VTT Technical Research Centre of Finland

Digital product passport promotes sustainable manufacturing

Saari, Leila; Heilala, Juhani; Heikkilä, Tapio; Kääriäinen, Jukka; Pulkkinen, Antti; Rantala, Tuija

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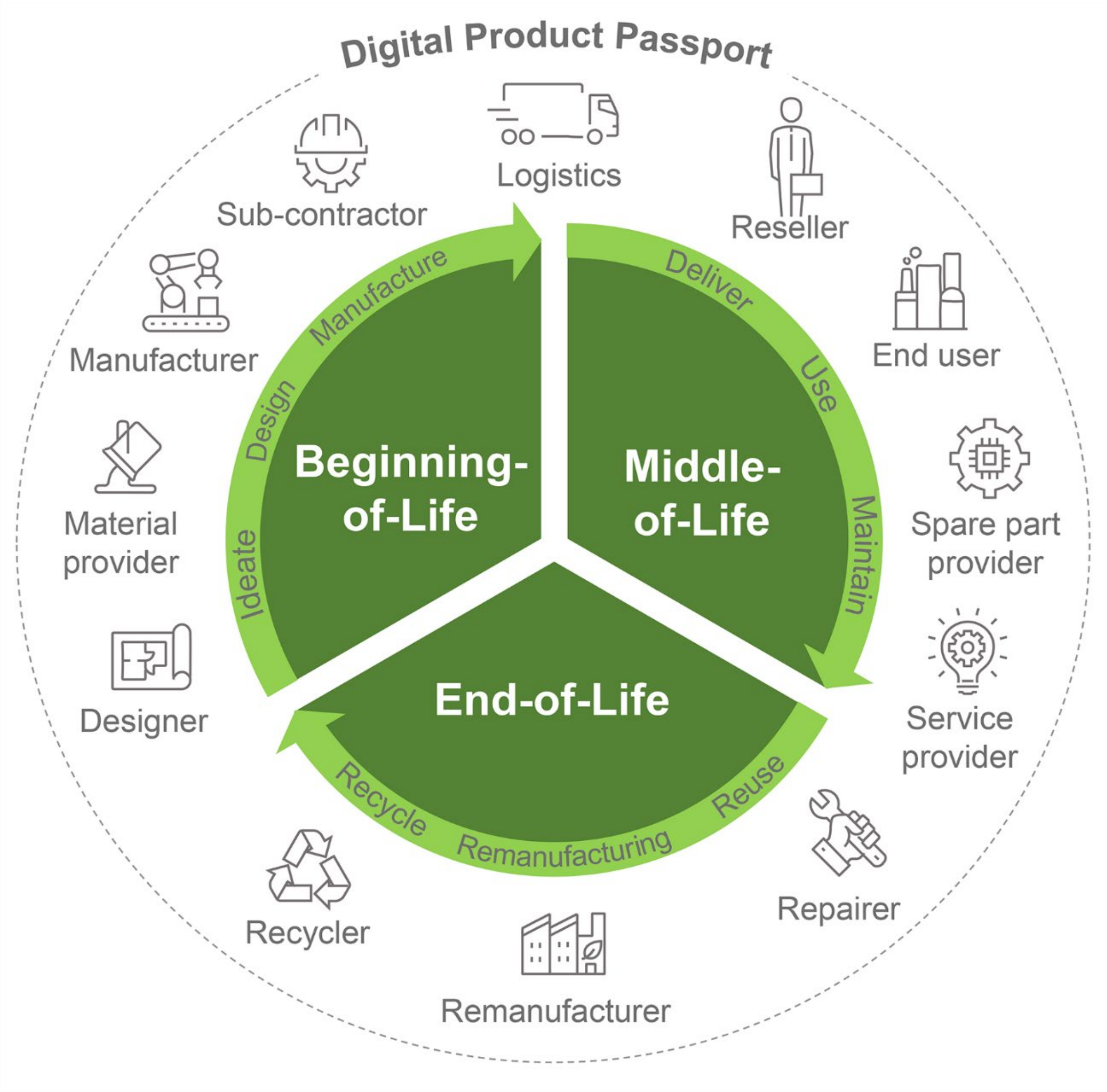

Leila Saari, Juhani Heilala,
Tapio Heikkilä, Jukka Kääriäinen,
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Preface

This white paper was written to gather, open and share the overflowing initiatives and concepts concerning twin transition and digital product passport (DPP) raised by European Commission. The authors hope this paper will help manufacturing industry to proceed with their sustainability goals and to develop circular economy through new R cycles. Further, the authors believe that the DPP is a concept worthwhile to study and further pilot in industrial cases.

In future the DPP will be used by the European authorities monitoring product regulations in Europe. The DPP can help consumers to make better (more sustainable) purchase decisions based on the available product information. The DPP shall help and guide the repair, remanufacturing and recycling activities of a product. Further, all product value chain actors can optimise their own operations based on the data shared via the DPP.

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Oulu, Thursday, 22 September 2022

Leila Saari, Juhani Heilala, Tapio Heikkilä, Jukka Kääriäinen, Antti Pulkkinen and Tuija Rantala

Content

I. Introduction

The consumption of materials and products is one of the drivers of biodiversity loss, which in turn affects ecosystem functioning and has socio-economic consequences worldwide. Industry and business have an impact on nature, but they also produce important innovations, partnerships and expertise that can help address biodiversity loss.

The current economic model is still based on “take-make-replace”. It depletes/consumes our resources, pollutes our environment, and damages biodiversity and climate. It also makes Europe dependent on resources from elsewhere. To address these problems, the European Union (EU) aims to move to a more circular economy (CE) model based on more sustainable products.

Despite this urgent moral, economic and environmental imperative, nature is in a state of crisis. The five main direct drivers of biodiversity loss – changes in land and sea use, overexploitation, climate change, pollution and invasive alien species – are making nature disappear quickly.

The European Commission (EC) is working on the Sustainable Product Initiative (SPI), which involves widening the scope of the Ecodesign Directive to the broadest possible range of products and developing the European Digital Product Passport (DPP). A DPP is a combination of i) a unique product identifier, and ii) data collected by different value chain actors related to this unique identifier. This data may include the characteristics of the product and information about its value chain and life (dynamic data). Smart management of materials, components, products and assets in a CE requires large amounts of information. Such information is not readily available today to those who could use it, leading not only to huge losses of value to consumes, producers and the entire economy but also to pollution and waste.

The DPP provides information about products’ environmental sustainability.

The DPP helps consumers and businesses make informed choices when purchasing products, facilitates repairs and recycling, and improves transparency about products’ life cycle impacts on the environment. The passports also help public authorities perform checks and controls better.

Addressing the environmental impact of products throughout their life cycle will lead to more sustainable, circular and resource-efficient products in Europe and thus also help retain biodiversity.

Both industrial alliances and companies seek and develop the DPP service from their perspectives, and some commercial services already exist. Solutions for the battery, textile and construction industries are the most advanced. Sub-solutions like online life cycle assessment (LCA) calculations or material passports already exist. The manufacturing industry lacks a total solution that would take advantage of existing standards and data sources.

For the authors, it is interesting to find out what is the minimum viable DPP for the manufacturing industry and thus help companies to proceed with the implementation of new R-cycles, more generally towards CE and to reach sustainability goals. Obviously, further studies are required to gain documented and shared success stories as well as impact assessments of those.

In the next section the background and drivers for the DPP are presented. State of the art is described in the third section and fourth brings in the basic elements. Last section displays both potential future research topics and VTT competences.

II. Background and drivers

This paper presents the important drivers and trends that need to be addressed. First, even the United Nations (UN) has called for **Sustainable Development Goals** (SDG) (United Nations, 2015). The SDGs have been adapted, for example, to the European Union (EU) funding structures and need to be factored to in any new project or venture. The SDGs and other relevant global or European initiatives are listed in chronological order in the attachments (see Table 6). Table 7 lists major domestic initiatives. The UN stated:

> **Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.**

This elaborated on the meaning of sustainability and presented it in three dimensions, i.e. environmental, social and economic responsibilities, commonly known as the triple bottom line concepts (see Figure 1) (United Nations, 1987).

The general principle of sustainable manufacturing is to reduce the intensity of materials use, energy consumption, emissions and the creation of unwanted by-products while maintaining, or improving, the value of products to society and to organisations. Enhancing the sustainability performance of the production process is an important contribution to developing a stronger and cleaner economy. Also, the manufacturing industry is willing (or forced) to consider sustainability and circular economy (CE) and to implement new R-cycles—e.g. reuse, remanufacture, recycle (see further Table 1) within their partner networks.

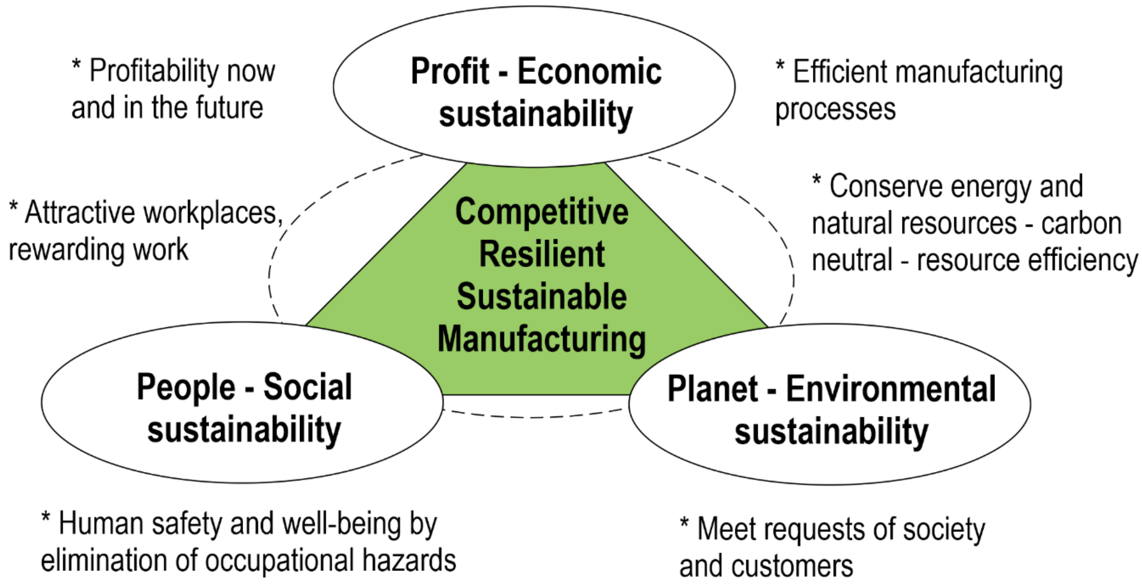

Figure 1: The UN Sustainable Development Goals (SDGs) have three pillars: environmental, economic and social (Heilala, 2022; United Nations, 2015)**.**

The **twin transition** combines digitalisation and green transition and turns Europe into a green, digital and resilient economy (von der Leyen, 2020). According to our understanding, the sustainability of manufacturing can be pursued 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 ICT solutions for energy and material consumption optimisation;
- developing (and applying) sustainability tools and methods.

In the next chapters we try to clarify the cross-cutting topics nearby sustainability, circular economy and digital product passport from the viewpoint of the manufacturing industry. We start with sustainable manufacturing. Although sustainability has three pillars (economic, environmental and social), most of the activities are focused on the economic goals. Together with the inevitable climate change also environmental aspects have been brought to the table. Still, the social aspects are barely touched.

Circular economy contributes mainly to environmental challenges via implementing various R-cycles such as reduce, repair, recycle, remanufacture etc. Various R-cycles are both solving environmental challenges and contributing to the maintenance of biodiversity.

The hypothesis of this paper is that the digital product passport will help manufacturing companies to proceed with the twin transition, i.e. both with digitalisation and sustainability goals. Product life cycle management is an essential concept and requires attention and interoperable interfaces with existing legacy systems and standards.

Sustainable manufacturing

The transition path towards sustainable and autonomous manufacturing is expected to take place with consecutive steps from integrated manufacturing to learning and intelligent manufacturing, which precedes autonomous manufacturing. The steps are taken in the three contexts of industrial cooperation, the changing role of humans and level of autonomy. According to VTT's vision

> **Data is shared in real time in industrial communities... Factories have minimised their environmental footprint with extended life cycles of assets, reduction of material loss and waste, utilisation of sustainable energy and recycled materials and lower logistics footprint in just 13 years from now.** (Salminen et al., 2022, p. 13)

According to Paasi et al. (2021), energy and material savings in industry have improved in recent years. However, they argue that there exists huge potential for utilising IoT, big data and RFID in the processes and practices of CE (Paasi et al., 2021). Salminen et al. (2022) suggested six practical steps as follows:

- Adopting shared visions and targets;
- Increasing data transparency and accuracy;
- Redesigning manufacturing processes and life cycles;
- Redesigning both products and production;
- Developing and investing in key capabilities for a sustainable transition; and
- Going beyond, which means radical multi-domain innovation.

Turning sustainability into customer value and financial profit is challenging for manufacturing companies. Forefront customers understand better the meaning of sustainability, technological development, and data utilisation, but the situation varies greatly (Rantala et al., 2022a). Many manufacturing companies are still at a stage in which they are trying to understand the meaning of sustainability for themselves in general. The potential for value creation, for example, in speeding up the customer's decision process, decreasing life cycle costs, seeing the bigger picture and offering data-based services, was mentioned as challenging by some manufacturing companies (ibid).

Translating sustainability into the level of operations and product or service design is still very challenging. There is a clear need for a sustainability framework that assists in the formulation and implementation of sustainability strategies in manufacturing companies and their value chains (Rantala et al., 2022a). Manufacturing companies are still trying to understand both data utilisation and sustainability and their meaning to their businesses and operations. Although they may see themselves as advanced data utilisers with a sustainability focus, they might see sustainability from quite narrow perspectives (ibid). Sustainability data is the core enabler of sustainable innovation and it can be defined as

> **any data that enables sustainable innovations, increased sustainability performance or indication of sustainability in companies** (Rantala et al., 2022b).

Orko et al. (2022) interviewed 81 companies, R&D and regional support organisations from battery, textile and food value chains. Data management in companies is mostly based on traditional ERP and Excel tools and some experiments to develop own tools or apply emerging circular data platforms, blockchain solutions or cloud services. Excluding process or customer management data, much of the sustainability data is still collected manually. There is a need to develop automated value chain data management tools. The practical data opportunities are still blurry, and the willingness to share data relies on valid business reasons and the means to control the use of the data (Figure 2). The boundaries of the different roles in the value chain blur in the CE. New circular business models seek value in combining circular product manufacturing with waste management, or end-of-life recycling service with retail or manufacturing. (Orko et al., 2022)

Data needs

- Harmonised data on side streams
- Data and methods for logistics optimisation
- Data relating to material passports and material inventories
- Local LCA data
- Bencmarking data
- Value chain data

Circularity data drivers

- Compliance and sustainability reporting
- Regulation
- Customer demand
- Climate change mitigation, sustainability and CO2 reduction targets
- Leaning operations, cost savings
- CE collaboration to manage the supply chain Logistics optimisation

Role of data in CE operations

- Efficient processing and material use
- Sustainability reporting
- Product pricing and sales, esp for second-hand products
- Sustainable procurement
- For platform operators, data is the business enabler of the core service

Future Data opportunities

- Pay-as-you-throw models and deposits
- Compiling data on volumes of side streams to enable trade and cost efficient processing, e.g. ashes
- Reduction of CO2 emissions and water use based on real-time data
- Local reuse and cycling
- Tailored solutions for optimised customer value
- Business models and designs based on data collected from the use phase/customer

Figure 2: Findings from stakeholder interviews (Orko et al., 2022)

Circular manufacturing

CE is transforming manufacturing through the adaptation of different strategies (R-cycles in Table 1 and Figure 4) and CE business models (CBM). Still, there is no common definition of circular manufacturing (CM). Researchers have published one CM definition: “The concurrent adoption of different CM strategies, which enable to reduce resources consumption, to extend resources lifecycles and to close the resources loops, by relying on manufacturers’ internal and external activities that are shaped in order to meet stakeholders’ needs.” (Acerbi & Taisch, 2020b)

More precisely, circular design, disassembly, remanufacture, reuse, recycle, servitisation, cleaner production, resource efficiency, waste management, industrial symbiosis–closed-loop supply chain and reverse logistics–represent the CM strategies identified in the systematic literature review performed by Acerbi and Taisch (Acerbi & Taisch, 2020b).

In CM, the enterprise strategy and CBMs are the key drivers for the design of products, production system, supply chains and services during the extended life cycle of the product. These functions influence each other in different ways; they also define the needs and requirements for ICT infrastructure for handling the complexity of information management throughout the value chain. There is a need to cover various life cycle–related data.

Managing the data in current manufacturing and production systems over the life cycle of individual products and assets and across manufacturing enterprise processes and networks is a challenging task. Further challenges to life cycle data management are posed by the requirements of sustainability and CE (Kortelainen et al., 2019). The National Institute of Standards and Technology (NIST), among others, has studied standardisation in smart manufacturing (Lu et al., 2016). NIST describes the SME that encompasses the manufacturing pyramid with three dimensions – product, production and enterprise (business) (Li et al., 2018).

- **Product**. The product life cycle ranges from design, process planning, production engineering, manufacturing, use and service to EoL and recycling. The information flows and control signals along the product life cycle can be huge.
- **Production**. The production system life cycle ranges from design, build, commission, operation and maintenance to decommissioning and recycling. These life cycle phases are mainly about an entire production facility, including its systems.
- **Business**. The supply chain cycle ranges from plan, source, make and deliver to return, which mainly addresses the functions of interactions between supplier and customer.
- **Manufacturing pyramid**. This dimension is based on the IEC/ISO 62264 model—enterprise level, manufacturing operations management (MOM) level, supervisory control and data acquisition (SCADA) level, device level and cross levels, which is the vertical integration of machines, plants and enterprise systems. (Li et al., 2018)

Three dimensions converge on smart manufacturing: **digital thread, smart factory and value chain**. Data and information on product design are collected from multiple heterogeneous digital systems, from CAD/CAE to PLM. The digital thread is a digital representation of the physical product life cycle. Under a smart factory, production provides resources and processes according to product design data, production engineering, physical material handling actions and transformation on the factory floor. The value chain focuses on minimising resources and accessing value at each stakeholder function along the chain, resulting in optimal process integration, decreased inventories, better products and enhanced customer satisfaction. It includes customer, compliance, operations, resource and supplier (information) management.

The supply chain operations reference (SCOR) model was developed to describe the business activities associated with all phases of satisfying customer demand. The SCOR reference model consists of four major sections: performance, processes, practices and people. The performance section of SCOR focuses on the measurement and assessment of the outcomes of supply chain process execution. SCOR recognises six primary management processes—Plan, Source, Make, Deliver, Return and Enable. The latest version SCOR 12.0 (2017) includes sustainability aspects using the Global Reporting Initiative (GRI) standardisation (APICS, 2017).

Standardisation is an enabler of heterogeneous ICT systems and infrastructure interoperability. For the DPP, international or European standards will be needed, at least in the following areas (Galatoga, 2022):

- Data carriers and unique identifiers;
- Access rights management;
- Interoperability (technical, semantic, organisational), including data exchange protocols and formats;
- Data storage;
- Data processing (introduction, modification and update);
- Data authentication, reliability and integrity; and
- Data security and privacy.

For environmental assessment, an inventory of all input and output, elementary (resources, emissions) and non-elementary (energy, waste, materials) flows shall be compiled for all processes included in the value chain. All flows must be modelled until the elementary flow level to calculate the associated impact on the life cycle of the product or organisation in scope (e.g., from the output waste, the specific air, water and soil emissions generated by the treatment processes are determined). The mandatory life cycle stages included in an **environmental footprint** (EF) study are as follows (European Union, 2021a):

- Raw material acquisition and pre-processing: e.g. extraction of resources, pre-processing of all materials (including recycled materials), agriculture, forestry, packaging production, and transportation associated with these activities.
- Manufacturing: all processes taking place from the entry to the exit gate of the production facility (e.g. chemical processing, manufacturing, assembly).
- Distribution: transport and storage of the finished product(s), including the refrigeration and warehouse activities consumptions (e.g. energy).
- Use stage: product(s) use for the defined function and lifetime, including all necessary inputs (e.g., energy, maintenance materials, coolant).
- End of life: all activities occurring from the moment the product(s) ceases to perform its function and is disposed of or recycled. This includes, for example, collection and transport, dismantling, sorting, processing into recycled material, landfill and incineration. (European Commission, 2021d)

In addition to the phases listed above, Sitra et al. also identified product design. Figure 3 maps the inefficiencies within the manufacturing value chain. (Sitra; Technology Industries of Finland; Accenture., 2020)

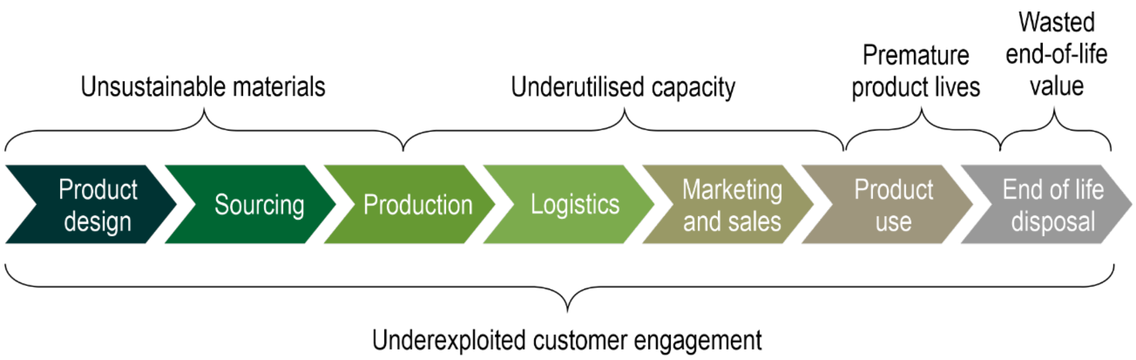

Figure 3: Inefficiencies within the manufacturing value chain (Sitra; Technology Industries of Finland; Accenture, 2020)

Circular economy and R-cycles in the manufacturing industry

We adopt the definition of circular economy (CE) sealed by Korhonen et al.:

> **CE is an economy constructed from societal production-consumption systems that maximize the service produced from the linear nature-society-nature material and energy throughput flow.**
>
> **This is done by using cyclical materials flows, renewable energy sources and cascading type energy flows. Successful CE contributes to all the three dimensions of sustainable development. CE limits the throughput flow to a level that nature tolerates and utilises ecosystem cycles in economic cycles by respecting their natural reproduction."** (Korhonen et al., 2018)

Figure 4 illustrates how the linear economy produces waste after the usage phase. In the recycling economy, the amount of waste is already diminished as some products or materials are recycled during the end-of-life phase of a product. In the ideal CE case, no waste is produced, as everything can be exploited within various R cycles.

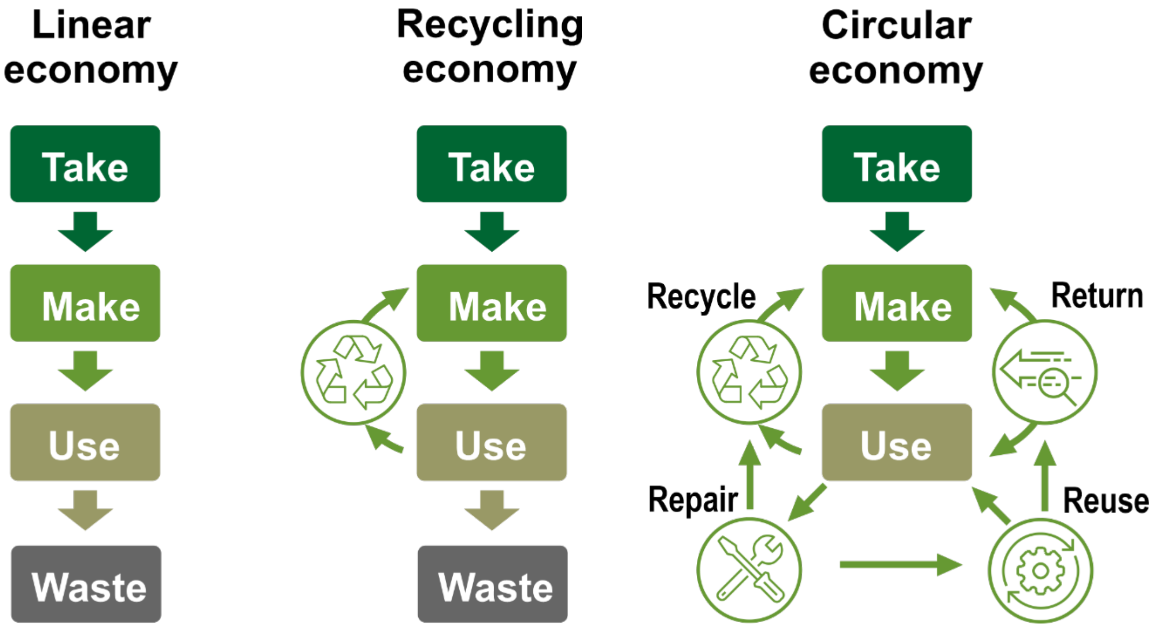

Figure 4: The amount of waste decreases when recycling. In CE, there is no waste.

CE is often described through R framework, such as 3Rs: reduce, reuse and recycle (Kirchherr et al., 2017); 4R adding reduce to 3R (EUR-Lex, 2008); 6R including recover, redesign and remanufacture on top of 3Rs (Yan & Feng, 2014) and 9R, such as refuse, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle materials, recover energy and re-mine (Potting et al., 2017; Reike et al., 2018). Of these R concepts, 3R has been the most prominently used; nevertheless, it does not demonstrate the systemic nature of CE. The benefit of describing and visualising CE via long-loop Rs (starting from 6R forward) is that it depicts the complexity of CE systems and demonstrates the crucial stakeholders that operate within the system, emphasising the collaborative nature of CE. 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, i.e. useful applications of materials. In 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.

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

	R strategy	**Description**
Smarter product use and manufacturing	**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.
Extend lifespan of product and its parts	**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.
Useful application of materials	**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.

Connected Factories coordination and support action (CSA) project defined the maturity levels of CE for manufacturing industry, such as: linearity, industrial CE piloting, systemic materials management, CE thinking and circularity (Figure 5). These maturity levels together with the manufacturing value chain form a matrix giving examples of actions needed to be fulfilled in each level and phase (Acerbi et al., 2021; Saari et al., 2021).

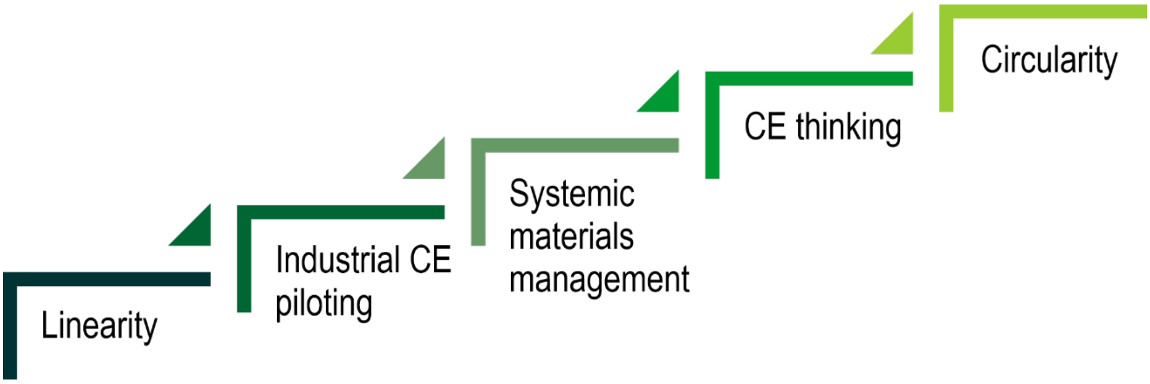

Figure 5: The maturity levels of CE for the manufacturing industry (Acerbi et al., 2021; Saari et al., 2021)

Biodiversity

Biodiversity—the variety of life on Earth, including plants, animals, fungi, micro-organisms, and the habitats in which they live—and ecosystems where living species form provide us with food, materials, medicines, recreation, health and well-being. They clean the water, pollinate the crops, purify the air, absorb vast quantities of carbon, regulate the climate, keep soils fertile, provide us with medicine and deliver many of the basic building blocks for industry. (European Commission, 2020b)

Damaged ecosystems are more fragile and have a limited capacity to deal with extreme events and new diseases. Well-balanced ecosystems, by contrast, protect us against unforeseen disasters, and when we use them in a sustainable manner, they offer many of the best solutions to urgent challenges. Losing biodiversity is:

- a **climate** issue—destroying and damaging ecosystems and soils speeds up global warming, while nature restoration mitigates climate change;
- a **business** issue—natural capital provides essential resources for industry and agriculture;
- a **security** and **safety** issue—loss of natural resources, especially in developing countries, can lead to conflicts and increase vulnerability to natural disasters everywhere;
- a **food security** issue—plants and animals, including pollinators and soil organisms, play a vital role in our food system;
- a **health** issue—the destruction of nature increases the risk of diseases and reduces our resistance to them. Nature also has a beneficial effect on peoples' mental health and welfare;
- an **equity** issue—loss of biodiversity hurts the poorest most of all, making inequalities worse;
- an **intergenerational** issue—we are robbing our descendants of the basis for a fulfilled life. (European Commission, 2020b)

Product life cycle

The term product life cycle indicates *the set of phases, which could be recognised as independent stages to be passed by a product, from its "cradle to its grave,"* and it can be divided into three main phases: Beginning-of-Life (BoL), Middle-of-Life (MoL) and End-of-Life (Eol). The BoL phase relates to the ideation, design and manufacturing of the product in the supplier network. Therefore, in the BoL phase, the product is in the hands of the manufacturing company within the boundaries of the (extended) enterprise. The MoL phase relates the distribution of the product to its use environment, its usage and support. In the MoL phase, the product is typically in the hands of customers and service providers. EoL is the phase in which the product is no longer used and is recycled or disposed. At this point, the product may return to the manufacturer or proceed to a recycling service. Product Lifecycle Management (PLM) provides an information management viewpoint on the product life cycle—a kind of business integration platform. The concept of PLM is well established to describe

> **the management of all the business processes and associated data generated by events and actions of various life cycle agents (both human and software systems) and distributed along the product's life cycle phases.**
> (Matsokis & Kiritsis, 2010)

When considering the effective implementation of the CE, the appropriate data flows to support it play an important role. Traditionally, information management has been focused on the BoL phase, but data from the subsequent life cycle phases should also be mobilised (de Oliveira & Soares, 2017). Therefore, the modern product life cycle is characterised by an interdisciplinary interaction between a large number of internal and external stakeholders (Acerbi & Taich, 2020). As an enabler of information management, PLM must consider the entire network of supply chain stakeholders to improve information access and sharing inside and outside the company. This may include information, such as the actual recycling or reuse rate of the products, lifetime information of the product or, for example, actual environmental impact information. For instance, for the manufacturer, this data should make it possible to design the product to facilitate its subsequent circular management (Acerbi & Taisch, 2020a). Further, they introduce the concept of circular product life cycle management that could support reasoned decision-making during the product lifecycle from BoL to EoL. This requires that the appropriate information is collected from the right life cycle stakeholder (internal or external), managed and passed on in the appropriate form to the right party for decision-making. This is complex since the creation and exploitation of product-related information during the product life cycle involves a rich coverage of actors, such as product manufacturers, subcontractors, material suppliers, logistics companies, resellers, end product users, spare parts and service vendors, authorities, repair shops and recyclers. Figure 6 exemplifies the variety of actors during product BoL, MoL and EoL.

Recently, the concept of System Lifecycle Management (SysLM) has been introduced after the introduction of concepts and technologies such as digital twins, digital thread and IoT. SysLM emphasises the idea that

> **all phases of the product lifecycle and specialist disciplines must be consistently transformed in the interdisciplinary, model-based development world** (Eigner, 2021, p. 18).

SysLM covers well the BoL and MoL, i.e. the life cycle stages from requirements to after-sales and service, but it does not cover the needs of CE and is still quite engineering-oriented. Eigner (2021) emphasises the role of standards in enabling interoperability and enhancing MoL processes. The most important standard for the support of MoL processes is the Product Life Cycle Standard (ISO 10303-239 PLCS) (ISO, 2012) that is intended for product data representation and exchange. The PLCS standard provides resources for extending the original content of PLM systems from product definition to manufacturing. The extension addresses the needs of service operations and networked manufacturing but may not suffice the needs of CE with an indefinite product life cycle. The cases of deploying standards in real life have shown the advances of interoperability between the locked-in software of stakeholders, but an OEM still holds all the access rights to product master data. Even though the PLCS standard is a step in the right direction, the need for DPP still exists because means for the public identification of products are needed.

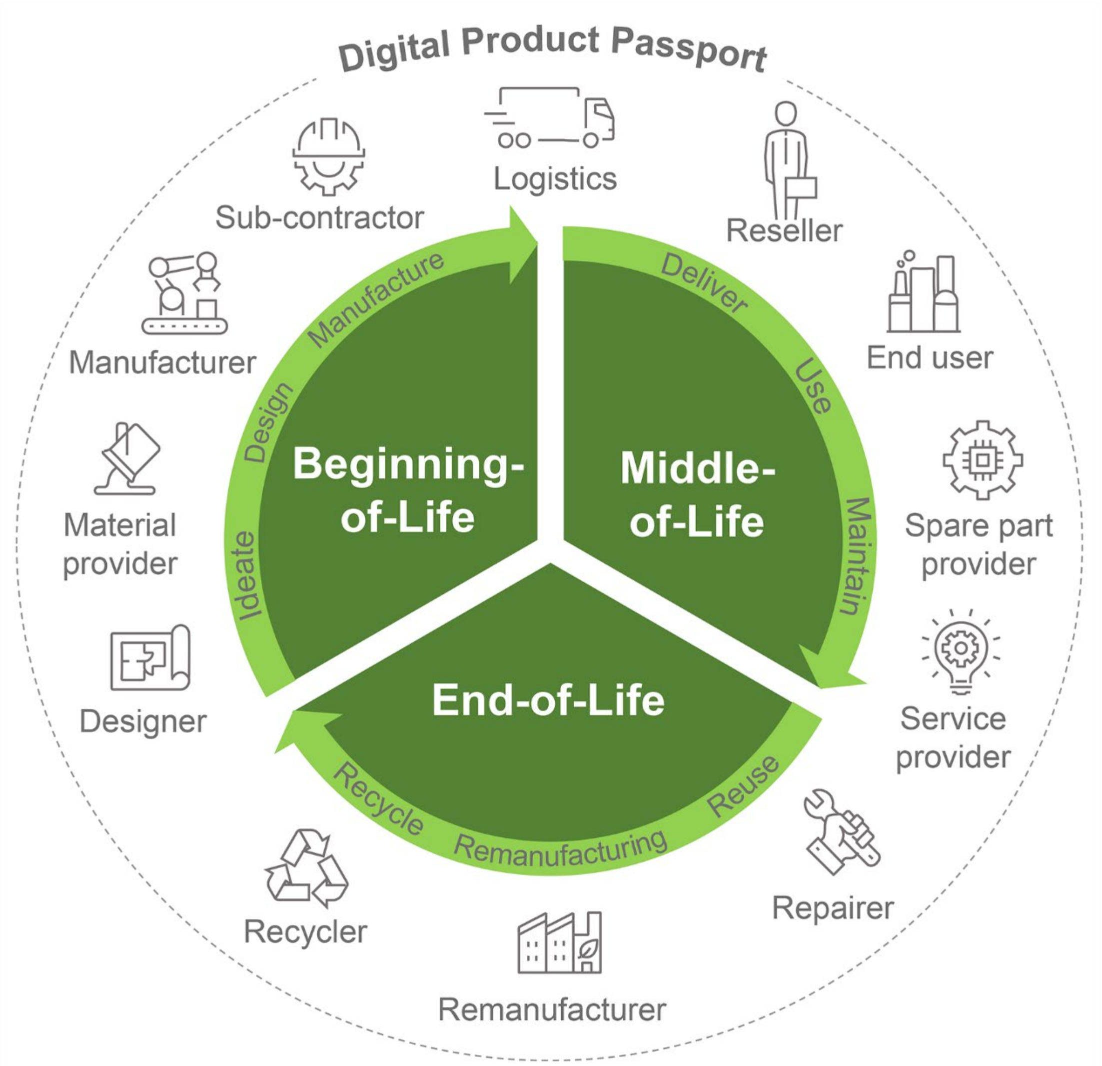

Figure 6: DPP links the product-related information of various actors during the product life cycle.

European Commission drives towards the Digital Product Passport

In addition to the environmental goals listed in Table 6 (in Appendices), there are several initiatives promoting environmental challenges of manufacturing, such as product environmental footprint (PEF), ecodesign and the European Digital Product Passport (DPP).

Reliable and correct measurement of and information on the environmental performance of products and organisations are an essential element in the environmental decision-making of a wide range of actors. The product environmental footprint (PEF) and the Organisation Environmental Footprint (OEF) are LCA-based methods for measuring and communicating the potential life cycle environmental impact of products (goods or services) and organisations, respectively. Together, they form the basis for the EU Environmental Footprint (EF). The EF builds on existing approaches and international standards, such as the ISO 14040 series (ISO, 2006) and the European International Reference Life Cycle Data System (ILCD) guidelines (European Commission, 2010). The overarching purpose of PEF and OEF is to provide information that can enable the reduction of the environmental impacts of goods, services and organisations considering all the value chain activities (from extraction of raw materials through production and use and to final waste management). (European Union, 2021a, 2021b)

Ecodesign requirements relate to product': i) durability; ii) reliability; iii) reusability; iv) upgradability; v) reparability; vi) possibility of maintenance and refurbishment; vii) presence of substances of concern; viii) energy use or energy efficiency; ix) resource use or resource efficiency; x) recycled content; xi) possibility of remanufacturing and recycling; xii) possibility of recovery of materials; xiii) environmental impacts, including carbon and environmental footprint; and xiv) expected generation of waste materials. (European Commission, 2022a)

Transition to sustainability and CE requires smarter management of product-related data across the product life cycle, from manufacturing to use, reuse and recycling. Most of this information exists somewhere but is not available to all actors along the value chain for now (see Figure 7). This is lost potential for the entire economy and increases EU dependency on primary materials. CE is primarily about value retention in the economy, and increasingly, the value of products is bound up in the data they hold or generate. Therefore, the loss of this data implies lost value for companies and the wider economy, less informed consumers and authorities, less efficient processes along the life cycle of the product (production, maintenance, repair, recycling), lost functionality for consumers, and negative environmental impacts of premature replacement. (European Commission, 2022b, 2022c)

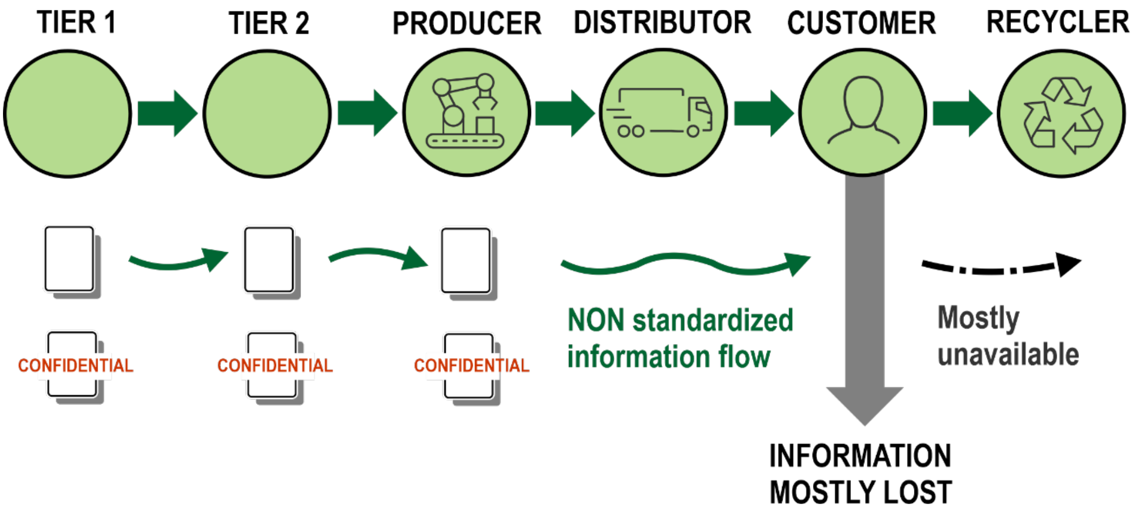

Figure 7: Information flow in linear economy (European Commission, 2022b)

III. State of the art: Digital Product Passport

Digital Product Passport (DPP) stores and shares all relevant information throughout the product life cycle (European Commission, 2022b, 2022c). The objective of the DPP is to support sustainable production, enable the transition to CE, provide new business opportunities for economic actors, support consumers in making sustainable choices and allow authorities to verify compliance with legal obligations (Figure 8).

Figure 8: Objectives of the DPP concept (European Commission, 2022b, 2022c)

EC defines the basic concepts as follows:

- **Product passport** means a set of data specific to a product that includes the information that is accessible via electronic means through a data carrier.
- **Data carrier** means a linear bar code symbol, a two-dimensional symbol or other automatic identification data capture medium that can be read by a device.
- **A unique product identifier** means a unique string of characters for the identification of products that also enables a web link to the product passport. (European Commission, 2022d)

Guth-Orlowski lists four requirements for the DPP as follows: access control, inclusivity, flexibility and data quality (Guth-Orlowski, 2021).

- **Access control**: Certain information about a successful product, e.g. its composition or supply chain, is often a well-guarded company secret. For it to remain possible to differentiate from competitors, secrecy is a requirement for the access control mechanisms of the system that implements the DPP.
- **Inclusivity**: The costs and technical hurdles to participating in the battery passport must not be so high that they exclude small economic actors. Inclusivity also means that standards must be used for the solution that enables all actors to build their own solutions to access the product passport system. Dependencies on one technology provider must be avoided from the beginning.
- **Flexibility**: In global value chains, a large number of players change frequently. The required

attributes that a product passport must contain are also constantly evolving. This requires a system that can flexibly add new companies, people or product attributes and remove actors or information that is no longer required.
- **Data quality**: The DPP is only effective if the information it contains is correct and verifiable. To avoid “garbage in–garbage out,” the technical solution concept must ensure the highest level of data quality. This can be achieved by performing audits or letting independent parties verify the trustworthiness of the information, actor or process used. (Guth-Orlowski, 2021)

EC identifies a number of areas where digital transformation plays a key role in enabling the CE—in particular (European Commission, 2020a):

- Designing sustainable products and business models: mobilising the potential of digitalisation of product information, including solutions such as DPPs, tagging and watermarks, as well as enabling circular business models, such as product-as-a-service;
- Circularity in production processes: promoting the use of digital technologies for tracking, tracing and mapping of resources;
- Construction and buildings: promoting measures to improve the durability and adaptability of built assets in line with the CE principles for building design and developing digital logbooks for buildings;
- Driving the transition through research, innovation and digital transformation: Digital technologies can track the journeys of products, components and materials and make the resulting data securely accessible. The European data space for smart circular applications will provide the architecture and governance system to drive applications and services, such as product passports, resource mapping and consumer information. (European Commission, 2020a)

Expected benefits of Digital Product Passport

DPP could provide benefits to the actors in the product life cycle. According to the EC (European Commission, 2022b, 2022c), private sector voluntary product passport initiatives already demonstrate the benefits that an EU DPP could also provide. Furthermore, companies will be better able to address financial, operational and reputational risks due to increasing transparency in value chains. The anticipated benefits or applications are listed in many reports and references (European Commission, 2022b; Guth-Orlowski, 2021; Plociennik et al., 2022; Re-Tek, 2019). Different actors may benefit from DPP, for instance:

- **Designers** will be better able to take into account the feedback from middle- and end-of-life in product design (e.g. improving a product’s recyclability or maintainability).
- **Manufacturers** will be better able to collect complete product life cycle information and use it for various purposes, such as traceability for warranty claims and recalls, establishing the link between product flaws and the set of parameters used in the manufacturing process, predictive maintenance, etc.
- **Repairers and maintenance service providers** may benefit from detailed technical information, history and spare parts information to provide better services.
- **Remanufacturers** will benefit from access to important information regarding components.
- **Recyclers** will benefit from information on hazardous or valuable materials.
- **End users** will be informed about different aspects of the product to support environmentally conscious purchase decisions and the handling of the product (e.g. spare parts, CO2 footprint of the product, allergens, etc.).

Potential use cases

DPP follows the physical product throughout its life cycle, allowing different stakeholders to produce and use a product and its usage-related information at multiple levels (Walden et al., 2021). When this is done comprehensively, the DPP may help to switch from mixed physical and digital information to a digital-only information supply, including technical and safety data sheets (Adisorn et al., 2021). It can be stated that DPP can increase transparency for both consumers and businesses, enable improved sustainable practices throughout a product life cycle (material grades, carbon footprint, etc.) and provide centralised information flow among stakeholders to, for instance, avoid losing data during a product's life (Re-Tek, 2019).

Since it will be likely that manufacturers and suppliers are the primary source of DPP information, attractive circular business models are needed so that manufacturers have incentives to participate in DPP. These could be, for example, that IoT-equipped products deliver information for manufacturers enabling them to expand their business model (e.g. better predictive maintenance) as is envisaged for the asset administration shell (AAS) (Adisorn et al., 2021). Another potential service that could be provided by DPP is automated LCA calculation (Plociennik et al., 2022). This is possible if DPP collects a rich set of data throughout the product life cycle to enable a comprehensive or streamlined LCA. Furthermore, the manufacturer may be able to use field data or end-of-life data in design phase decisions (Terzi et al., 2010) to develop new product versions to make them easier to maintain and recycle.

Retailers can utilise DPP information to make their product range more sustainable and provide sustainability information at the point of sale—depending on which data retailers receive and to what extent this is allowed to be used in customer advice. The potential of the DPP for product users comes with information transparency that may guide the user to make more conscious purchasing decisions. **Repair shops** need precisely disaggregated information about repairs and spare parts. Opening this information could result in a rise in the number of repair shops for many product sectors. **Waste management companies** also benefit from life cycle data, such as materials included in products, dismantling instructions and end-of-life handling guidelines. This information may help reduce dismantling costs or facilitate the sale of recycled materials at higher qualities. (Adisorn et al., 2021)

According to the EC, the European DPP contains information on a product that supports (European Commission, 2022b):

- **operators** along the supply chain to consolidate (a) the data received from their suppliers on the environmental and social impacts of their input, (b) the environmental and social impacts of their own operations into a figure (for each category of impacts) ready to be transmitted to and used by their own customers and (c) the data received from their suppliers on the environmental and social impacts of their input (if relevant and appropriate);
- **operators** along the supply chain to perform their work efficiently in terms of natural resources and energy and of economic value, specifically as regards value-retaining operations (maintenance, repair) or value-restoring operations (refurbishment, upgrade, retrofit and recycling);
- **final consumers** in their purchasing decisions towards higher environmental and social sustainability of products; and
- market surveillance and customs authorities.

Applications related to DPP

The European Parliament highlights the management of **battery** waste (EUR-Lex, 2020), which is one reason DPP applications for batteries are promoted. In addition, the Global Battery Alliance (GBA) is setting up an electronic information exchange system for batteries and a passport scheme for industrial and electric vehicle batteries (GBA, 2022). It is desired that by the end of 2022, the **Battery Passport** will be fully operational.

Finland will become a forerunner in the sustainable and knowledge-based **textile** industry by 2035, and the road map has been published (Kamppuri et al., 2021). In the future, the environmental claims for (textile) products should be based on LCA calculations, according to the PEF method, and a DPP is being developed to ensure the availability of product-related information throughout the product life cycle.

Adisorn et al. (2021) studied regulated and voluntary product information initiatives and presented a comparison of different approaches related to the DPP (Table 2). Some of the approaches are more mature than others. For instance, Energy label[1] and cradle-to-cradle (C2C) passport[2] have already been implemented while some are at the demonstration phase. Based on their analysis, Adisorn et al. (2021) made a few remarks that are interesting from the perspective of this article. First, online databases may contain confidential and non-confidential information that can be accessible to selected user groups in a product value chain. These needs must be able to be identified and addressed. Second, product information can be relevant to different user groups but with different levels of detail. For instance, market surveillance authorities need more detailed information than end users do. Third, finding attractive business models related to the initiatives is key to creating acceptance, especially for manufacturers. This is highly important since finding smart business models facilitates the acceptability of data collection and enables new businesses based on the rich data collected.

Table 2: Comparison of approaches related to the DPP, adopted from Adisorn et al. (2021)

	Digital Product Passport	**Energy label**	**Material passport**	**Cradle-to-cradle passport**
Status	Pre-conceptual phase	Implemented	Demonstration	Implemented
Product category	In theory, for all products discussed	Energy-related products	Building materials	E.g., ships
Key information categories	Origin, composition, repair and dismantling, handling at EoL	Energy consumption, technical aspects	Information on reuse of materials, cross-references to data sheets, environmental product declarations (EPD)	Location of material use, material characteristics
Life cycle phase targeted	Production, repair, disposal to complete life cycle	Use phase	EoL	Production, repair, disposal
Data tool	unknown	European product registry for energy labelling, EPREL[3]	Materials passport platform, E.g. BAMB[4], building information model (BIM)	Database for material information, 3D modelling
Information providers	Suppliers, manufacturers	Manufacturers	Manufacturers	Suppliers, manufacturers
Target group	Market surveillance, consumers, repair shops, waste operators	Market surveillance, consumers	Architects, builders, deconstruction companies	For example, ship operator/ owner

Table 3 lists some application examples of product environmental footprint (PEF) including both in-house and external applications.

[1] Energy label helps consumers make a choice based on the relative energy efficiency, energy consumption, and performance of a product in typical operating conditions.

[2] Cradle-to-cradle passport, which will be updated throughout the life of the ship, is a database listing the material composition of the main parts of the ship.

[3] https://eprel.ec.europa.eu/screen/home

[4] https://www.bamb2020.eu/topics/materials-passports/

Table 3. Applications of product environmental footprint (PEF) (European Union, 2021a)

In-house applications	External applications, e.g. business to business (B2B), business to consumer (B2C)
• optimising processes along the life cycle of a product, • supporting environmental management, • identifying environmental hotspots, • supporting product design that minimises environmental impacts along the life cycle, • environmental performance improvement and tracking	• applying or complying with policies referring to the PEF, • responding to customers' and consumers' demands, • marketing, • cooperation along supply chains to optimise the product along the life cycle, • participating in 3rd-party schemes related to environmental claims or giving visibility to products that calculate and communicate their life cycle environmental performance.

Life cycle thinking forms one of the basic principles of sustainable development, and life cycle assessment (LCA) is the leading method for assessing the potential environmental impacts of a product, process or service throughout its life cycle (Pajula et al., 2017). Life cycle assessments are often complex and extensive since they involve a huge amount of input data as well as various factors. Therefore, various calculation software programmes have been developed to help calculate them (Pajula et al., 2017). These tools typically include databases and impact assessment methods to help with calculations. One example of this kind of tool is SULCA (Semantum & VTT, 2020). SULCA software allows the user to perform ecodesign and various kinds of life cycle assessments. With SULCA, the environmental, carbon and water footprints can be calculated in a transparent and user-friendly way. Tool supports the evaluation of sustainability and environmental performance of a product, process, technology or any other system. SULCA utilises inventory databases for calculations, such as LIPASTO, covering the viewpoints of transportation.

The LIPASTO service developed by VTT contains calculation models that enable us to **calculate emissions from transport**. It already contains three parts: i) scenario models for calculating future scenarios for transport emissions, ii) inventory models for calculating historical data, i.e. traffic emissions inventory, for Statistics Finland, and iii) a unit emission database with unit emission factors for calculating transport emissions. (Markkanen et al., 2017)

Distributed online LCA has been demonstrated successfully in research projects. In 2019, VTT's online LCA computation module was connected remotely to the Tampere University distillation column to receive a few key measurement values. VTT LCA computation module then computed the current environmental impact of the distillation column online. These values (both the inputs and the outputs of the LCA module) were displayed simultaneously in Outotec's system, which was located in the third geographical location. (Kannisto et al., 2019)

The MORSE project developed model-based, predictive raw material and energy optimisation tools demonstrated in the steel industry to increase yield and product quality (A.SPIRE, 2019). One of the developed tools was VTT's **Online Quality Monitoring Tool** (QMT), which is used to collect and integrate information flows from different process phases for further analysis and information aggregation. QMT provides more detailed information about the quality status of the process and products. It helps users to monitor, adjust and re-operate tasks during the steel making process based on information from its quality models and helps understand root causes for quality deviations. (Tamminen et al., 2019)

LCA can be used to identify those issues of the life cycle that have the greatest impact on the environment so that those issues can be focused on and cost-effectively pursued to improve environmental performance and reduce negative impacts. This, of course, requires means to test new product solutions beforehand, e.g. related to the durability, performance and economic viability of products. One solution that can be used to contribute to this is VTT's ProperTune (Malkamäki, 2020). **ProperTune** is an Integrated Computational Materials Engineering (ICME) concept that uses multiscale modelling for optimal computational material design, replacing expensive, time-consuming testing and shortening the time-to-market for new products by an average of 50%. It allows us to create microstructurally accurate materials and loads in realistic conditions—and this all digitally. The approach can be used to optimise a wide variety of material properties, such as lifetime endurance, wear and corrosion resistance, and fracture and fatigue durability. It thereby contributes to the cost-effective durability and sustainability of the product throughout its life cycle.

Modelling factory supports advanced material efficiency and sustainable CE by enabling the creation of different types of computational models and design solutions and validating them against measured and simulated data from industrial, environmental and academic sources. In addition to materials modelling, it contains both network and online LCA services. (EIT RawMaterials, 2020)

Verderon.io is a commercial service calculating environmental impact on a daily basis using data sources such as process measurements, historical data(bases) and enterprise resource planning systems (ERP). (Verderon.io, 2020)

Another essential element of the DPP is the **material passport**. Material passports should contain information on the use and operation phase, transportation and logistics, production datan and unique product identifiers in addition to physical, chemical, biological and process data (Heinrich & Lang, 2019). In the literature, the material passport has various titles, such as building, product, circularity and resource passports (Hansen et al., 2018). Some commercial passports are listed in Table 4.

Table 4: Some commercial DPPs

Name	Domain	Note	Source
Madaster Passport	Construction	Building Information Model (BIM)	(Beeks, 2020)
True Twins	Consumer goods, retail	Brand authentication by blockchain, NFC, QR codes.	(TrueTwins, 2020)
Excess Materials Exchange	CE	Reuse options for materials or (waste) products	(EME, 2020)
Circulor	Battery	Traceability as a service	(Circulor, 2021)
Provenance	Retail	Sustainable marketing technology	(PROVENANCE, 2020)
EPEA	Construction	C2C to buildings	(EPEA, 2022)
C2C	Ship building	C2C for ship building	(MAERSK, 2014)

Kristoffersen et al. (2020) gathered potential CE applications to a table (Table 5), with three columns reflecting the life cycles of a product: beginning, middle and end of a life cycle. The rows indicate the smartness of the application, and the top row is the “smartest.” Smartness grows together, with the focus of analysis starting from description (what has happened) and ending with prescription where the analytics (or AI) may even act on behalf of the human.

Table 5: Illustrative examples adopted from Kristoffersen et al. (2020)

	BoL **Restore, reduce and avoid (deny) raw materials**	**MoL** **Extended life cycle of parts and products**	**EoL** **Recycle and reuse materials**
Prescriptive	Automatic waste-to-resource matching and execution with self-managing adaptive sourcing plans or configuration.	Autonomous determination of the parts/products in need of attention and scheduling of the appropriate life cycle–extending operation, e.g. prescriptive maintenance and autonomous part replacement.	Autonomous cost–benefit analysis and execution of end-of-life strategy based on material quantity, composition and quality.
Predictive	Anticipate changes to sourcing and value chain dynamics and alert for potential upcoming issues, e.g. changing availability or supply-demand mismatches.	Predict and/or automate planning of life cycle–extending operation based on condition data and user-activity cycles for minimal disruption of operations, e.g. predictive maintenance.	Predict end-user behaviour to increase recycling rates and optimise material treatment.
Discovery	Identify and explore new and alternative waste-to-resource matches and possible eco-networks for their application.	Explore different options for life cycle–extending operations, e.g. condition-based maintenance.	Identify and explore new and effective material cascades with a minimum environmental impact, e.g. digital material market places.
Diagnostic	Determine the application of different grades of materials for impact hotspots and improvement opportunities of waste-to-resource patterns.	Determine the need for life cycle–extending operations based on elapsed time and use statistics for product.	Automatic identification of material grade for correct selection of EoL strategy, e.g. automated smart waste sorting.
Descriptive	Identify quantity and timing of current material flows for enhanced traceability and waste-to-resource application.	Trigger request for repair based on alert of sudden product failure, e.g. reactive maintenance.	Determine material location and quantity for optimal treatment, e.g. smart bins with pay-as-you-throw models.

IV. Basic elements of DPP

The EU DPP could be implemented via a system that relies on data collected along the value chain, including a unique product identifier. This data should be structured with a clear, standard ontology of meta-data so that it will be susceptible to automated searches and processing. (European Commission, 2022e)

The EU DPP system aims to integrate existing information, but this may require some adaptations to how the database hosting this information is structured and may require technical changes to the systems. The extent of these changes and the assessment of costs and benefits will be analysed in depth in the context of the detailed design of the EU DPP data architecture to achieve the highest degree of interoperability with the minimum degree of changes to existing systems and related adaptation costs. The EU DPP is not meant to accumulate exhaustive data but rather to make available to different stakeholders targeted information on a "need-to-know" basis. (European Commission, 2022e)

In this section, we first present the functional requirements of DPP. This is followed by the data content proposals of a DPP. The third section highlights IoT solutions that enable data collection throughout the life cycle of a product.

Functional requirements

According to the EC, the DPP should comply with the following general requirements (European Commission, 2022b):

- A unique identifier (data carrier) links the product with the data contained in the European DPP;
- The data present on the EU DPP remains available even after bankruptcy, liquidation or the cessation of activity in the EU of its originator;
- Its content is written in an open, standard, inter-operable format;
- This standard is usable under open licences or under Fair, Reasonable and Non-Discriminatory (FRAND) legal and economic conditions;
- This standard is usable over very long periods;
- The EU DPP (and its content) is machine-readable;
- The content of the EU DPP is searchable;
- The rights to access and modify information are controllable;
- Access to information is on a "need-to-know" basis;
- The author of the information is authenticated;
- The reliability of the information is assured; and
- The integrity of the information is assured.

DPP data typology and models

Figure 8 (on page 15) displays the objectives of DPP, which is storing and sharing all relevant information along the product life cycle. The EU DPP includes two typologies of information: i) **track and trace** are a set of information related to the producer and events related to the track and tracing along the value chain; and ii) **attributes** are information specific to the sustainability, circularity, compliance history and other technical characteristics of the component or product. The preliminary list of data content contains the data elements shown below. (European Commission, 2022a)

Possible track and trace identifiers (European Commission, 2022e):

- The manufacturer's name, registered trade name or intellectual property right (e.g., trade

mark);
- The global trade item number or equivalent;
- TARIC[5] Code;
- Global location number or equivalent;
- Documents/information supporting legal compliance
- Name, contact details and unique identifier of the authorised representative based in an EU Member State and/or person responsible for regulatory compliance; and
- Name, contact details and other references of the service provider acting as technical backup data repository, permanent URL of the technical backup.

The track and trace attributes are the “core business” of the EU DPP, as they include all the information related to sustainability, circularity and other technical characteristics of the component or product. Examples of attributes that could be included in the EU DPP are as follows (European Commission, 2022b):

- Size, colour and picture of the (product) model;
- Origin of raw materials;
- Environmental impact indicators, product environmental footprint (PEF) profile (if calculated);
- Circularity indicators;
- Social indicators/due diligence compliance in supply chain;
- Chemical content;
- Recycled content;
- Use instructions, manuals;
- Recycling instructions;
- Dismountability instructions; and
- Other labels, such as green claims.

There are three main levels of identification for the information related to a product (granularity of the traceable asset): Class level, such as product model (e.g. SmartPhone AB), batch/lot level (e.g. SmartPhone AB, produced in factory XYZ) and items (e.g. SmartPhone AB, serial number 123456789). (Galatola, 2022)

Galatola (2022) listed the key product aspects under the proposal for Ecodesign for Sustainable Products Regulation (ESPR), such as durability, reliability, reusability, upgradability, repairability, possibility of maintenance and refurbishment, presence of substances of concern, energy use or energy efficiency, resource use or resource efficiency, recycled content, possibility of remanufacturing and recycling, possibility of recovery of materials, environmental impacts, including carbon and environmental footprint, and expected generation of waste materials (Galatola, 2022).

According to Carlsson (2020), the product passport should include information on

- Durability—expected lifetime ideally aligned with free guarantee period
- Repairability—including access to manuals and schematics
- Recyclability—sorting, dismantling and hazard guidelines
- Environmental performance—environmental footprint (LCA), notable global warming potential, resource depletion, material footprint and water footprint
- Energy use efficiency—for energy products
- Contents of hazardous substances—bill of materials and bill of chemicals
- Social data—such as due diligence and fair-trade certificates (Carlsson, 2020)

Platform CB’23 has defined the data architecture for the passport of the construction sector (Platform CB’23, 2020). Acerbi et al. conducted a literature review and created a conceptual data model for circular manufacturing. It has four main classes: product, process, technology and management. (Acerbi et al., 2022)

[5] A TARIC code, sometimes referred to as a Harmonisation code or Commodity code, is a code which is used to classify the type of goods you are importing/exporting.

IoT enables data acquisition

The current linear economy is causing excess consumption and waste of natural resources and energy (Miaoudakis et al., 2020). The CE proposes a new innovative approach, supporting restorative and regenerative operations, but it also requires the alignment of government policy, business practices, and consumer preferences. The CE is positioned to decrease new materials consumption by 32% within 15 years and by 53% by 2050 (Ellen MacArthur Foundation & McKinsey, 2015). Just moving towards a CE could eliminate 100 million tons of waste globally in the next five years (Lucero, 2016).

IoT can play a key role in the CE, e.g., by allowing companies to better execute remanufacturing tasks and by enabling access to real-time information related to product status, location and condition. It can also support the design of products that can be easily maintained, upgraded, disassembled and recycled through appropriate analysis of data collected from external devices (Bressanelli et al., 2018). IoT can make stand-alone products smarter and connected, support material tracking, and contribute significantly to gathering end-of-life products and managing wastes. It can also enhance renovation procedures and end-of-life activities. As a result, it helps to close the loop through reusing, remanufacturing and recycling (Cui et al., 2021).

The literature indicates that the opportunities provided by the IoT for CE have not been completely realised in real life. Using the IoT as an enabler for CE, there are fundamental questions to be considered (Miaoudakis et al., 2020):

- How can IoT-enabled circular provisioning be exploited to create business value?
- What is the best way to reorganise supply, delivery and value chains in the interplay of the CE and IoT?

Figure 9 illustrates the linear and CE models in the conceptual architecture IoT (Miaoudakis et al. 2020). It shows the interrelationships of IoT smart assets and other field devices, programmable networks, the cloud and back-end services with the three key technical challenges, connectivity, interoperability and trustworthiness, that must be addressed.

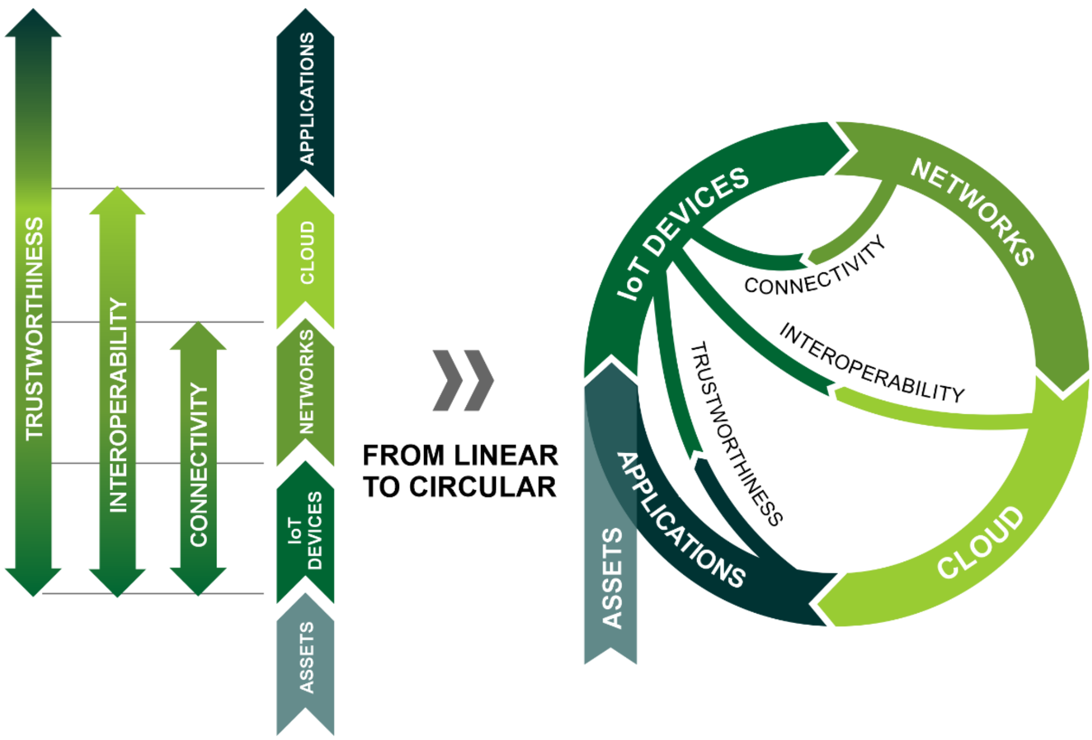

Figure 9: Towards IoT-supported CE: A concept by Miaoudakis et al. (2020)

The implementation of a usable CE–IoT-enabled ecosystem must support the interplay between the business processes and the supply chains and their operations. Core requirements include:

- The circularity-enabling properties of smart assets: Location, Condition, and Availability (LoCA)
- Key enabling IoT technologies: Connectivity, Security, Privacy, Dependability and Interoperability (CSPDI)

A product–services–systems supply chain framework is needed, with effective and secure reverse logistics capabilities. The essential LoCA and CSPDI properties of CE–IoT deployment, concrete business models and IoT-enhanced supply chains, as well as robust networking, interoperability, monitoring and adaptation capabilities, will need to be encompassed to address the needs of application domains. The architectural patterns for the core IoT technologies should consider the following (Miaoudakis et al., 2020):

- standardised networking and IoT protocols, such as OpenFlow and MQTT;
- security mechanisms (e.g., authentication and authorisation schemes); and
- the existing capabilities of the IoT platforms and service interfaces with adapters for accessing services as necessary.

Another view of CE and IoT technologies by Rejeb et al. (2022) is given in Figure 10. It organises the conceptual elements in the left part of the figure into details in the right part.

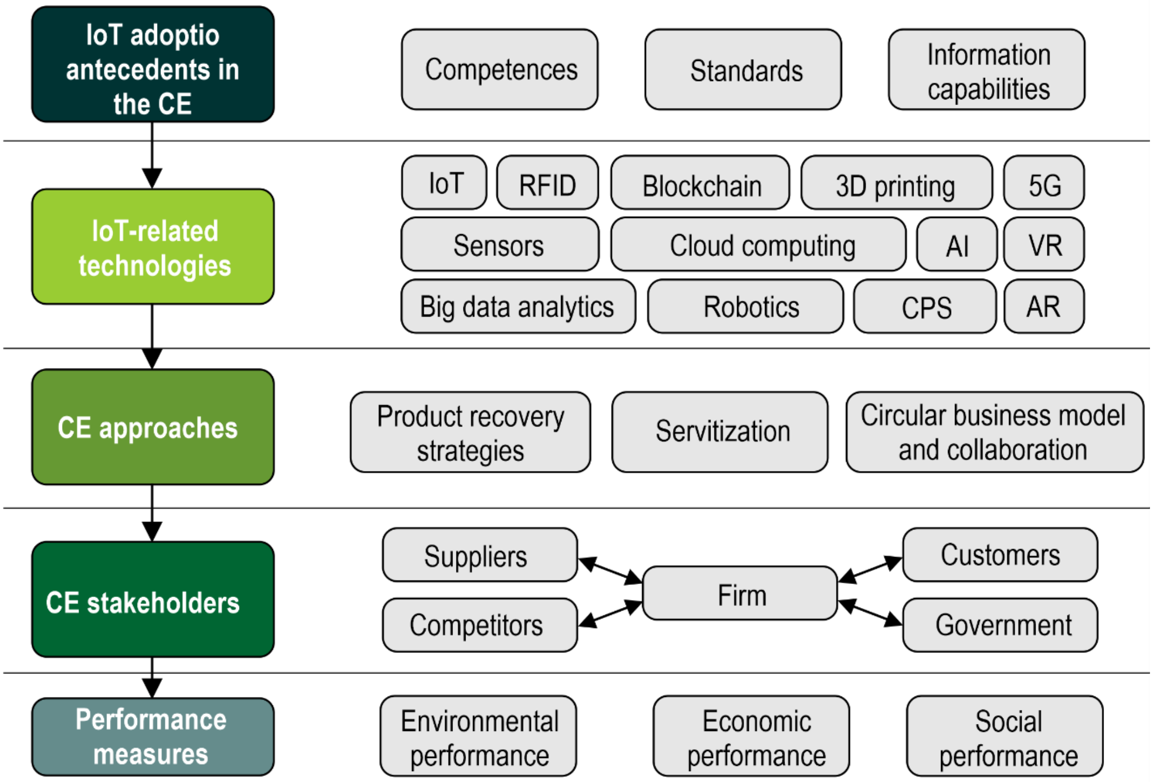

Figure 10: IoT-based sustainability framework (Rejeb et al., 2022)

The IoT adoption antecedents address the prerequisites of the implementation: the company's competences, standards to simplify the deployment of the IoT in CE processes, and knowledge sharing and communication within and across company functions. This is followed by IoT-related technologies, adding the technical perspective, e.g., smart robots, cyber-physical systems, artificial intelligence, big data analytics, and 3D printing. Based on these two categories, ways can then be identified to bring the CE approach to life: end-of-life product recovery strategies, servitisation and collaboration in circular business models. To do so, CE stakeholders need to be addressed. Finally, performance measures need to be identified on all three dimensions, namely environmental, social and economic. (Rejeb et al., 2022)

A global network of smart assets creates great potential for new IoT applications and business models, but the current state of the art leaves open issues for some major technical challenges, especially i) scalable connectivity, ii) seamless interoperability and adaptability of services, and iii) highly trustworthy chains with low cost and complexity (Miaoudakis et al., 2020).

The increasing number of wirelessly interconnected devices affects the wireless bandwidth, increasing interference (physical/access layer) and congestion (access/networking layer). The availability of networks and systems is also affected by the intense demand for network connectivity in IoT settings. Networks have to automatically serve the requested resources and administer intermediate networking equipment. A promising option for the implementation of programmable connectivity, service chaining and rapid service provisioning to accomplish the necessary end-to-end optimisations constitutes the combination of Software Defined Networking (SDN) and Network Function Virtualization (NFV) technologies. (Askoxylakis, 2018)

There is still limited semantic interoperability in the IoT domain regarding interconnected smart devices that operate through different IoT platforms. The current interoperability options in IoT platforms or applications also have to be designed and engineered statically into IoT platforms and/or smart objects. Three main properties are considered regarding semantic interoperability in IoT (Askoxylakis, 2018):

- the discovery and recognition of the communication and functional features of smart objects that are integrated into IoT applications;
- the correct interpretation of data conveyed and/or communicated by these objects so that they can be processed meaningfully and produce the required data transformations; and
- the establishment of meaningful interoperability between heterogeneous IoT networks and the platforms through which such objects function and become available. (Askoxylakis, 2018)

IoT objects, applications and the associated IoT platforms are vulnerable to various cyber-attacks and remain sensitive to unpredicted changes in context and operating conditions. Successful attacks can compromise security and harm dependability, either for the whole setting or for specific components (e.g., network components or sensors). IoT systems also process high volumes of personal data in ways that could lead to potential breaches of privacy and legal obligations. The main problem arises from the difficulty in the protection of security, privacy and dependability (SPD) in the IoT domain and the administration of the involved smart equipment (Askoxylakis, 2018):

- analysing end-to-end vulnerabilities for the three SPD properties in the complex compositions of large and heterogeneous IoT systems;
- making optimal decisions for the delegation of SPD issues to alternative mechanisms that are usually available and provide solutions to them at the level of smart object, device and/or IoT platform (e.g., different schemes for key and ID management, different cryptographic techniques, inability to use robust mechanisms like elliptic curve cryptography on smart equipment with constrained resources); and
- retaining the targeted SPD level when the components and/or architecture (composition) of the IoT system change, stop operating according to the specifications, or are compromised. (Askoxylakis, 2018)

Fragmentation of the current IoT landscape is a substantial challenge. For IoT technologies, several reference models are available. However, with the current technologies, IoT reference model coverage is very sparse, only a few suppliers provide “Whole Products,” and customers must work with multiple IoT solution providers to deploy solutions. (Juxtology, 2015)

There are several commercial IoT platforms that might be feasible for DPP data gathering, such Mendix (Siemens, 2022), ThingWorx (PTC, 2022) and IoT-TICKET (Wapice, 2022), to mention a few. The EU naturally favours open solutions to disable any vendor locks.

Storing and accessing DPP data

According to Europe's technology industries, the DPP should i) follow the data minimisation principle (as much data as needed, as little data as possible), ii) have a decentralised approach, iii) be designed in a flexible and feasible manner, and iv) the data model should reflect the mechanisms of experts and not mirror and copy data in centralised databases (Orgalim, 2022).

EC is willing to manage the registry containing track and tracing identifiers and attributes on the dedicated products. EC will have backup storage of distributed local data storage in the event of bankruptcy. (European Commission, 2022b; Galatola, 2022)

In future, the DPP will be mandatory for the products for which there is a dedicated act (identified in ESP). Two possible scenarios are foreseeable with reference to EU DPP **access rights: "Need-to-know"** or "Open access." In access granted on a "need-to-know" basis, the sensitive information will only be seen by public authorities and other companies in the value chain—like recyclers—beyond the manufacturer. Other information will be generally available to the public, who can consult it, but it can only be introduced and modified by the responsible manufacturer or importer. In the "open access" basis scenario, most of the information would be available to every operator that scans the data carrier. (European Commission, 2022b)

The data gathered need to be stored and accessed too. By reading or scanning the tag, the producers, consumers, waste operators and law enforcement agencies can easily access and possibly also upload relevant and targeted information for other stakeholders. The typology of **data carriers and unique identifiers** used (such as barcodes, 2D identifiers, watermarks, data matrix, RFIDs) shall be compatible with a different typology and number of information that the passport carries on. Linear data carriers, such as barcodes, are probably not adequate for the scope due to the limited amount of information they can support (European Commission, 2022b). The identifier can be attached via additive manufacturing to the surface (or even below) of the product or component. (Vaajoki, 2020)

Figure 11 illustrates the working principle of a DPP. A potential user reads the unique identifier of a product via a device, which may be a smartphone with an application. The identifier carries the URL address to the product's DPP homepage. The DPP broker gives (or denies) access to the DPP, and the user receives the information he or she was requesting. The related product data is inserted into the latest DPP in the distribution or sales phase, where the product enters Europe. Similarly, other actors and stakeholders in the product value chain, including authorities, can have access and possibly also upload relevant and targeted information for other stakeholders.

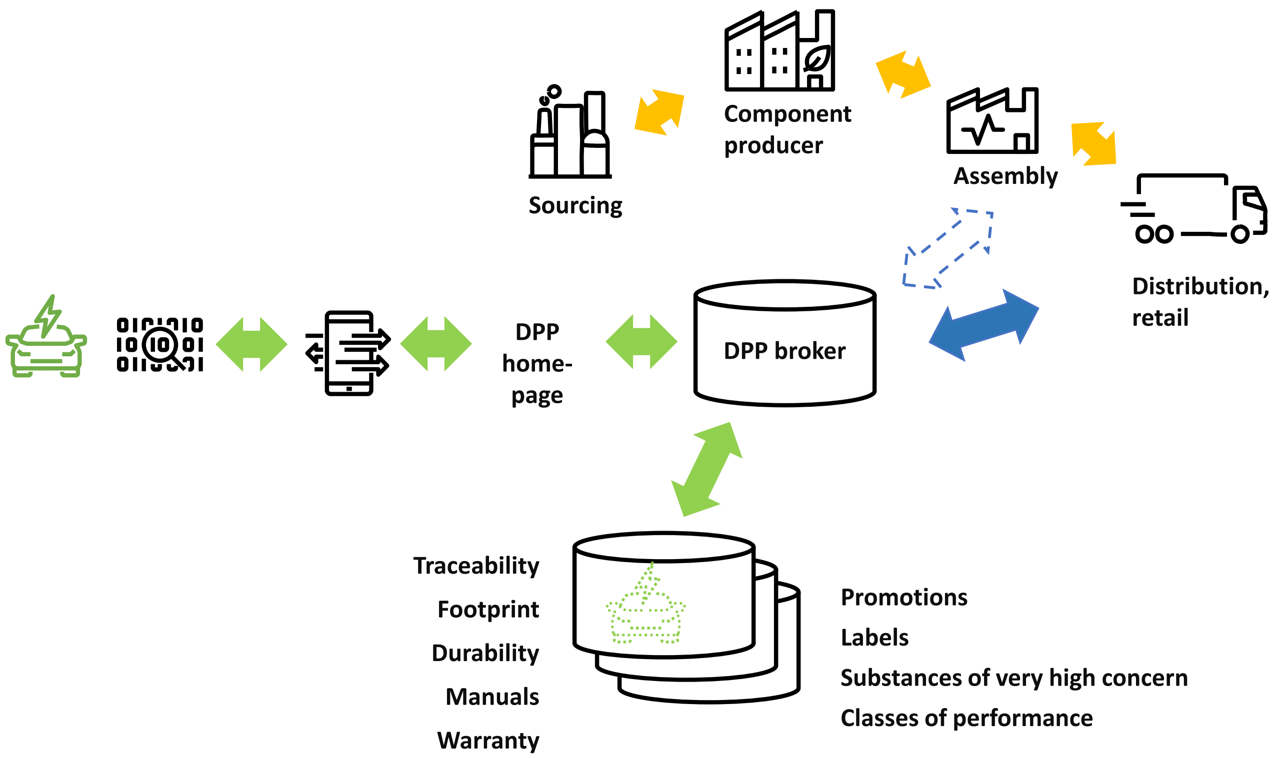

Figure 11: DPP working principle modified from (European Commission, 2022b)

V. Conclusion

The transition to a sustainable economy requires the smarter management of product-related data across the product life cycle. Most of this information exists but is not available to those that could use it best. Digital technologies provide the possibility to tag, trace, localise and share product-related data along value chains, down to the level of individual components and materials. Circularity is an essential part of a wider transformation of industry towards climate neutrality and long-term competitiveness. It can deliver substantial material savings throughout value chains and production processes, generate extra value and unlock economic opportunities.

The EU is strongly driving the concept of DPP, together with ecodesign and other sustainability goals. The DPP will be required for dedicated products (sold in Europe) in the future. Battery, textile, ICT, buildings and toys are among the dedicated focus areas, but DPP will emerge for all physical products in future. Until now, there are some commercial DPP solutions as well as technical sub-solutions, but no implemented and sufficiently mature solution is available.

Interoperability is an emerging issue when dealing with heterogeneous systems and data. EC has initiated both the European CE Stakeholder platform (European Commission, 2017), Biodiversity platform (European Commission, 2021a) and Rolling Plan for ICT standardisation (European Commission, 2019a). The EU is also funding the Environmental Coalition on Standards (ECOS, 2022). In addition to potential regulation, European technology industries also have a strong influence on the future the DPP concept (Orgalim, 2022).

Future research topics

Because the DPP is still taking shape as a practical solution, further research and scientific debate are needed. These should cover how to increase incentives for manufacturers to deliver certain information for DPP, as well as how relevant data can be compiled and made available to relevant stakeholder groups (Adisorn et al., 2021). Walden et al. (2021) have called for discussions between practitioners and research to which degree DPPs can become an easily usable information system not only to satisfy the policy and regulatory requirements but also to drive design, sourcing, manufacturing, purchasing and financing decisions. They continue that DPP as a central element of the digital CE needs to be developed through multistakeholder collaboration across the entire industry value chain (Walden et al., 2021). Potential research topics related to the DPP concept are discussed next.

From a data perspective, it would be interesting to find out which **additional data fields** could enable new R-cycles during the product life cycle. This would, of course, require an industrial use case.

DPP should include social and environmental impacts, both in the use phase and along the value chain. **Social aspects** are considered important, but they are often not included yet due to unclear agreements on which are the most relevant and how they need to be reported (according to which standards). Usually, the social aspect is considered to be covered by occupational safety and product safety viewpoints. Collaboration with the Global Reporting Initiative (GRI) (GRI, 1997) or something similar related to transparency at the corporate level is recommended.

It would be ideal to link the EU DPP with the product environmental footprint (PEF) methodology in order to capture the environmental impact in a harmonised way. **SMEs, in particular, need support for PEF method implementation**. When discussing the CE matrix with subcontractors, they raised the question of their own roles. What can a **subcontractor** do to improve sustainability? What are the roles of the main contractor and the subcontractor in a sustainable ecosystem? What can a subcontractor do in addition to its own environmentally friendly facilities (LED lamps, wind and solar energy, etc.)?

Life cycle assessment (LCA) is a reference methodology for appraising the environmental impacts of products along their value chains. Currently, a generally accepted **life cycle impact assessment** (LCIA) framework for assessing biodiversity impacts is lacking. The existing LCIA models present weaknesses in terms of the impact drivers considered, geographical coverage, and the indicators and metrics adopted. Sound ecological indicators and metrics need to be integrated to better assess the impacts of value chains on biodiversity on global, regional and local scales. (Crenna et al., 2020)

DPP gathers valuable information over the life cycle of a product. However, its real benefits are realised through the intelligent use of newly collected information using applications to support smart reporting and decision-making. DPP collects product life cycle information related to the product, such as materials, how manufacturing has happened, logistics, product repairs and upgrades, and the product's energy consumption. An example of a use case utilising DPP data may be as follows. DPP data can be used in automated LCA calculations to provide faster and more case-specific life cycle calculations for products. The DPP solution collects comprehensive information about the product life cycle from different actors, as well as the different stages (see Figure 12) related to the product. This product-related life cycle information is then utilised in the LCA calculation, for example, according to the SULCA LCA calculation model (Semantum & VTT, 2020), by combining DPP data and unit emission database data (such as LIPASTO and Ecoinvent) in the SULCA calculation. This provides calculations of the product's life cycle emissions. Next, it is necessary to consider how that information will be used in practice to achieve the goals of CE. For example, the results of an LCA calculation should be interpreted to identify the stages in the product life cycle that have the greatest impact on the environment. This information helps business management and product development to focus on the essential parts of the product or its manufacturing and supply chain, which can cost-effectively improve the environmental performance of future product versions and products and reduce negative impacts. If it is found that a product's energy consumption or durability (short life cycle) is the issue, then related improvement measures can be planned for future product versions related to these issues or to guide current users to be more energy-efficient. For instance, the wear resistance of the product can be improved by using ProperTune modelling to increase the product's lifetime while reducing the amount of material and the product's weight. Thus, intelligently integrated and utilised DPP data enables a range of data applications to enhance CE.

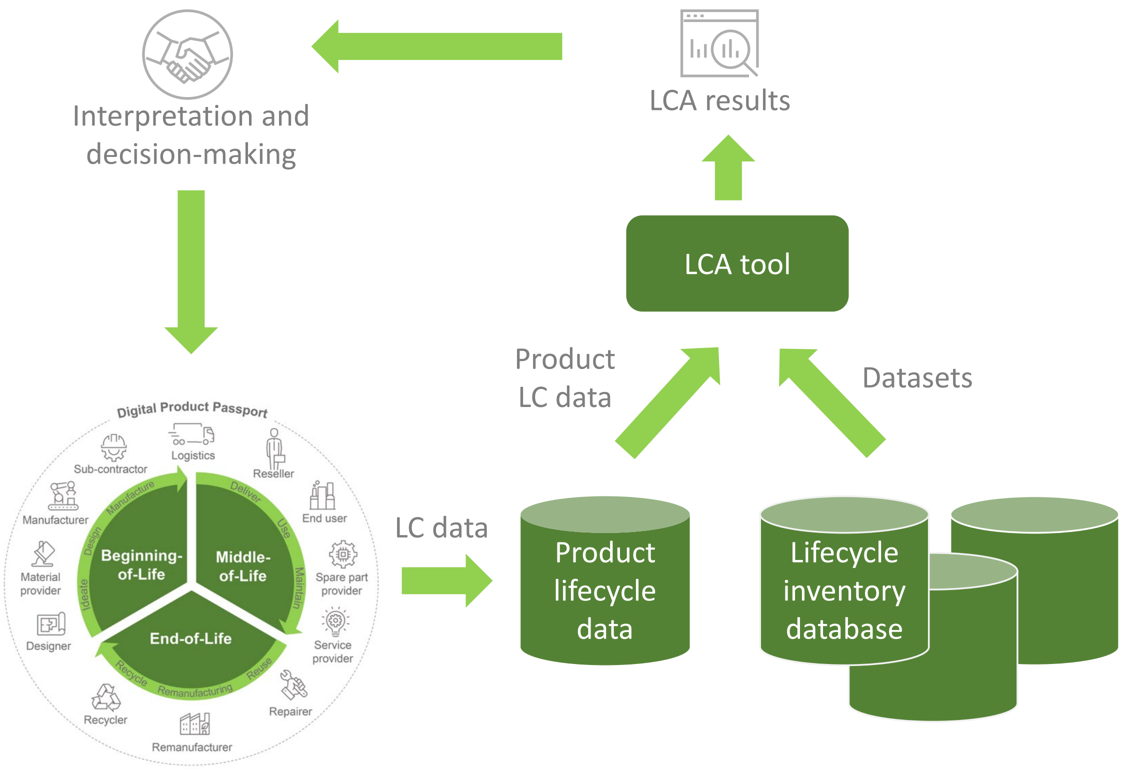

Figure 12: DPP with sufficient sustainability calculations bring feedback to the BoL (and MoL) phases of the product

In the manufacturing of industrial systems, the product definition must be available for the planning and execution of production operations, and a temporal constraint exists between the two processes. However, integrated product development (Andreasen & Hein, 1987) as well as design for produceability (Huhtala & Pulkkinen, 2009) require that the markets, products and production must be co-developed. Obviously, the planning of product life cycle properties against the requirements of the CE, as well as the management of traceability, must be defined along with business model innovation (BMI) and modern product development as a part of it (Pieroni et al., 2019). Here, DPP can be an essential mean for carrying the information from cradle to circle and enabling BMI activities.

Nowadays, most manufacturing operations are carried out by supply networks. Moreover, value networks deliver the product from cradle to customer, and the value of a product is captured when it is in use. The networks can be digitally integrated, modelled and/or managed. The **digital twin of a supply network** can have several purposes varying from quality control and traceability to situational awareness, network manufacturing operations management and shared resources. The essential aspects of digital twins are as follows:

- There is a physical/real counterpart for a digital twin.
- There is a bi-directional information flow between the real and digital counterparts.
- The digital twin must be able to represent the dynamism of its real counterpart (Pulkkinen et al., 2021).

There are plenty of potential benefits for understanding, predicting and controlling the properties and characteristics of the real counterpart of digital twins. In sharing the product definition and tracing the individual products or parts, the unique, standardised identifier is a cornerstone for collaboration, modelling and information exchange. Also, having neutral organisations responsible for maintaining the DPP can be an asset, because the deeper collaboration becomes, the more trust is required.

A generic remanufacturing process (Sundin, 2004) is composed of seven main activities: Inspection, Cleaning, Disassembly, Storage, Reprocess, Reassembly and Testing. Especially in inspection, the correct identification of a product is essential for defining the suitability of the product or its parts for remanufacturing. With easily accessible information on the identity of the product, remanufacturing becomes economically feasible. Moreover, having knowledge of the product characteristics that affect **remanufacturability** is decisive for deciding the objects of remanufacturing. These are the durability of used material, the utilised joining technologies that may prevent disassembly and features that prevent or discourage upgrading or that require banned substances or processing methods, as well as the features that may make returning to as-new functionality cost prohibitive (Ijomah et al., 2007). Thus, the product definition and changes to it should be carried along and related to a DPP to enable decision-making for remanufacturing. The potential future research topics are summarised in Figure 13.

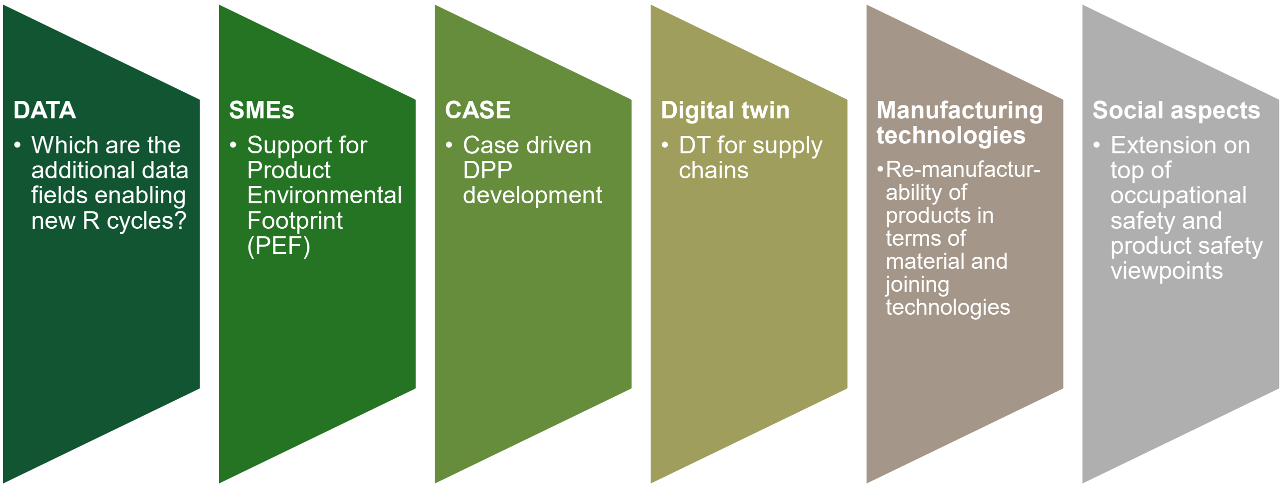

Figure 13: Future research topics

Related VTT competences

Our future activities support the DPP development activities of the manufacturing industry by:

- increasing data sharing and the use of artificial intelligence (AI) by
  - developing product and service life cycle management (resource efficiency) and thus enabling decision support and better decisions at different stages of the life cycle;
  - gathering and importing sustainability aspects (e.g. emission parameters) already for product design and method development (such as STEP-NC product data model and Unit Manufacturing Process, UMP);
  - promoting CE and product life extension via product and usage data management; and
  - exploiting European initiatives for manufacturing data spaces, such as GAIA-X[6] and Industrial Data Spaces, (IDS[7]), by providing test beds for industrial piloting.
- co-creating digital products and services instead of physical products as much as possible (digital twins, simulations, etc.);
  - enabling individual digital twins based on the ability to track individual products
- exploiting ICT solutions for energy and material consumption optimisation;
  - developing new materials and production processes, for example, energy and material savings in manufacturing via new processes, e.g. additive manufacturing, 3D printing, process monitoring, optimisation (IIoT, AI, analytics, etc.);
  - optimising supply chain logistics (transport, storage, packaging, etc.);
  - enabling energy savings in product MoL phase via new product-related services (IIoT, AI, analytics, etc.)
- developing (and applying) sustainability tools and methods;
  - boosting digital transformation, especially digitalisation of manufacturing value chain, e.g. production processes promoting the use of digital technologies for tracking, tracing and mapping resources;
  - providing calculation methods for footprint, handprint and analytics (LCE, LCI, LCIA, LCA, PDM/PLM, Digital Twins, simulation, modelling, optimisation, AI, ML, etc.)

For VTT, it is interesting to find out what is the minimum viable DPP for the manufacturing industry and help companies to proceed with the implementation of new R-cycles more generally towards CE and to reach sustainability goals.

Clearly further research is required. In addition, the industrial success stories and their impact assessments should be documented and shared.

VTT promotes manufacturing companies in their sustainability goals and activities by implementing new R-cycles. For the manufacturing industry, it is better to take on the role of early adopters instead of laggards.

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[6] Gaia-X is an initiative that develops a software framework of control and governance and implements a common set of policies and rules that can be applied to any existing cloud/ edge technology stack to obtain transparency, controllability, portability and interoperability across data and services. https://gaia-x.eu/

[7] IDS enables new ”smart services” and innovative business processes to work across companies and industries while ensuring that the self-determined control of data use (data sovereignty) remains in the hands of data providers. https://internationaldataspaces.org/

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VII. Appendices

Table 6: International—mostly European—initiatives that guide towards sustainable manufacturing

Name	Goal(s)	Reference
17 Sustainable Development Goals (SDG)	17 SDGs: no poverty, zero hunger, good health and well-being, quality education, gender equality, clean water and sanitation, affordable clean energy, decent work and economic growth, industry, innovation and infrastructure, required inequalities, sustainable cities and communities, responsible consumption and production, climate action, life below water, life on land, people justice and strong institutions, and partnership for the goals.	(United Nations, 2015)
Three CE Principles and CE Butterfly Diagram	CE rests on three principles: i) preserving and enhancing natural capital by controlling renewable resource flows and finite stocks, ii) optimising resource yields by circulating components, products, and materials in both technical and biological cycles at the highest utility, and iii) fostering system effectiveness by revealing and designing out negative externalities such as land use, air, water and noise pollution. The two main cycles in the CE butterfly diagram include: i) technical cycle, in which products and materials are kept in circulation through processes such as reuse, repair, remanufacture and recycling, and ii) biological cycle, in which nutrients from biodegradable materials are returned to the Earth to regenerate nature.	(Ellen MacArthur Foundation, 2015)
European CE Platform	Aims to make the CE a reality by: • Advancing the CE concept in member states, regional and local governments, civil society and businesses and also linking to the global dimension; • Strengthening the cooperation among stakeholders' networks to facilitate the exchange of expertise and good practices on the CE; • Helping to identify social, economic and cultural barriers.	(European Commission, 2017)
Green Deal	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; and • no person and no place left behind.	(European Commission, 2019b)
Twin transition	Twin transition transforms Europe towards a green, digital and resilient economy. It is supported by Horizon Europe calls since 2020.	(Von der Leyen, 2020)

Name	Goal(s)	Reference
CE Action Plan (CEAP)	CEAP aims to • make sustainable products the norm in the EU; • empower consumers and public buyers; • focus on the sectors that use most resources and where the potential for circularity is high such as electronics and ICT, batteries and vehicles, packaging, plastics, textiles, construction and buildings, food, water and nutrients; • ensure less waste; • make circularity work for people, regions and cities; and • lead global efforts on CE.	(European Commission, 2020a)
Biodiversity strategy 20-30	Four pillars, such as protect nature, restore nature, enable transformative change and EU action to support biodiversity globally	(European Commission, 2021c)
New Circular Economy (CE)	The EU aims to transition to a CE to make Europe cleaner and more competitive • enable a healthier planet and reduce pollution; • reduce pressure on natural resources such as water and land use; • reduce emissions to help the EU become the first climate-neutral continent; • create new business opportunities and local quality jobs; and • enable more resilient value chains.	(European Commission, 2021b)
Updated eco-design of sustainable products	• improving product durability, reusability, upgradability and reparability, addressing the presence of hazardous chemicals in products, and increasing their energy and resource efficiency; • increasing recycled content in products while ensuring their performance and safety; • enabling remanufacturing and high-quality recycling; • reducing carbon and environmental footprints; • restricting single-use and countering premature obsolescence; • introducing a ban on the destruction of unsold durable goods; • incentivising product-as-a-service or other models where producers keep ownership of the product or responsibility for its performance throughout its life cycle; • mobilising the potential of digitalisation of product information, including solutions such as digital passports, tagging and watermarks; and • rewarding products based on their different sustainability performances, including by linking high performance levels to incentives.	(European Commission, 2022b)
European technology industries	DPP should i) follow the data minimisation principle (as much data as needed, as little data as possible), ii) have a de-centralised approach, iii) be designed in a flexible and feasible manner, and iv) data model should reflect the mechanisms of experts and not mirror and copy data in centralised databases.	(Orgalim, 2022)

Table 7: Domestic initiatives that guide towards sustainable manufacturing in Finland

Name	Goal(s)	Reference
Finnish road map to CE	Three main goals according to the SDG pillars: • Economy: The CE will be a new cornerstone for the Finnish economy; • Environment: Finland as a model country for the challenge of scarcity; and • Society: From adapter to pioneer.	(SITRA, 2016)
Business Finland's sustainable manufacturing	The Sustainable Manufacturing Finland program focuses on renewing business models and increasing productivity, while actively seeking solutions to the challenges of climate change	(Business Finland, 2020)
Strategic programme to promote a CE	• sustainable products and services are mainstream of the economy and the sharing economy is part of our everyday lives; • our choices are future-proof and they strengthen our fair welfare society; • more for less: the use of natural resources is sustainable and materials remain in circulation longer and more safely; • the breakthrough of a CE has been achieved through innovations, digital solutions, smart regulation, and responsible investors, businesses and consumers; and • with a CE, Finland is a strong player in the global arena and a provider of sustainable solutions on the international market.	(Ympäristö ministeriö, 2021)
Technology industries of Finland	Technology Industries of Finland is committed to the Finnish government's target of achieving a carbon-neutral Finland in 2035. They • strive to influence the content and enforcement of environmental legislation in accordance with the interests of our member companies; • seek to encourage companies to utilise life cycle thinking and legislation in their operations; • promote the development and utilisation of environmental technology while spurring companies to participate in projects advancing top expertise in the sector; and • support the aforementioned goals by implementing Technology Industries of Finland's environmental principles in partnership with member companies.	(Teknologia-teollisuus, 2021)

Authors

Leila Saari

Saari has expertise on the tools and methods supporting the manufacturing industry, especially small- and medium-sized, to proceed with digitalisation, artificial intelligence and circular economy. Her current research activities consider the maturity of subcontractors in acting in an open smart manufacturing ecosystem. She is a senior scientist in the team called Data-based Asset Management and Business Models at VTT. ORCID 0000-0001-6789-3497, https://cris.vtt.fi/en/persons/leila-saari/publications/

Juhani Heilala

Heilala has expertise in the field of smart, sustainable production system design, integration of production system simulation with other analysis methods, resource-efficient manufacturing, sustainability and efficiency analysis, and use of ICT in manufacturing. His current research activities focus on smart and sustainable connected factories. Currently, he is a Senior Scientist in Agile and Integrated Production Systems research team at VTT Cognitive Production Industry Research Area. ORCID 0000-0002-9420-9061, https://cris.vtt.fi/en/persons/juhani-heilala

Tapio Heikkilä

Dr. Heikkilä has extensive experience in embedded systems, communication protocols and platforms, mechatronics and sensors, sensor networks, and intelligent robotics. Currently, he works at VTT Ltd as the Research Team Leader of the Intelligent Robotics team. His main research interests include skilled robotics and smart automation. ORCID 0000-0001-7180-2148, https://cris.vtt.fi/en/persons/tapio-heikkil%C3%A4

Jukka Kääriäinen

Dr. Kääriäinen has experience on the research topics of digitalisation, digital transformation, configuration management and application life cycle management. He has focused especially on supporting the digitalisation of small- and medium-sized companies. He has worked as a project manager, work package manager or researcher in various national and European research projects, such as ITEA, ITEA2, Artemis, Business Finland and ERDF projects. He works as a senior scientist in the team called Data-based Asset Management and Business Models at VTT. ORCID 0000-0001-5611-1509, https://cris.vtt.fi/en/persons/jukka-k%C3%A4%C3%A4ri%C3%A4inen

Antti Pulkkinen

Dr. Pulkkinen has experience in research and education of interdisciplinary topics within the fields of Machine Design, Production Engineering, Supply Chains and related Information Systems. Pulkkinen has planned, managed and executed research projects in the field of product configuration, Design for X and Product Lifecycle Management. Currently, he is leading a team Agile Intelligent Production Systems at VTT Cognitive Production Industry Research Area. In addition to academic publications Dr. Pulkkinen has edited and written several chapters for a book on Product Planning for Productivity (in Finnish). ORCID 0000-0001-7442-5931, https://cris.vtt.fi/en/persons/antti-pulkkinen

Tuija Rantala

Rantala has expertise in business development, data utilisation and decision-making. Her current research activities focus on data-based decision-making, new business creation, sustainability, value creation and business-to-business sales in manufacturing companies. Rantala has over 20 years of experience as a project manager and researcher in company assignments and research projects on diverse topics related to new B2B business creation. Currently, she works as the Research Team Leader of Data-based Asset Management and Business Models at VTT. ORCID 0000-0001-9816-3163, https://cris.vtt.fi/en/persons/tuija-rantala

For more information, please contact

Leila Saari
Tel. +358 408208929
Leila.Saari@vtt.fi

Tuija Rantala
Tel. +358 405117722
Tuija.Rantala@vtt.fi

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