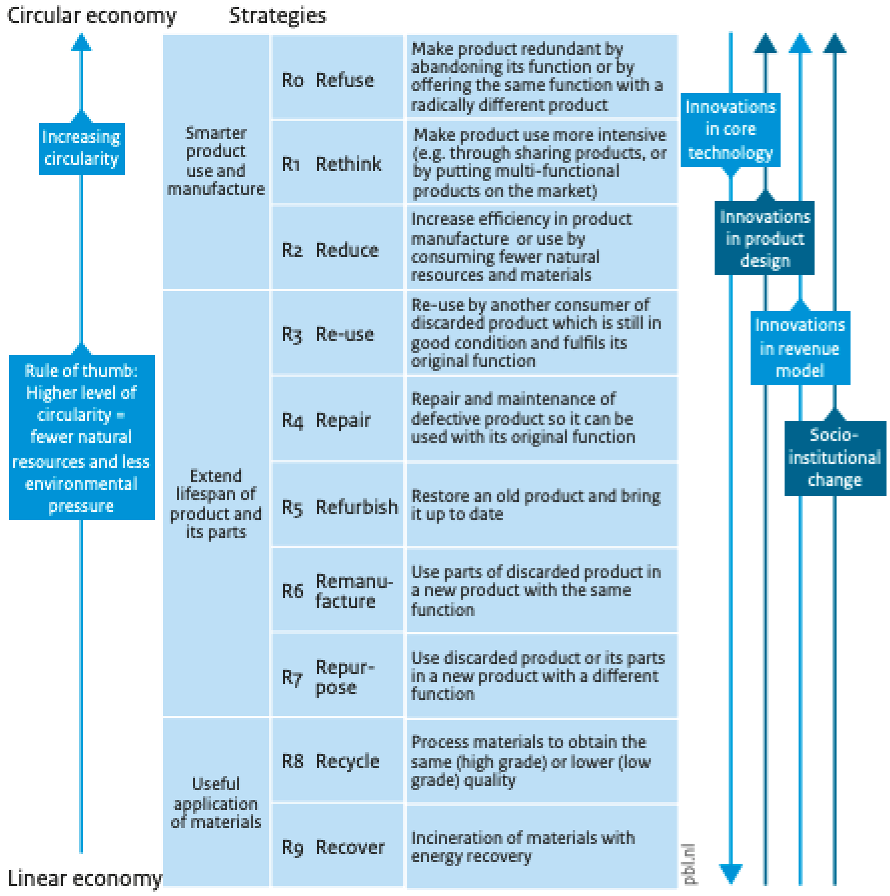

Figure 5: R-ladder, describing the 10 fundamental circular strategies in a quasi-hierarchical fashion (Potting et al. 2017)

Years of interacting with stakeholders demonstrate that this R-ladder might introduce unnecessary discussions about semantics ("What exactly is my company doing?"). Further landmark academic publications on CE theoretical framework further demonstrate the fact that no stone is left unturned in looking for academic richness (Kirchherr 2017, Geissdoerfer 2020). But interpretation of concepts can move the focus away from business realities.

Conversations about possible circular strategies stand the risk to get bogged down in long debates. Moreover, in these discussions, the role of key economic concepts was too often left out of the conversation.

2.3. Steady but not inherently strong: EU Policy

The EU has clear ambitions and several directives to become more sustainable and circular. Ambitions or directives do however not equal binding regulations on a European level. Directives need to be implemented on a member state level by adopting national laws, something many countries are reluctant to do. Therefore, current national and EU policies are considered important, but currently not as the strongest driver.

The European Union is addressing climate change and environmental degradation, and recognizes the importance of CE and digitalization in this. Through the Green Deal the EU aims to *"transform the EU into a modern, resource-efficient and competitive economy, ensuring: no net emissions of greenhouse gases by 2050; economic growth decoupled from resource use; no person and no place left behind."*(European Commission Green deal)

The Circular Economy Action Plan (CEAP) is part of the Green Deal. "*The new action plan announces initiatives along the entire life cycle of products. It targets how products are designed, promotes circular economy processes, encourages sustainable consumption, and aims to ensure that waste is prevented and the resources used are kept in the EU economy for as long as possible.*" (European Commission 2020)

The CEAP addresses the whole lifecycle of a product to enhance circularity. The CEAP emphasizes the role of digitalization to empower the customer. This can be accomplished by providing trustworthy and appropriate information to the customers at the point of sale of products or services. Improving Ecolabels is important for providing the right information to customers, by including information on durability, repairability and recyclability as well. Also offering relevant information on repair services, spare parts and repair manuals is important. For this, the transfer of material and product information is very important.

A common European data space for smart circular applications, including data on value chains and product information is seen as a very important action by the European Commission. Sharing this information with different actors, such as governments, consumers and producers could significantly improve the design, use, reuse, recycling and disposal of products. However, trust and collaboration in the value chain are key for such an initiative to be successfully deployed. (EPC 2020).

EU's Eco-design for Sustainable Products Regulation (ESPR), published in March 2022, states that "a Digital Product passports are a set of data specific to a product that includes a set of information to be determined & is accessible via electronic means through a data carrier.[3]" This is one of several statements that anticipate the arrival of a system that can support the circular transition through the provision of better data. Data that can help to start an upward feedback loop of rewarding frontrunners and enforcing more policies more stringently.

2.4. The strong drivers: fruits of the information revolution

Developments in information technology are taking place at a breath-taking speed. This external societal driver is mostly independent from research or policy efforts to foster the circular transition. It is therefore necessary for public and private stakeholders aiming to spur the circular transition to enrich their actions with the growing possibilities offered by the ICT sector (e.g. reliable precision data sharing on large scale, tools for improved product design for circularity, advanced take-back systems). But at the same time, it is assumed that any drivers based on CE theoretical frameworks or policy will be dwarfed by the market power of ICT innovation (WEF and EMF 2016). Given the sheer technological, political and financial power of this sector, it seems futile to pretend to reverse these drivers. And affordability, financial incentives and market power should be managed. It is vital that tools and available ICT solutions are accessible to virtually all of Europe and indeed global manufacturing. At the same time, governments and SME are probably not eager to place themselves in a position where they are dependent on ICT solutions on a few companies. New propositions of ICT service providers that aim to support a circular economy should therefore be offered on markets with a low threshold for new businesses. Thereby, businesses can evade some of the platform based path dependencies that can be observed in current ICT services.

[3] See for instance the SSbD framework from JRC: https://publications.jrc.ec.europa.eu/repository/handle/JRC127109

3. Main technology trends in the manufacturing context

At this point, the question beckons: which ICT concept and technologies exactly are relevant for the circular manufacturing industry? In this field there is a lot of material being produced on specific technologies and initiatives. However, for the sake of clarity we will limit ourselves to painting a picture of key technologies with broad strokes. A more detailed breakdown of individual technologies popping up can be found in Annex 1.

3.1. The three obvious trends: connectivity, digitization and production technique

We recognize **3 big trends currently ongoing in the manufacturing domain**, also sometimes referred to as Smart Industry, Industry 4.0 or Next Gen Manufacturing (European Commission 2021).

The **first trend** is how companies are getting increasingly connected to each other and forming a network of manufacturers. This **network centric approach** is facilitated by increasing usage of connected IT systems (i.e. ERP systems being interoperable with each other through SCSN – the Smart Connected Supplier Network). As well as companies needing to communicate product data between each other both for sustainability purposes (i.e. Carbon Footprinting), as well as the increasing market demand for small product batches with unique requirements. These requirements need to be propagated through the value chain. The result of this networking is that increasingly a number of SMEs can behave not dissimilar to larger more vertically integrated enterprises. These SMEs may share stock levels, order forecasts and manufacturing capabilities. As traditionally departments within a company may do.

The **second trend** we are seeing is the continuing **digitization of manufacturing processes** within factories. This trend is driven by more systems recording data and exposing controls through APIs. At the same time, these APIs are getting more standardized and integration layers are being added to improve interoperability between them. Product design plans don't exist on paper anymore, but as 3D models that can be shared with operators in the production line, informing human operators and enabling them to do more complex jobs with less training and fewer mistakes. Machines are being digitized and connected as well, so that these can be used more dynamically: Work a bit faster when the sun is shining and electricity is cheap, and a bit more efficient when energy comes at a premium. The result of this development is increased overall equipment effectiveness and more flexibility in how to utilize the available manufacturing capabilities. Especially in this area the influence of new AI development is clearly felt. In order to analyse, optimize and utilise all the available data AI systems are increasingly used, for example to determine how to minimize power draw of the production line, schedule production orders and analyse product quality.

The third and final trend is that apart from connected and digital manufacturing, the **production techniques** are subject to continuous innovation. Maybe the most visible example of this in popular culture is the rise of 3D printing which allows the creation of complex shapes out of a variety of materials without the need for expensive tooling to be made. But similar developments are happening elsewhere too, robotic systems no longer just do one action time after time, but can take sensor input to react to the actual state of the product and more data gathered of products as made in line of the production process allows tweaks later on in the manufacturing to offset undesired deviations. For example, detecting that a piece of metal is slightly bent may be alleviated by heating it up a bit more than usual in a next production step. These new manufacturing technologies allow the usage of new materials, better utilization of available material and responding to incoming parts which are not exactly as expected.

The trends together give the manufacturing industry more tools that are being used more effectively. At the same time this is becoming accessible to smaller enterprises who collaborate with each other to share products, production capacity and capabilities.

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3.2. Why these trends are crucial for the transition towards a Circular Economy

These trends have major implications for the emergence of a circular economy, as many of these digital innovations could be enablers of CE propositions. Considering that manufacturers are becoming increasingly connected, that their manufacturing processes are increasingly digitalized, and that these companies are innovating at a rapid pace, the sharing of product data throughout a product's life cycle becomes increasingly feasible. More specifically, these trends contribute to the emergence of a Digital Product Passport (DPP). A DPP makes it possible to keep track of how a product was manufactured, what materials were used, and what the associated emissions have been. A DPP may provide opportunities to reduce emissions, identify ways to manufacture them in more environment friendly ways and use less carbon intensive energy and materials. Finally, a DPP also provides opportunities at the end of life of a product, by providing information relevant for remanufacturing, repairing, or refurbishing more efficiently through smarter, more responsive, and more flexible manufacturing practices. However, what remains unclear so far is what is needed for manufacturers to indeed make use of these trends, pick up the DPP developments, and adopt more circular economy related strategies and business models. To move to a circular economy, it is crucial manufacturers pick up circular business models. Hence the next section will address the relevance of such business models and how digital trends may facilitate their adoption.

Within the context of a circular economy, these developments facilitate the sharing of product data throughout its life cycle, as often presented as a Digital Product Passport, keeping track of how it was manufactured, what materials were used and what the associated emissions are. These products can be manufactured in a more environmentally friendly way, using less carbon intensive energy and material. Finally, when these products reach their end of life, they can be remanufactured, repaired or refurbished more effectively thanks to smarter, more responsive and more flexible manufacturing practices.

3.3. Towards synthesizing technology and circular business models

Starting with the trend of increased connectivity; this is an important trend that can facilitate the new collaborations throughout the value chain that are needed to implement circular business models (further elaborated in section 4.1) that embed circularity in the value chain. For example, with the use of privacy enhancing technologies, sharing sensitive data across industry partners to make collaborative computations becomes possible, while guaranteeing that privacy is preserved. This leads to increased trust between parties and opens the door to new collaborations and services. Also trust towards the data can be increased, as these methods can guarantee that certain data is legit, as all inputs are verified. With this, it can for example be checked whether a certain ingredient is in a certain product with full certainty. Examples of relevant technologies are multi-party computation, federated learning, and zero-knowledge proofs.

Besides the connectivity between organisations, it is important that within one organisation processes and activities are streamlined as well. Digitalisation of factories has the potential to prevent waste streams and make the production process more efficient, e.g., it allows to coordinate activities in line with available capacities. A more fundamental example would be that a better understanding of the manufacturing processes and activities gives the necessary insights to redesign the processes or the product itself.

Lastly, innovation in technologies can be valuable stimuli for implementing servitisation business models and support circular activities, for example because:

1) This can be relevant in the design phase of product, it can be challenging to produce with secondary material since this flow is sometimes quite low and variable. Through certain technology innovations manufacturing becomes more flexible, which might make it possible/easier to switch between the use or ratio of raw and secondary materials.

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2) Some innovations give better insights in the use phase of a product and are helpful to identify what the problem is when a certain product is defect. This makes it easier to add repair services to your product.

3) There are also opportunities in terms of after use processes, such as recycling. High tech cameras could be used to recycling materials or identify parts of a product that can be re-used.

4. Circular business models: the business logic behind circularity

Circular business models help the implementation of circular practices in all kinds of organisations including the manufacturing industry. There are various circular business models and they all have different implications for how a company should organize itself and different ways of generating income. Logically, there are also different implementation challenges to be addressed. For some of these challenges the earlier described information and technological developments can provide solutions or opportunities to enhance the business models. So, this section will both elaborate on the circular business model concept as well as illustrate the complementarity between digital trends and the implementation of circular business models for the manufacturing industry.

4.1. Circularity through rethinking your value offerings

Retaining value is key in a circular economy, however, in 'traditional' business models there is not always an incentive for this. Business models traditionally focus on selling products and occasionally some services are added, such as repair or maintenance. However, this often leads to difficulties in prolonging the lifetime of a product or regenerating a product after a customer does not need/use it anymore. Which leads to (sometimes avoidable) value destruction (Figure 6).

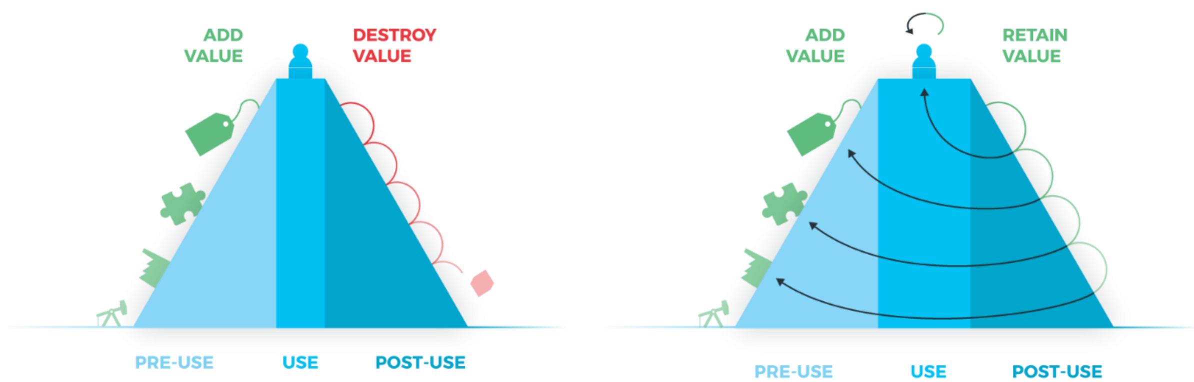

Figure 6: The value hill concept

Circular business models can be used to prevent value destruction and to create a logic/incentive to retain value. Many types of such business models exist, either focussing on changing the value offering at the start (e.g. modular design) or the end (e.g. collection for reuse) of the product lifecycle. Examples of circular business models include (OECD, 2018);

- circular supplies – using only fully recyclable input materials and energy
- resource recovery – recovering materials or energy from the end product, waste or by-products
- product life extension – making sure that a product's use phase becomes longer by e.g. repair, upcycling, reselling
- sharing platforms – increasing the utilization rate of products by enabling shared usage/access
- product-as-a-service – offering only usage/access to a product instead of ownership

In each of these the traditional chain of value creation is rethought and redesigned, and new forms of value are obtained. Several of these concepts can be combined by one company or they can focus on solely one.

Although there are various circular business models, servitisation business models are considered as relevant business models to enhance circularity and sustainability by retaining value in several ways. Servitisation is described as the activity of adding value to (product) offerings by means of providing (additional) services (Vandermerwe & Rada, 1988). Instead of (solely) focusing on selling a product, a

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more integrated solution is offered. Value is delivered through in the use experience. Besides enhancing circularity and sustainability, such business models can provide financial, strategic or marketing benefits due to an increased relation with customers and from the ability to deviate yourself in the market (Zhang &Banerji, 2017 & Palo, Åkesson & Löfberg).

4.1.1. Servitisation archetypes and the value of smartness

There are different archetypes of servitisation business models and different frameworks describing them. In this deliverable we use the Product Service System (PSS) framework from Tukker (2006), since this captures a broad variety of archetypes, categorised in 3 main groups: product-oriented, use-oriented and result-oriented, see Figure 7.

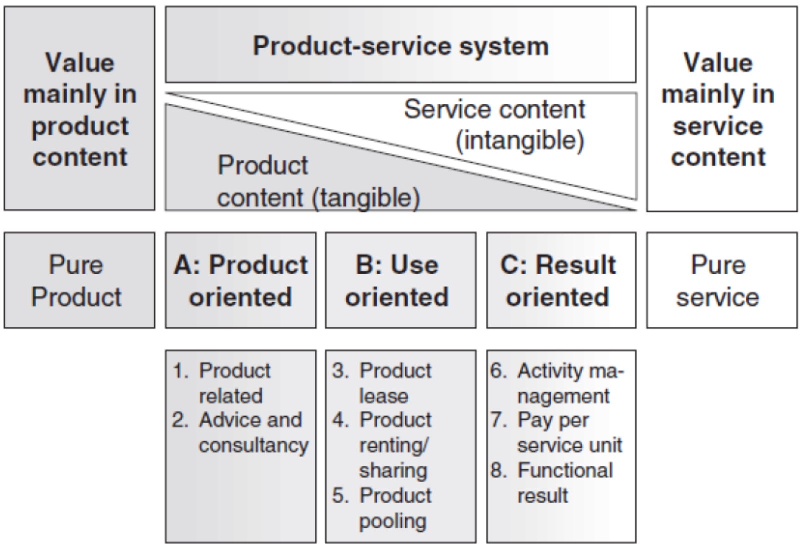

Figure 7: Product Service System framework (Tukker et al 2006)

For the **product-oriented business models** the focus still lies on the product and the ownership of the product is transferred to the customer. However, additional services are offered such as repair or maintenance of the product or information is provided on how to use the product properly. Such a business model could be supported by redesigning a product as well, to increase its repairability or ease of use. All these services could prolong the lifetime of a product/material and thus enhance circularity.

In the **use-oriented business models** a product is still involved, however the focus is now on facilitating the use of the product and not on the single transaction of selling it. Therefore, often the ownership of the product remains at the company instead of being transferred to the customer. Renting, sharing or pooling products all fall under this category. In terms of circularity this could reduce the amount of products needed (e.g. not everyone needs a car if cars are shared and when products are rented for a short period they could be rented to another customer again, instead of being disposed). This gives an incentive to a producer to design a product in such a way that the product lasts long and is used as efficiently as possible. Additionally, it is beneficial for the company that owns the product to retain the product's/material's value that is left after a first lifetime. An aspect that could already be considered while designing a product.

Lastly, in **result-oriented business models** the focus shifts from the product to the result, the reasoning behind this is that customers are often not interested in the product, but the result it delivers, e.g., customers do not necessarily want a boiler, but they are interested in the result; a warm home. Again, this could lead to more efficient use of materials and energy and thus potentially enhance circularity. This type of business models gives the highest degree of freedom to the producers. They can

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rethink how the result is offered and limit the use of material in this design. Additionally, they can find ways to optimize the use phase and after use phase. Although this sounds very promising to enhance circularity, implementing such a business model is often very challenging, since it requires a new way of organising organisations, collaborations and interaction with clients. Designing servitisation business models has many implications for the way of operating; e.g. for the value proposition, the way of interacting with customers and which activities are taking place. Additionally, there are implications for how costs and benefits are generated and distributed. Such implications are also varying between the different types of servitisation. Figure 8gives an overview of some forms of how a business case can be built by exploiting circular strategies in a servitisation business model. This can be illustrated for any individual business case (Figure 8). The vital parameters are either represented in the axes value (expressed in EUR or time. The utility ("does the monetary value accurately capture the utility of the user") and ownership parameters are added based on a customized view.

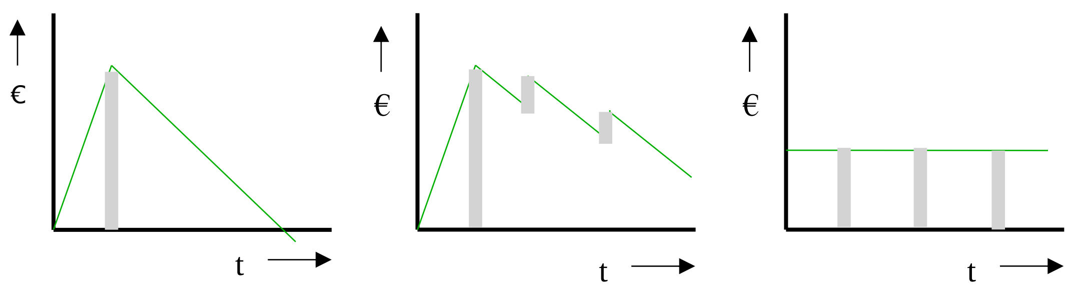

Figure 8: illustrative business cases for manufacturing companies

The transaction om the left in Figure 8 is highly simplified. Current manufacturing transactions are rarely a one-off affair and are usually part of a continuous client-customer relationship. Yet, the success or failure business models can be explained by reducing a transaction into a single decision that combines the contact, contract and control phase of that transaction. The simplified transaction reminds us that several businesses, especially SME's, are chiefly focused on an operational time frame, which either spans only several weeks, the end of the month or a single transaction.

The centre graph describes a transaction that incorporates repair and maintenance. The main question for this illustration would be: who is performing the value-adding activities, the OEM or a different service provider? This simple question implies a slew of questions about ownership, risk, liability, utility, future value retainment and opportunities to learn and innovate. The most common situation of complicated manufacturing products in use (machinery, transport equipment, medical appliances, measuring equipment etc.) is that companies are risk averse. An increase of technical requirements therefore typically equals an internalisation of risk, represented by a large and varied number of additional transactions with often very technically determined terms and conditions.

The right-hand graph illustrates a situation where products are used as-a-service. All risks that exist in the centred illustration are borne by the manufacturer.

Figure 7 and Figure 8 can be summarised in a simple conclusion: more data, better information and better abilities to control production and use of assets fundamentally determine the potential for circular strategies and their corresponding business cases.

4.1.2. Implementation challenges

The circular business model provides a different way to create and offer value, where circular strategies play a central role. It is already shortly highlighted that this has many implications for the company/organisation: for example, new activities need to be executed, new partners are needed to collaborate with or the way of collaborating with existing partners change, new ways of interacting with your customer are needed, and costs and benefit structures change. Moving toward PSS business models can therefore be complex. The level of complexity depends on the type of servitisation model that is chosen (i.e. product-oriented business model will in most cases require less changes than result-oriented business models). Additionally, it depends for a large part on the characteristics of the manufacturer, the products they offer and the organisational structure they have. Moreover, the ecosystem plays an important role; which market regulations are there and what are the characteristics of the supply chain.

4.2. Be aware of trade-offs

Digitalization and CE business models designs do not automatically lead to a more sustainable and resource efficient way of operating, e.g., increased efficiency in production or easier access to platforms that sell services or products might lead to an increased consumption rate. Additionally, the interconnectivity of the supply chain means that when changes in terms of sustainability are made in the operations of one company in the supply chain, other companies might be influenced and their operations might become less sustainable in response. It is important to be able to have indicators to assure these trade-offs are accounted for. Digital Product Passports could for example help to reduce the trade-off effects throughout the supply chain.

Figure 6 illustrates the **relation between adopting a practical solution relevant for a business and greater societal goals.** Four levels can be considered at which digitalization can help develop CE business models: efficiency (easiest), value retention, deploying all CE strategies and meeting societal goals (hardest).

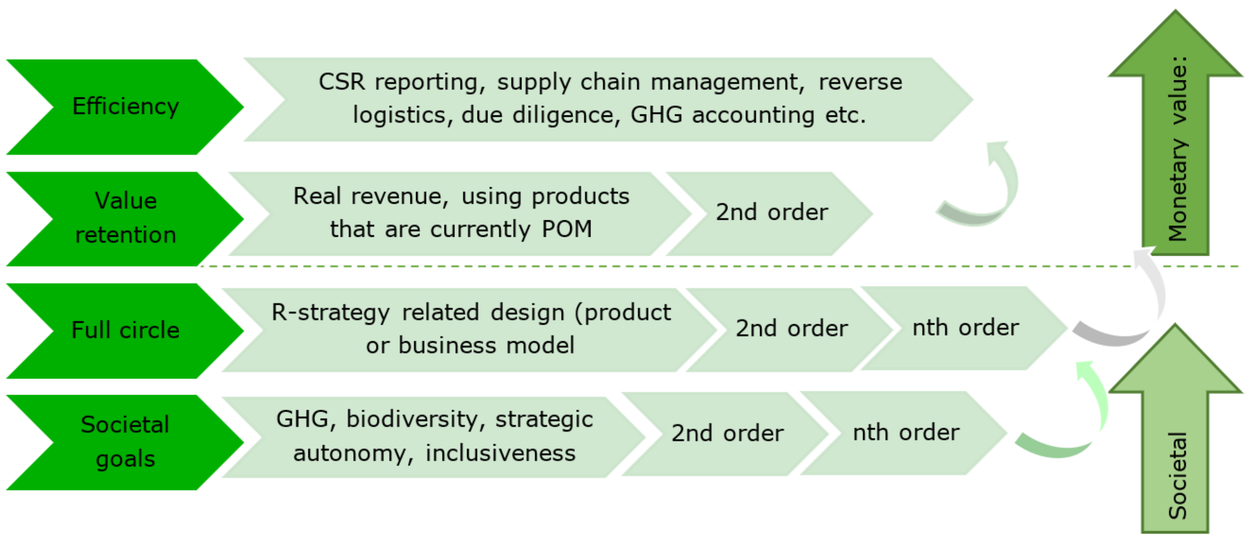

Figure 9: four layers that describe how data and information can aid sustainable production.

4.3. Case study status-quo: The current business models adopted by companies in the DaCapo case studies

The business model of Fairphone is based on customers that understand and appreciate the core mission of the company. These customers value the fact that raw materials are used as efficient as possible, in designs that rely partly on unique designs and partly on components available on global markets. Customer interaction is developed more extensively compared to competitors i.e., major smartphone OEM's to enable post-sales service provision. The long lifetime and repair and spare parts replacement is something that customers appreciate positively in Fairphone.

GKN, the Swedish company, has three clear priorities in its business model: zero accidents, zero downtime and zero arrears. An overarching goal is also to apply sustainability in its business endeavors. Aims to minimize its ecological footprint and positively impact society with a set of in-house defined indicators. To fulfil its ambition of increasing sustainability, GKN seeks to meet the demands of the three priorities by increasing data and information about their products as there are operating in their aerospace assets. The business model is therefore defined in a flexible frame: create and maintain better products that have a lower negative footprint, thereby securing their market position.

The business model of PESMEL lies in its ability to provide customized automation and material handling solutions. Unlike deploying standard warehouse equipment, PESMEL aims to tailor their systems to the specific needs of diverse industries, ensuring optimal efficiency and productivity. Their expertise in robotics, conveyors, and intelligent software allows them to design and implement solutions that precisely match the technical requirements of customers. Moreover, PESMEL's comprehensive approach, encompassing design, manufacturing, installation, and service. This business model sets them apart, aspiring to make long-term partnerships and providing a seamless end-to-end experience.

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5. Towards a brave new world with circular manufacturing

5.1. The grandiose overview of Smart Industry

The future of manufacturing has profound effects on human society, leading to many grandiose labels such as for example industrial revolution 4.0 or the Intelligence Revolution. The label "Smart Industry" will be our label to describe all innovations that comprise manufacturing innovation. Figure 10 shows a comprehensive overview of transforming developments in the Smart Industry domain.

The orange part of the Smart Industry wheel contains three trends: acceleration of industry digitization (digitalization), more, better and safer connectivity (connectivity) and new product and production technologies (manufacturing technologies). The grey ring are the transformations. The DaCapo project refers most to the following transformations: circular business models (CE-DSS), digital factory (DPP), sustainable factory (CE strategies in general) and the smart working (AI) transformations, as will be discussed in this chapter.

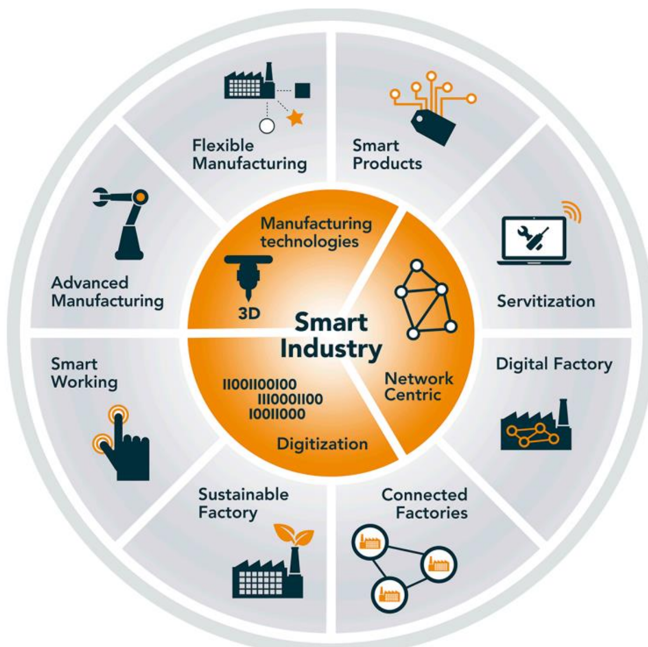

Figure 10: Smart Industry Wheel, providing an overview of the Smart Industry domain (source: TNO)

Manufacturing enterprises will continue to **explore ways to securely exchange data via international standards for linked ICT systems** and are prepared for an integrated chain enable optimization. Quotations, drawings, orders, transport information, invoices, production/quality data from machines, etc., are digitally identified/described in accordance open industry standards and can be securely exchanged without vendor lock-in. The challenge is to achieve optimal use of resources across the entire value chain (lower costs, faster and error-free deliver) from quote to delivery/payment (e.g. blockchain based automatic marketplace negotiations). Cybersecurity, IoT links, but also the use of fibre optic connections and 5G (large data and short response time) make this possible, but require the correct legal contracts (copyrights on sensor data, database law, privacy law, rights of use on software in equipment).

EU manufacturing can increasingly see itself as a service provider, adopting servitisation business models, that have expanded the revenue models of its service organization. Examples are leasing services with associated financing of hardware products, but also predictive maintenance (condition-based or predictive maintenance) using remote monitoring installations. Through fundamental drivers such as 5G and blockchain technology, suppliers can develop technologies so that a supplier who owns hardware/software builds, manages, maintains or takes back everything can follow. The use of artificial intelligence (AI) on the collected data from (many) sensors for remote monitoring for predictive maintenance is especially relevant for DaCapo.

5.2. DaCapo aspiring to make European manufacturing more circular using Smart Industry concepts

One of the many proponents of the Smart Industry development in Europe is the Horizon 2020 innovation program, with the DaCapo project being one of the many efforts to increase the innovative manufacturing. The general view of the project is illustrated by Figure 11, identifying archetypical stages in the production and use-phase and technologies.

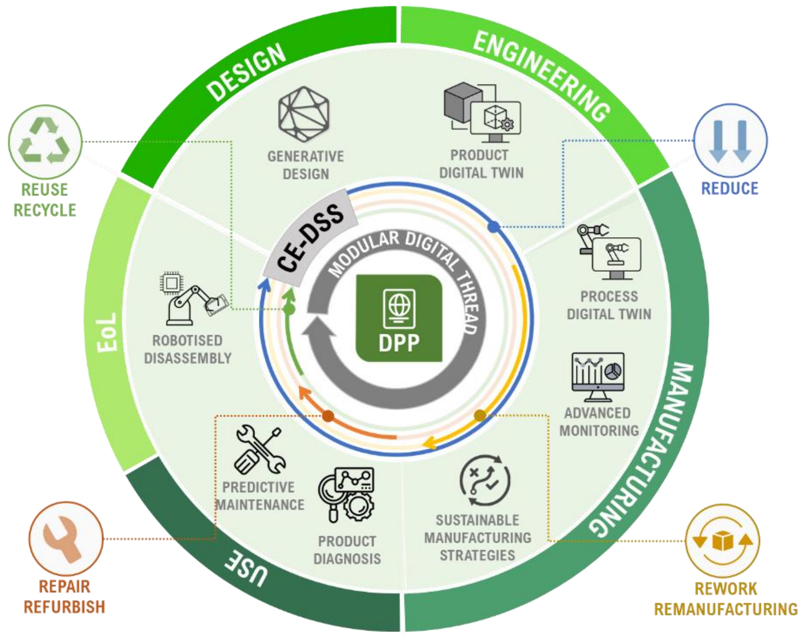

Figure 11: DaCapo systemic approach for a digitally enhanced Circular Economy for manufacturing products lifecycle

The backbone of the project will be the development of an agile methodological approach supporting the decision-making accounting business models. In support of the main thesis of this deliverable does the DaCapo project aim to make this support accessible and affordable for a large group of manufacturing enterprises. Using these tools, they can determine relevant indicators and data-sharing circular strategies along the manufacturing value chains. Circular Economy Decision Support System (CE-DSS) will be considered as high-level tools, facilitating the trustful exchange of assets, the selection of optimum circular stock management strategies, and the definition of informed and coordinated products lifecycle management decisions along the value chains in a safe, reliable, and agile way. A Modular Digital Thread concept will be developed as a normalized method for orchestrating the gathering and contextualization of data at different points of the product lifecycle (design and engineering, manufacturing shopfloor, use phase, End-of-Life -EoL), enhancing data availability for the definition of specific sustainability and circularity indicators and optimisation criteria. This will enable the development of a range of circularity-enhancing digital tools and services based on the use of AI and Digital Twins along the manufacturing products lifecycle.

5.3. Completing the synthesis

The final step to be taken in this deliverable is to create a synthesis between circular strategies, business-models and novel applications of available smart technologies.

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The Table 1 below links the systemic approach of DaCapo to the many concepts that play a role in capturing (circular) economic value through digitalization. After outlining the DaCapo systemic approach in row and columns, the relevant CE strategies and the benefits and impacts of a business case are added in an expansive overview.

Table 1: overview table, linking DaCapo framework to technologies, CE strategies and company benefits. The [RE] denotes DaCapo. [*table is under review at graphic designer who will be converting this table into a figure*]

Fase	Design	Engineering	Manufacturing	Use	Manufacturing
Use case Dacapo	Fair Phone	Fair Phone | PES	GKN | PES	Fair Phone	Use case
Dacapo technology	• Cloud computing, AI, 3D modelling • Generative Design Technology • VAE	• Machine learning, sensors, AI • Product Digital Twin: Advisory Engine	• IoT sensors, cloud computing • Process Digital Twin	• PET (privacy enhancing technologies), IoT connectors • Digital Twin	• Robotics
Application of technologies	• Generative Design: • Circular Economy • Advisory Engine	• Verification with AI, virtual testing	• Advanced Monitoring: • Asset Administration Shell (AAS)	• Predictive maintenance, product diagnosis	• Robotised disassembly
Benefit	More effective selection of design options from support of AI, more efficient evaluation of tweaking design parameters	DT enabled experimenting, Optimization of small scope design decisions using AI, Verification and testing	Improved defect tracking, more traceability of errors, reduction of defect rate, more efficient easier adjustment of settings, better IP protection and non-registered company technology, more efficient asset management	More effective use of sensor data, increase of scope for repair, increase of lifetime, reduction of down-time, more efficient stock management, better customer relations	Increase of scale of recycling operation, more efficient return logistics, more digital control over recycling flows, increase of purity of recyclate, better sorting capabilities, enabling disassembly
Deployment of CE strategy	• Function-for-function and product-for-product substitution	• Material-for-material and process-for-process substitution, including biotic materials	• Remanufacturing, Refurbish (closed-loop or open-loop)	• Repair, Reuse, Repurpose	• Recycling (closed-loop or open-loop)
Business Models connectie	• Can facilitate different types of servitisation Business models • Additionally, design for circular supply chain, biomaterials or renewable materials			• Servitisation • Prolonging lifetime • Sharing products	• Circular supply chain
Business Model specific	*To retain value by implementing servitisation business models technologies that can be used in every role can be used. Different technologies and application can be used to facilitate different types of Product Service System business models. In design and engineering; experimenting and optimising products helps to develop products in a way that places the functionality central or allows to share products.*				

It is expected that during the project, the stocktaking effort that is Table 1 can be populated and updated for cells, but that the overall structure will remain robust for the entire project and indeed for years to come.

A worthwhile speculation into the economic impact can be made. For this quantification, it is vital to understand the difference between merely adopting the Best Available Technology (BAT) by a significant share of European manufacturing and the potential that arises from R&D&I that enables to go beyond the BAT. We estimate that if BAT is deployed such that manufacturing labour productivity (amount of Value Added/Full Time Equivalent) of the EU manufacturing could be 0.15% higher on an annual basis (Bastein et al. 2013). And that amounts to something. Inflation corrected manufacturing Value Added in the EU-27 in 2015 and 2022 respectively were 1868 and 2358 billion EUR. Labour productivity in that same period rose by 9.9%. If labour productivity would annually be 0.15% higher, this would mean that around 30 billion of Value Added would be created in the EU-27. The benefits of deploying R&D&I that enables new business models and technology deployment is even harder to predict, but it would certainly be even greater.

5.4. Case study impact: How the discussed technologies can contribute to DaCapo case studies objectives

Fairphone currently stimulates reuse and recycling of end-of-use or end-of-life phones for example through the MyFairphone App. However, Fairphone is strongly interested to explore new digital tools and assets that will further increase the level of circularity of their smartphones. A key component for them is to track and trace smartphone components and understand how they constitute an operational smartphone. Innovative AAS and PET could be among the solution spaces that can provide the improved track & trace ability during the DaCapo project. Besides tracking components, being able to run certain diagnostics for components is equally important. This will enable us to implement predictive maintenance, and open up more opportunities for us to offer our products as a service as we would be able to accurately determine the value of used components based on the diagnostics as well.

Considering **GKN**, the ambitions in the DaCapo project are for example:

- Measure LCA for the life cycle and the whole value chain, using a Digital Twin and possibly Distributed Ledger technologies to account for the different stages of the chain;
- Look to replace some paperwork using an initial DPP product, where data sovereignty is one of the points of attention;
- Improve repair using adaptive process planning, with robotized support of executing the reparations might be an option.

The ambitions of **PESMEL** are discerned into four use cases:

- AI support for new warehouse configurations. The objective is to see if the AI can think of better solutions in the design and engineering phase;
- Optimizing the movements of the devices of warehouse system to save energy but still meet the operational goals (Just-in-Time). The use of reinforced learning might be relevant;
- Support the operator, by develop privacy-preserving AI methods to automatically recognize worker's physical and/or cognitive load using. This can be done using smart IoT solutions on the market that can measure key parameters;
- Maintenance support, using data from a preliminary DPP system of the most critical components such as drives and converters for the predictive maintenance.

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6. Conclusions

It is clear that a Circular Economy transition can contribute to meeting societal goals related to climate change, reducing other environmental impacts, improving social conditions and even building resilience in a dynamic global economy. However, the transition has thus far not delivered the desired reduction of negative impacts in recent years (Hanemaaijer et al. 2021; Circle Economy 2023). The policy actions on EU level that shape the circular transition require new tools to inform business decisions.

There is ample evidence that circular potential (expressed as the ability to retain and optimize the value of products throughout their use-cycle) is left unrealized. This untapped potential suffers from either a clear legal requirement or the absence of data, information and resulting knowledge to create a solid business-case.

We state that CE businesses potential can be found using digital tools and services. At **every stage** of the production cycle (from design to end-of-life/use) clear opportunities can be identified to create business value. This business value can stem from direct efficiency gains or more effective value retention, but can also come from novel deployment of circular strategies and even from value creations from public policy.

However, there is a clear disclaimer to be made about the feasible pace of change. It is observed that even for efficiency of value effectiveness measures, many enterprises do not see a reason to invest in new (digital) technologies with the aim of deploying circular strategies. The uncertainties and other barriers of investment are too sizeable compared to the positive business-case in case new technologies would be in place. **An even more significant barrier arises when looking to deploy novel circular strategies or pursue societal goals**. Persistent market failures prevent most companies for investing in R&D&I activities that need legal or societal change in order to create a positive business-case. Especially SME's can't afford to invest in complex R&D&I activities that have no assured return on investment.

The focus of R&D&I should therefore be on developing technologies that have both a use-case and a positive business-case. This means that technologies need to be deployed within one year, can be financed within (regional) peer-groups, clusters or branch organization and do not require a major (over 50% of exiting accounting value) change in corporate software, machinery or company staff. **More ambitious R&D&I will follow** as soon as either a new technology has proven itself on TRL 9, legal requirements are put in place or disruptive new business-cases are launched backed by significant financial investment.

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8. Annex 1

Digital application	Description
AAS (Asset Administration Shell)	The Asset Administration Shell (AAS) is the digital representation of an asset. The AAS consists of a number of submodels in which all the information and functionalities of a given asset – including its features, characteristics, properties, statuses, parameters, measurement data and capabilities – can be described.
Advisory engine	For sustainability impact forecasting, automatic scenario generation and smart impact comparison for circularity strategies, as well as critical circularity and sustainability hotspots identification will be established, generating the required knowledge base for DaCapo digital tools and services to be implemented”
Data Space	A distributed network of data end points (instances of the International Data Spaces connector) that enables the secure exchange of data and guarantees data sovereignty.
Didactic Factories Network	Open accessible pilot facilities hosted at the RTOs (each RTO is a network node) available for the EU manufacturing sector. This Network will provide an orchestrated effort in providing access to test and validation facilities and to a common training framework (methodology, materials and tools) based on in-situ training and access to latest technologies.
Digital Product Passport (DPP)	An instance of a distributed dataset describing a any physical product, aiming to enable sharing of key product related information that are essential for products along the supply chain.
Digital thread	A holistic approach that integrates, traces, and connects a series of complex data-driven events along the entire value chain
Digital Twin	A digital replica of an industrial process that is so good that manufacturing companies base their decisions for the real process on it. It combines data, models and the business process to create a digital life cycle in addition to the physical life cycle.
Digital Wallet	Digital wallets store the public and private keys required to buy cryptocurrencies and provide digital signatures that authorise each transaction.
Distributed Ledger (DL)	Distributed ledger technology is a platform that uses ledgers stored on separate, connected devices in a network to ensure data accuracy and security.
Generative Adversarial Networks (GAN)	Generative Adversarial Networks, or GANs for short, are an approach to generative modelling using deep learning methods, such as convolutional neural networks. Objective Reinforced approach (ORGAN) is a merger between RL and GAN. While RL biases the data generation process towards arbitrary metrics, the GAN component of the reward function ensures that the model still remembers information learned from data.
IDS RAM	The IDS-RAM (Reference Architecture model) is characterised by an open architecture (they publish their code as open source software), reliable and

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	federated for cross-sector data exchange, facilitating sovereignty and interoperability.
IoT connectors	Hardware that connects to cloud-base IoT gateways. They use MQTT and can feed AAS as an information model based on RAMI4.0.
Modular Digital Thread (MDT) concept	A normalized method for orchestrating the gathering and contextualization of data at different points of the product lifecycle (design and engineering, manufacturing shopfloor, use phase, End-of-Life - EoL), enhancing data availability for the definition of specific sustainability and circularity indicators and optimisation criteria”
MQTT	Lightweight communication protocol for M2M connectivity supported by the Organization for the Advancement of Structured Information Standards (OASIS). MQTT is a lightweight, publish-subscribe network protocol that transports messages between devices.
Multi Party Computation (MPC)	MPC is a ‘toolbox’ of cryptographic techniques. This enables multiple parties to compute data jointly, as if they had a shared database. Because the data have cryptographic protection, the parties can never view each other’s data.
Privacy Enhanced Technologies (PET)	Technologies that enable organisations to conduct joint data analyses in a privacy-friendly manner
RAMI 4.0	A Reference Architectural Model Industry, where 4.0 combines all elements and IT components in a layer and life cycle model
Reinforcement Learning (RL)	Reinforcement Learning is a branch of Machine Learning where an agent optimally learns to maximize the reward by interacting with the environment and understanding the consequences of good and bad actions
Self-Sovereign Identity (SSI)	SSI uses cryptographic technologies, such as public-key cryptography, zero-knowledge proofs, and sometimes blockchain. This enables the efficient exchange of verifiable digital information where a high degree of trust can be created, even between parties who do not trust each other by nature.
Variational Autoencoder (VAE) architectures	A variational autoencoder is an architecture composed of both an encoder and a decoder and that is trained to minimise the reconstruction error between the encoded-decoded data and the initial data