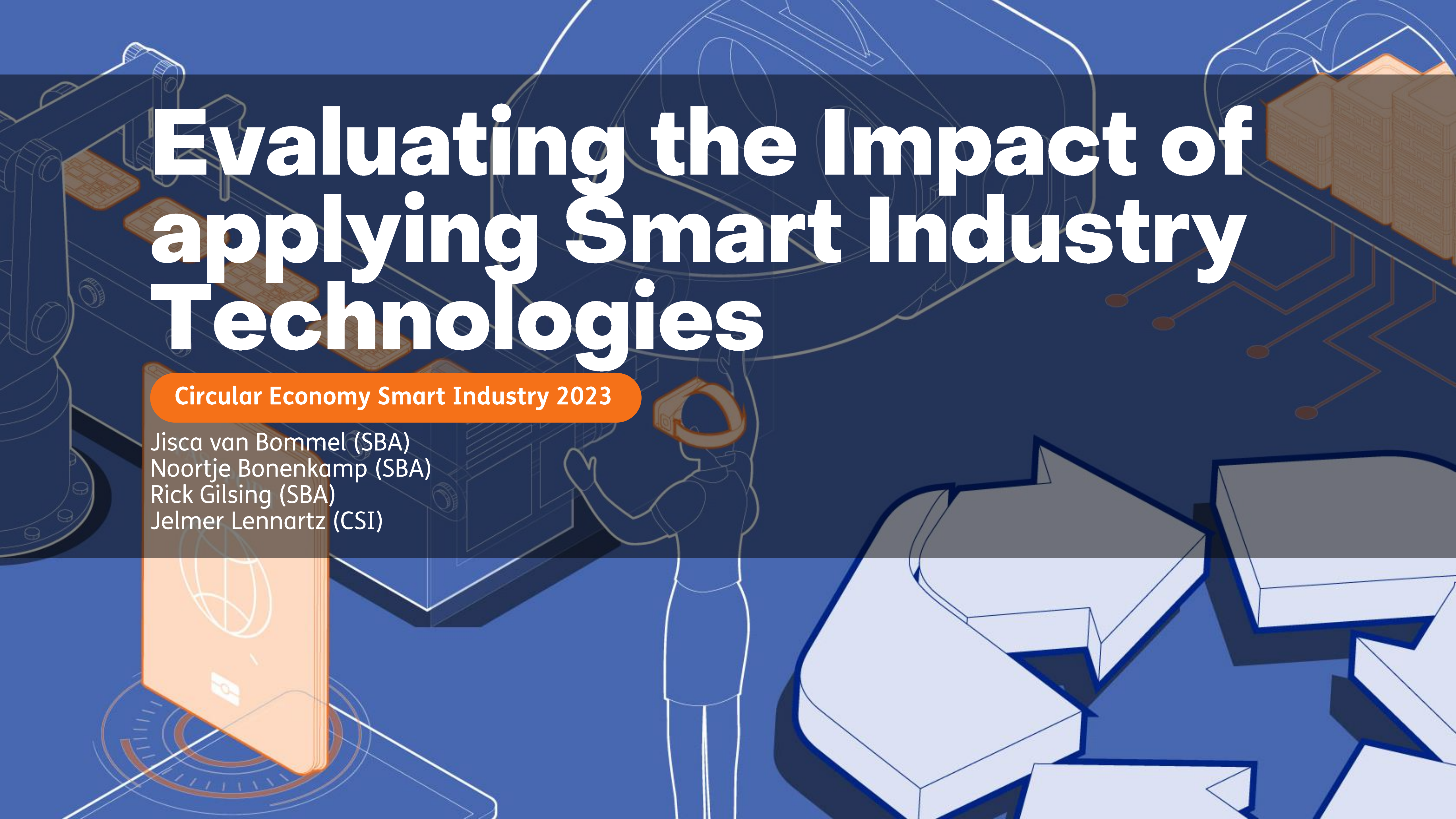

Evaluating the Impact of applying Smart Industry Technologies

Circular Economy Smart Industry 2023

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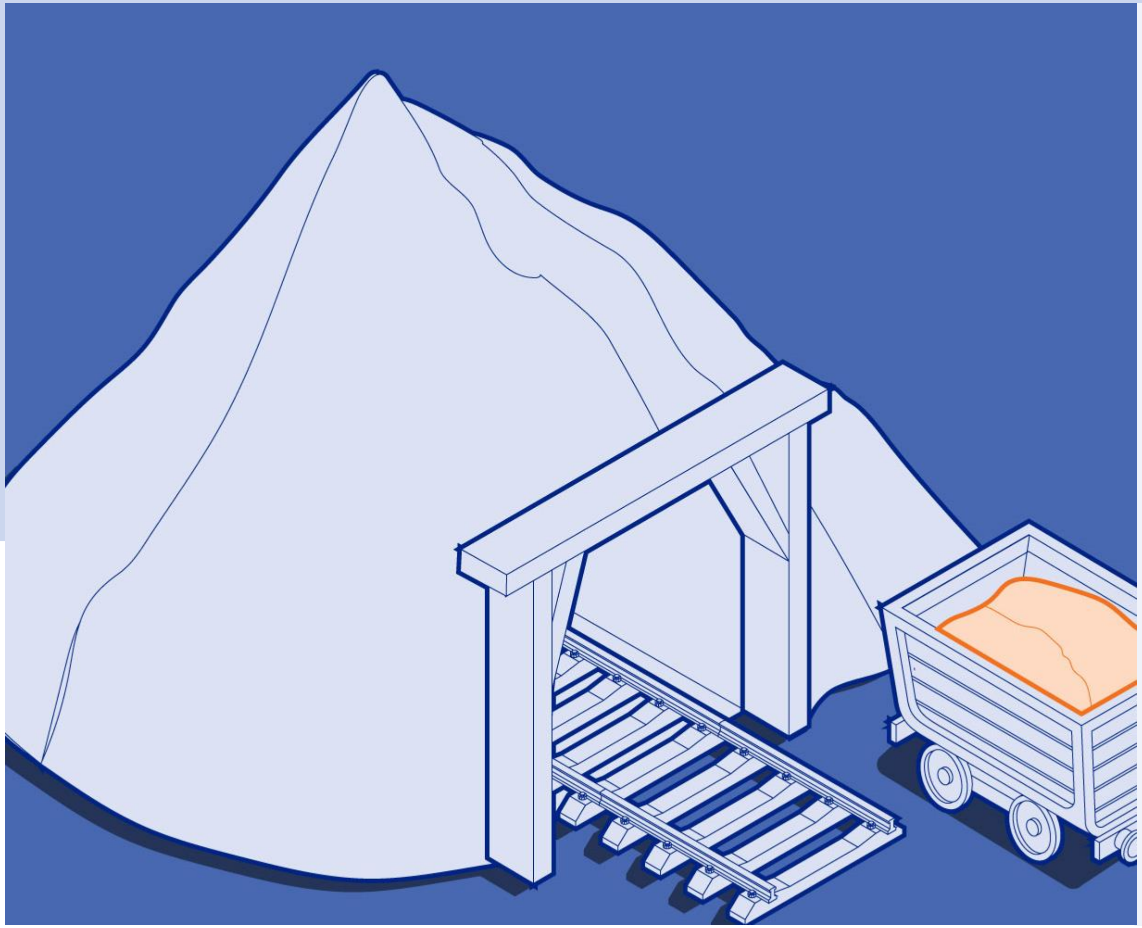

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Introduction

CESI, Towards a More Circular Economy with Smart Industry, was created in 2018 through an initial set of interviews with manufacturing companies from Gelderland (North Brabant, Overijssel and South Holland would follow later). The purpose of those interviews was to discover what innovations companies were working on and which of those innovations had a strong link to sustainability and circularity. Countless interviews later revealed that numerous companies were indeed undertaking activities (and sometimes had been for years) that lead to longer life spans through maintenance and repair, with new business models that focus on use and shared use of assets. These circular solutions were also often stimulated by applying all kinds of digital techniques.

Involvement Smart Industry

A characteristic of the CESI interviews with the manufacturing industry as conducted over the past year was, that by definition they involved innovations that were "market ready". After all, manufacturing companies could put technologies into practice. Characteristic of TNO activities around SI, however, is that they can/will only become market-ready at some (unknown) time in the future. The broad portfolio, demonstrated by the smart industry wheel, each could lead to strengthen the position of the Dutch manufacturing industry, increase the strategic autonomy and potentially play a role to become sustainable and circular.

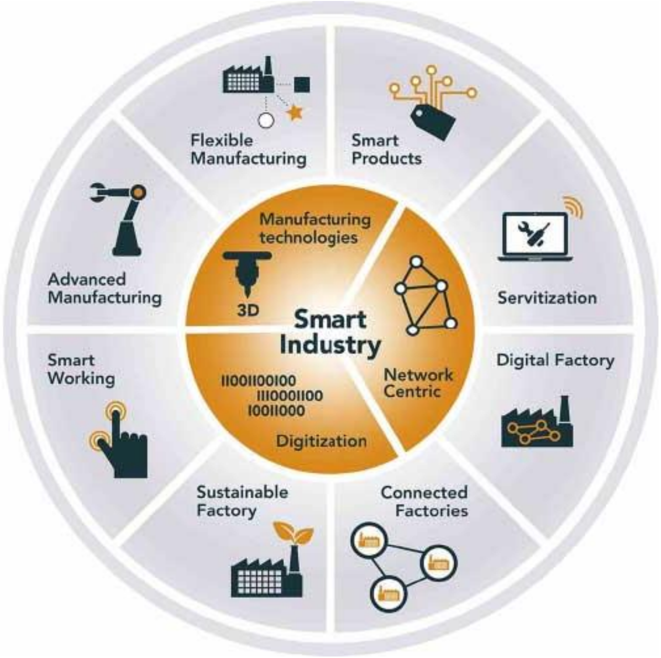
Research introduction

In order to develop a perspective on the direction of the development of circularity in the manufacturing industry, it is relevant to analyze the possible consequences of new technical (digital) developments on a company's operations, business model and subsequently its 'footprint'. Therefore, this research focusses on **how developments in the field of SI help sustainability and circularity move forward**.

In this research, for a selected number of cases extracted from the various SI propositions, the following is therefore assessed:

- What does the innovation entail?
- What business activities will it affect?
- What may be the relationship with sustainability and circularity?
- What are the drivers and barriers to introduction by business?

SI innovations have certain **intervention points** in manufacturing process (such as design, production, life cycle extension, use intensity, resource recovery, alignment of secondary material flows). In addition, there are various “**intervention strategies**” : Detecting, Optimizing and Disrupting (see also the next slide). Through information on intervention points and intervention strategies of different SI innovations, we can analyze what influence these innovations might have on circular economy strategies.



R strategies

The goal of the Circular Economy is to reduce the consumption of natural resources and reapply the residual materials. This can be achieved by different strategies. The R ladder is a framework used to describe the different circularity strategies. The rule of thumb is; strategies higher up the ladder saves more natural resources and avoid more environmental pressure. The strategies can coincide with innovations in the form of innovative product designs, technologies, or business models. The amount of R-strategies or steps on the ladder is a matter for discussion. For the research we apply the following ladder:

The 10 R-strategies are:

- R0. Refuse: Refraining from products by cancelling its function or by substituting it with a different product
- R1. Rethink: Intensifying the product use
- R2. Reduce: manufacture products more efficiently or make them more efficient in use;
- R3. Reuse: reuse of a discarded product for the same purpose;
- R4. Repair: Repair and maintenance of a product (broken or malfunctioning) to enable continuation of its original function;
- R5. Refurbish: refurbishing an modernizing a product so it can be used in its original function
- R6. Remanufacturing: Using parts of a discarded product in an new product while maintaining the function
- R7. Repurpose: Using parts of a discarded product in an new product with a different function
- R8. Recycling: processing and reusing materials;
- R9. Recover: energy recovery from materials by incineration.

The ' Nationaal Programma Circulaire Economie' (NPCE) differentiates between four type of overarching strategies for a circular economy:

1. Reducing the material consumption; by R0, R1 and R2
2. Substitution of materials other type of materials, such as secondary material from recycling
3. Lifespan increase; by R3, R4 and R5
4. High-quality processing; by R6 and R7 and otherwise R8/9

Additionally, the importance of circular design is highlighted, which allows mores easy implementation of the different R-strategies. Instead of only considering the ecological footprint, the detachability, repairability and reusability of the product or component is designed more sophisticated.

Approach & Reading Guide

The primary objective of this research is to investigate how innovations in the field of Smart Industry (SI) can enhance sustainability and circularity. The research & report is structured as follows:

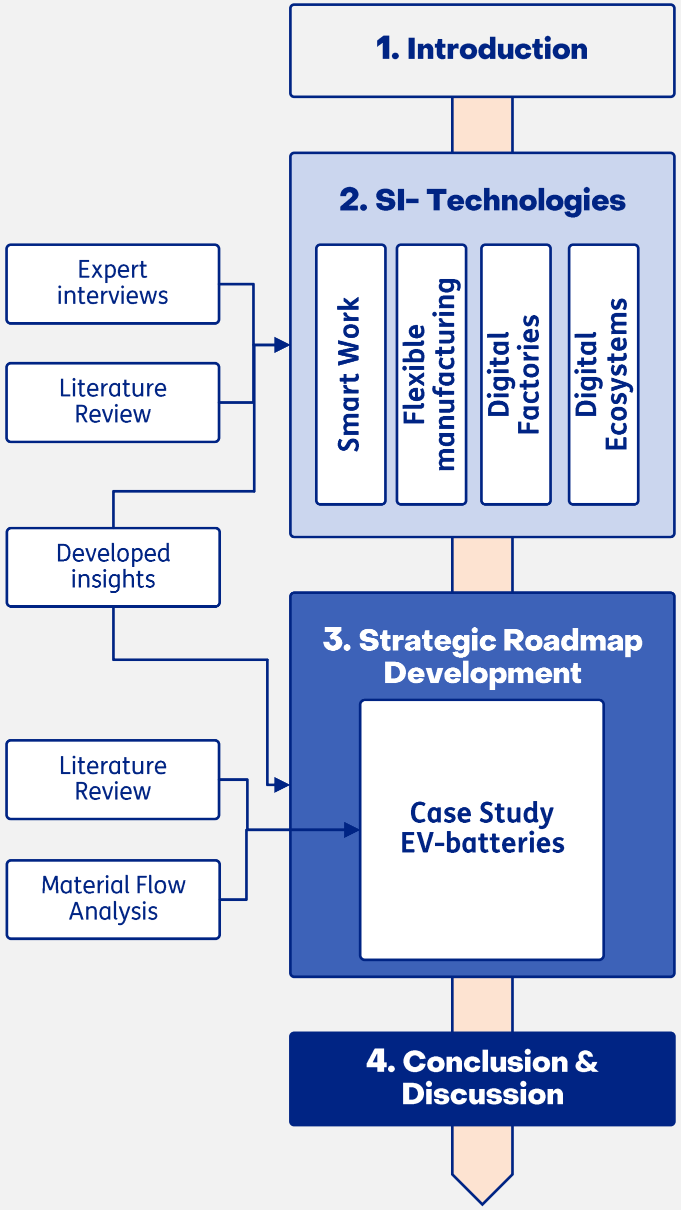
Chapter 1 | Introduction
In the first chapter the aim for the research is introduced, simultaneously with the research question. Next to that the circularity strategies are introduced to provide a common understanding.

Chapter 2 | Describing SI-technologies
Chapter 2 consists of a detailed description of various SI technologies and concepts under development by TNO, organized by the different SI clusters. The SI-technologies and concepts have been identified through interviews with SI-experts. It is important to note that the impact of introducing these new SI technologies is often unique to each case. Therefore, we have identified the product and system characteristics that enable their effective application, instead of quantifying the impact of a technology on its own. This identification is based on a combination of literature review, expert opinions, and insights gained from the executed use-case study in Chapter 3.

Chapter 3 | Creating a Strategic Roadmap Development Framework
Recognizing the case-specific nature of SI technology effectiveness, we provide the first version of a strategic roadmap development framework. The definite version of this framework should consider various aspects, including SI technology capabilities, robust business models, and circularity implications. These aspects are evaluated to design a strategic roadmap for the transition to a circular value chain enabled by SI technologies. In this chapter, we explore the elements that should be considered in the framework through a case study and uncover additional characteristics essential for successful SI technology application.

The chosen use-case for our study is the EV-battery due to the extensive information available, although the methodology can be applied to other capital goods in both B2B and B2C contexts. Our selection of SI technology interventions is based on the available knowledge concerning their potential within the use-case, but we acknowledge that other options may also be applicable. Using material flow analysis, we assess the circularity implications of these SI interventions and determine broader implications through brainstorming sessions and consultations with SI experts.

Chapter 4 | Findings, conclusions and synergy
Finally, in Chapter 4, we discuss the overarching findings of this research, draw conclusions, and highlight points of discussion. We also examine the synergy between this work and the Knowledge Investment Program (CESI-CVC) focused on the barriers to implementing Circular Business Models; We explore the consequences of SI technology implementation on this broader landscape and consider how the strategic roadmap development framework should be (re)-structured.



1. Introduction

2. SI- Technologies

Expert interviews

Literature Review

Developed insights

Smart Work

Flexible manufacturing

Digital Factories

Digital Ecosystems

3. Strategic Roadmap Development

Literature Review

Material Flow Analysis

Case Study EV-batteries

4. Conclusion & Discussion

2. SI-technologies

In this chapter, we provide an overview of the various SI-technologies and concepts. SI-concepts refer to the strategic integration of multiple SI technologies to achieve specific objectives. This integration is not confined to the use of a single type of technology for each concept. The selected technologies and concepts are collected through interviews with TNO SI-experts. Our selection of technologies and concepts is based on insights gained from interviews with TNO SI experts. It is important to emphasize that while our list is not exhaustive, it does encompass the technologies for which TNO possesses the requisite knowledge regarding development and application.

We organize these SI technologies and concepts into different TNO clusters. However, before delving into the details, we offer a comprehensive overview of how these technologies can intervene and at which stages of a product's life cycle this influence becomes most apparent. It's worth noting that SI technologies may not always directly align with circularity strategies. Some technologies primarily serve as enablers for the implementation of circularity strategies, like by providing essential information. Others are geared towards optimizing specific processes, while certain technologies possess the transformative potential to directly catalyze disruptive circularity strategies.

What interventions are possible?

The overview presents to which circular strategies, the different SI-technologies or concepts(combination of technologies) could contribute by the application. It's the results of the analysis SI-technologies and concept analysis as presented in slide x till x.

Summarizing, we see that all of these innovations could have an influence on material-reducing strategies (often in the production lines). Reducing strategies lead to more efficiency overall and often come with (rather straightforward) financial benefits, i.e., without the need to make significant changes in value chain collaborations or business models. On the other hand, for instance, for implementing Repair strategies it is necessary to think about how to create a value chain in which repair is beneficial – possibly requiring additional services being offered by a manufacturer or new collaborations with repairers.

The strategies that are not directly beneficial, or that require manufacturers to think more actively about the use phase and end of life processing of their products are therefore looked into most in this research (see also the table consisting of the different product lifecycle stages versus different SI innovations).

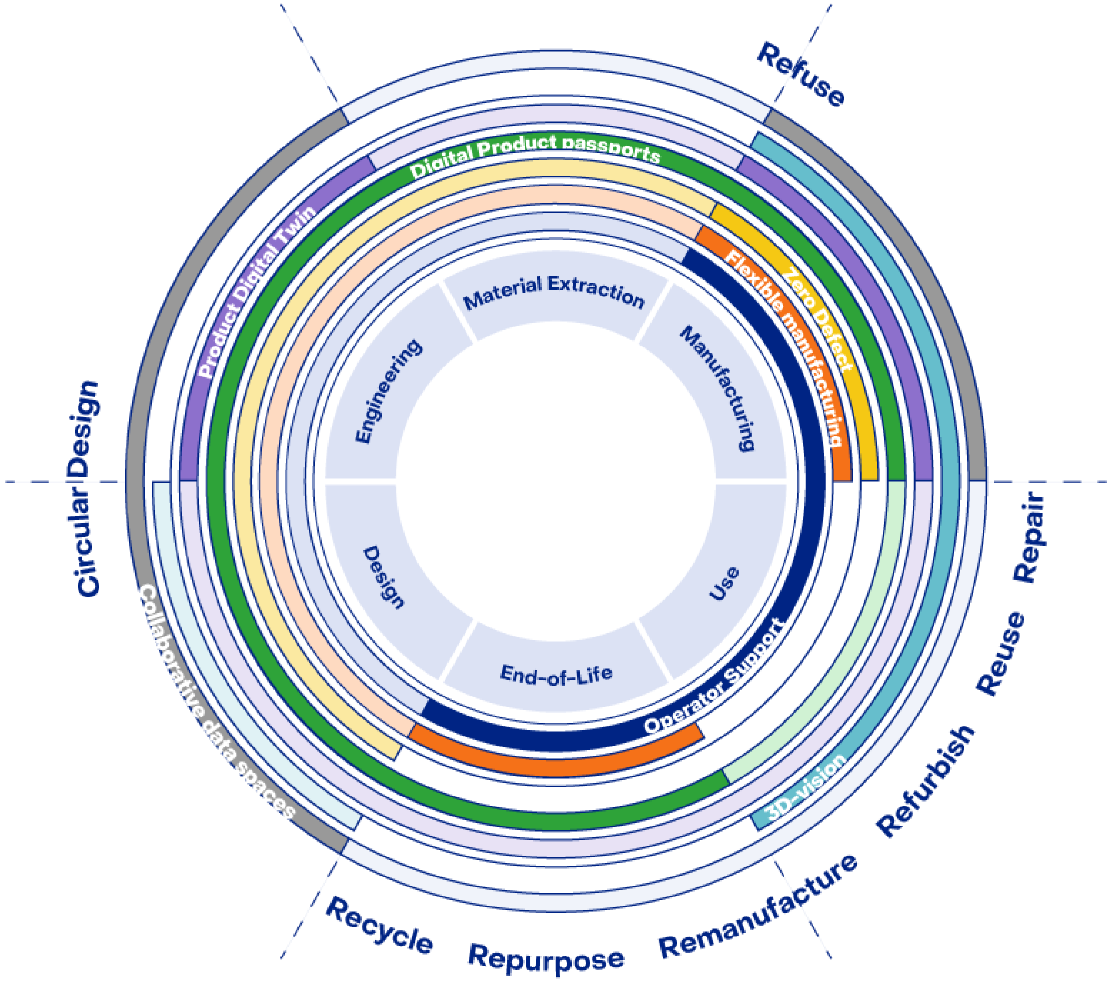
	Operator support	Collaborative robots	Zero Defect	Flexible manufacture	Digital product passports	Digital Twin	3D-vision	Collaborative data spaces
Refuse								
Rethink								
Reduce	X	X	X	X	X	X	X	X
Reuse					X			x
Repair	X		X		X		X	x
Refurbish	X			X	X	X	X	x
Remanufacture	X			X	X	X	X	x
Repurpose	X			X	X	X		x
Recycle	X			X	X	X		x
Recover					X			x
Circular Design	X		X	X	X	X	X	X

Where do they intervene?

The right figure visualize the life cycle stages for which the different smart industry technologies and concepts play a role. The dark color shows the direct relation, the light colors have a more indirect relation.

As elaborated before, strategies that require manufacturers to think more actively about the use phase and end of life processing of their products are looked into most in this research. It is there that SI innovations and concepts could have a large impact, but where often challenges occur, regarding business processes, consumer behaviour, policy, etc.

Lastly, it is important to note that interventions taking place in the design phase are only a starting point. To realize the benefits of circularity, these design principles need to be paired with concrete actions and strategies (for instance regarding repairing or recycling).



Smart Work

The SI-technologies stemming from the *Smart Work* program are dedicated to promoting effective collaboration between man and machine in order to ensure the efficiency, flexibility and sustainability of manpower within manufacturing companies. These technological concepts offer direct or indirect contributions to the environmental sustainability and circularity in the manufacturing industry. Notably, the operational support and collaborative robots (cobots) represent the most impactful technological concepts in this regard, with high Technology Readiness Levels (TRL) and widespread commercialization across various use cases.

These technologies have been driven by compelling factors, such as the challenges posed by a tight labor market. The enhanced interaction between humans and machines facilitates more efficient operations, reducing the need for extensive human labor. Furthermore, the demand for these technologies surged during the Covid-19 pandemic as it necessitated greater flexibility within value chains. Beyond these immediate drivers, the technologies bring added benefits, including increased adaptability and flexibility of the workforce and improved employee safety.

Operator support

This facet involves the provision of digital work instructions to operators through means like projection technologies and augmented reality. It primarily finds applications in assembly processes, service, and maintenance, driven by the imperative of quality assurance. This system allows for real-time process tracking, knowledge transfer to new operators, and enables remote maintenance, empowering non-expert on-site employees to independently execute specific tasks. Additionally, it can play a role in optimizing material flows and environmental performance within the value chain in various ways, as presented on the next sheet.

However, it's worth noting that current applications are focused on organizations, such as manufacturers and repairers, and not individual consumers. Exploring open source support could present an opportunity for individual users to engage in their own maintenance and quality assurance.

Collaborative robots

These robots work alongside human employees in the workplace, offering physical support. This collaborative approach enhances safety for workers, enables precision manufacturing, and optimizes resource utilization, thereby reducing material waste. While cobots bring substantial benefits, their direct connection to other circular economy strategies is not immediately evident, and we won't delve further into this aspect here.

Barriers/risks

Implementing Smart Work technological concepts involves an array of technologies. Acquiring knowledge about existing production processes is critical for implementation but can also pose a barrier to upscaling. The processes that require technology support across the value chain must be identified, made digitally available, and adapted for human interaction. Often, companies have limited understanding of their own processes, hindering the adoption of such solutions.

The process of capturing and digitalizing these processes is time-consuming and labor-intensive. Currently, it's not feasible to seamlessly integrate with existing enterprise resource planning (ERP) systems or automatically generate project libraries, making the adoption of SI technologies a substantial initial investment, especially given the case-specific nature of their application. Currently, Smart Work is working on semi-automatic generation of work instructions based on existing CAD-models. Specifically helpful to overcome the information barrier for upscaling in an situation with highly diverse product types.

Another barrier is the initial investment for the SI-technologies to allow application of the different concepts. Depending on the approach, the equipment could have a high initial investment required. Per case, the pay-back time will highly differ. Reluctance for implementation due to the investment costs can be expected.

Operator support

Operator support can significantly contribute to several circular strategies, including reduction, repair, refurbishment, remanufacturing, recycling, and circular design. Here's how:

1.a Reduce: quality assurance

Quality assurance is a pivotal driver for companies looking to implement an operational support system, particularly for complex tasks carried out by less skilled labor. This approach reduces the cost and time spent on training manpower for various production operations, leading to enhanced efficiency and a decrease in errors. This, therefore, results in fewer material losses along the production line, which avoids material use. This application is focused on optimizing existing processes.

1.b Reduce: avoid transport by remote maintenance

Operator support for maintenance goes beyond prolonging the lifespan of products; it also helps minimizing transportation. By enabling less skilled operators to perform tasks on-site, a practice known as remote maintenance, experts don't need to travel to specific locations. This not only reduces the environmental impact associated with transportation but also minimizes product downtime.

2. Repair

Operator support systems are employed for on-site maintenance and systematic issue detection in products. In the past, the lack of on-site expertise or the ability to diagnose issues quickly often led to replacements rather than repairs to keep process interruptions to a minimum. With operational support technologies, issues can be addressed promptly, increasing the likelihood of repair instead of replacement. This extends the lifespan of the product, reducing the need for substitutes.

3. Remanufacture/refurbish/recycle: Disassembly

Operator support could also be applied for the disassembly of products at the end of their life cycle, facilitating improved separation of components and materials. This enhances the opportunities for remanufacturing and recycling. Careful component separation preserves the quality of components, increasing their potential for remanufacturing.

4. Remanufacture/refurbish: alignment variety material flows

The wide variety of product types, qualities, quantities, and complexities often complicates the refurbishment and remanufacturing processes. Operator support can help address this challenge by enabling efficient analysis of products and the identification of second application opportunities. This ensures that the diverse material flows alignment required for second applications does not result into a barrier for applying the circular strategies.

5. Circular Design

Passively, the use of operator support could enable circular design. During the use of the technological concept, information is gathered which could serve as input, for example, on which components are regularly defect.

	Characteristics for useful application
1.a 2. 3. 4.	• Standardized elements • Large quantities or capital goods • Complex products
1.b 2.	• Large distances between locations of products • Vital equipment • Highly complex product; specific expertise required for maintenance activities

Flexman

The Flexman program is rooted in tackling manufacturing challenges that manifest on the shop floor, encompassing issues such as process improvement, error reduction and production configuration. At its core, the research group Flexman is dedicated to addressing these challenges within the context of small series complex products characterized by high variety. To maintain competitiveness in such production lines, there are critical considerations concerning quality, automation, and flexibility. Within this research group, a multitude of concepts and technologies can be identified, offering potential support for circular strategies, among which the following:

Flexible Manufacturing

Flexible manufacturing systems aim to minimize the time required to adapt and configure production lines for different products while simultaneously reducing errors. Challenges emerge in the seamless collaboration of robots, machinery, software, and other components, ideally with minimal human intervention. An example of such a challenge lies in reconciling automation with flexibility, as robots typically require reprogramming when tasks change. Digitization plays a pivotal role in harmonizing these aspects; for instance, zero programming solutions enable automatic adjustments of robot settings for various tasks.

Zero Defect

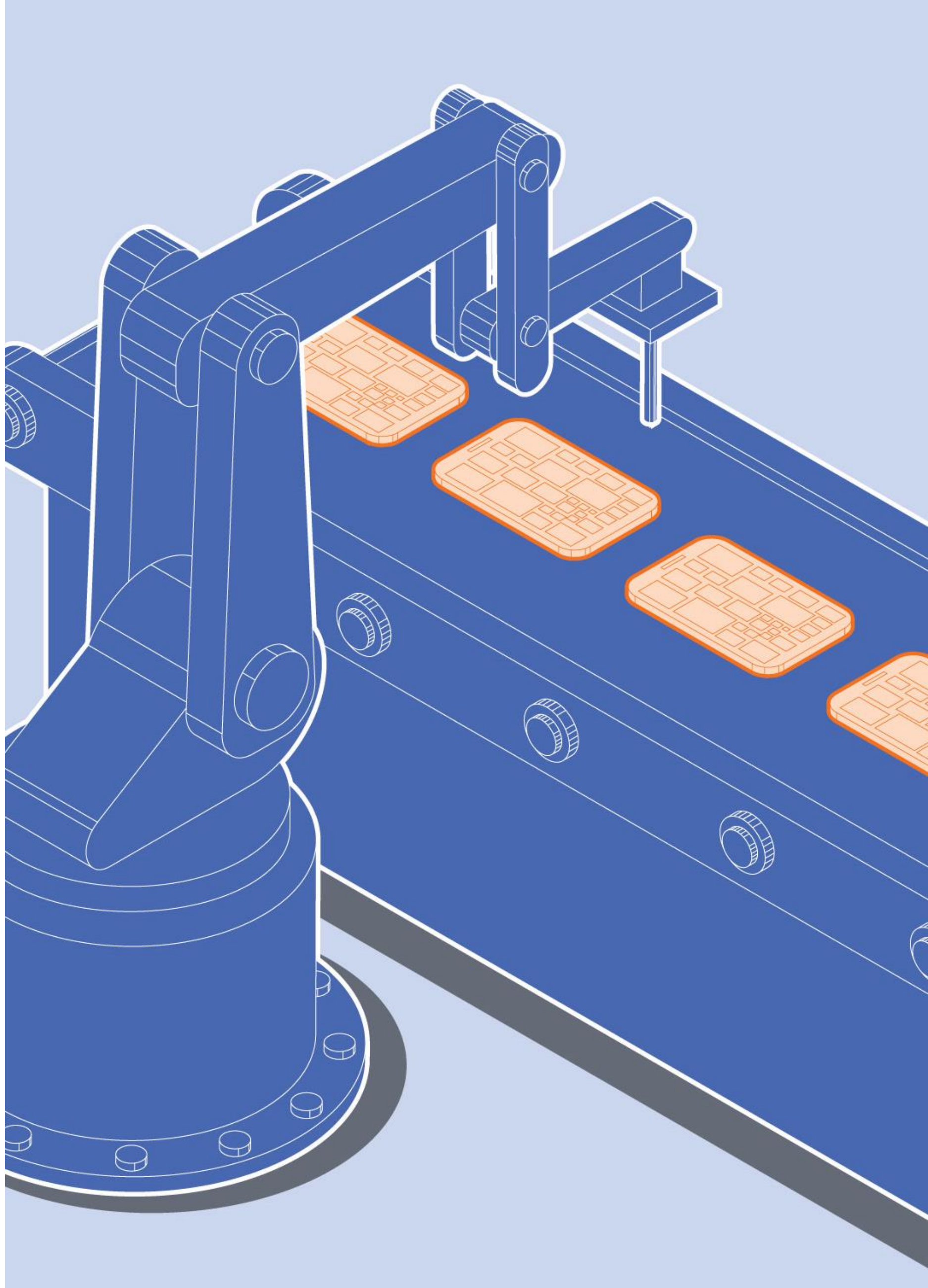
The Zero Defect concept is centered on quality control and the minimization of material losses and production issues. It operates through various strategies, including defect detection, prediction, prevention, repair, and management, all geared towards achieving impeccable compliance with specifications. Various technologies and concepts support this objective, encompassing in-line quality control, optical sensors, ultrasonic sensor arrays, high-speed image processing, and zero programming. Contributing to a most efficient and optimal production process.

3D-vision

Another technology from the Flexman portfolio is 3D vision (for robotics and quality control). This consists of an autonomous workflow for 3D image acquisition to point clouds and meshes. This includes various methods for sensor calibration to standards, 3D object reconstruction and comparing of objects with respect to other scanned objects or CAD. Application areas are quality inspection; 3D colour, shape and texture.

Barriers/risks

In the context of the circular economy, Flexman concepts and technologies possess the potential to impact various circular strategies, as described on the next slide. However, it's vital to acknowledge the possibility of a rebound effect. By optimizing production lines, the cost per unit of products may decrease, potentially leading to increased demand and, consequently, heightened overall production (and material use).



Flexible manufacturing system

Flexible manufacturing is a concept consisting of various technologies combined throughout entire production lines. Improving the flexibility of a complex production line can have an direct impact on the following R strategies:

1: Reduce: alignment supply and demand

Flexible manufacturing reduces the amount of time/energy spend in adapting production stations, while minimizing the amount of errors made in production. It allows multiple production lines to benefit from the same quality checks. Consequently. it avoids overproduction since the supply can better be aligned with the demand. Therefore, it has a clear impact on the third R strategy, reducing the amount of energy/material losses.

2: Refurbish / recycle / repurpose / remanufacture: alignment variety material flows

Enhancing production processes with secondary materials becomes more feasible when there's an ability to easily adjust to varying qualities of materials or objects. By easier adaptations of the production process, it becomes possible to effectively address the alignment barrier in second material flows (that might differ in quality) and manage smaller quantities of secondary products more efficiently.

3. Circular Design

Lastly, flexible manufacturing can enable more circular design of products. Flexible manufacturing technologies can enable more customized and on-demand production. Therefore, they can make sure products align with certain specifications, such as specific component design. In addition, these technologies make it easier to create modular products, which is beneficial for multiple r-strategies.

	Characteristics for useful application
1. 2.	• Small series, complex products of large varition • Preferably ‘high’ (more upstream) in the value chain (most profitable)

Zero Defect

The application of Zero Defect (manufacturing) technologies enhances the adaptive capacity to undesired events in production chains. Various technologies are applied to increase the adaptivity. The first principal of zero defect-manufacturing is detection of the issue through diverse sensing technologies. The situation will be assessed by, for example, high speed image processing, after which there could be acted upon with machinery controlled by zero-programming software. This way, Zero Defect can have an impact on the following R strategies:

1a. Reduce: machinery downtime and waste/scrap

By minimizing any levels of defects or errors, i.e., the amount of machinery downtime and waste/scrap, the efficiency of the production lines can be improved. Zero defect is a clear example of a ‘reduce’-strategy in the production line; reducing energy/material losses.

1b. Reduce: predictive

The application of Zero Defect technologies extends to predictive defect detection, preventing the occurrence of defects or errors in production lines. By intervening before issues manifest, the loss of materials, components, or products can be proactively avoided, contributing to a more sustainable and resource-efficient production process.

2. Repair: predictive maintenance

The application of Zero Defect technologies in high-capital equipment allows to identify the occurrence of issues early in the process. Sensors need to be placed in each product to detect the issues and avoid discarding products by repair activities. Important to note here is that applying zero defect technologies for predictive maintenance can be more challenging than applying them in the production line. This is due to high initial investments for the technology vs. effects on the return of investment that might not be directly clear in the latter case.

3. Circular Design

The data collected by Zero Defect technologies holds immense potential for improving the circularity of product design. Informed by this data, well-considered design improvements can be implemented, resulting in products with fewer defects. This cyclical approach aligns with circular design principles, fostering the creation of more sustainable and durable products.

	Characteristics for useful application
1a. 1b.	• Products that require high quality, which can be identified by (any type of) sensors; • Products with large quantity losses due to specific events; • Large quantity products (such as fast moving consumer goods).
2.	• Capital-intensive and complex machines

3D-vision

3D vision (for robotics and quality control) can have an impact on R strategies in the production line as well as in the products lifetime.

1. Reduce: avoid defects

By identifying defects early in the manufacturing process, 3D vision can improve the in-line quality control for products (on parts level, i.e., before assembly). Therefore, intervention can take place in a early stage, which avoids material, component or product losses.

2. Remanufacture / refurbish / repair: Improvement of surface structures

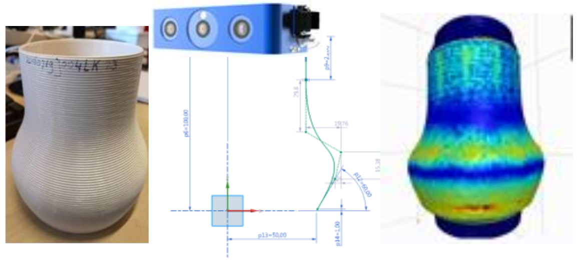
3D vision technologies present a valuable opportunity in the realm of remanufacturing, refurbishing, and repairing products where shape or surface structure is paramount for usability. Through precise surface scanning of discarded products, it becomes feasible to apply materials with accuracy, restoring the original shape and structure. This application facilitates the remanufacturing of products, offering a sustainable solution to extend their lifecycle

A compelling example emerged in interviews concerning defective airplane wings. Leveraging 3D vision technology, the geometry of these wings can be meticulously analyzed, identifying the implications of wear and tear. Subsequently, a strategic plan for precisely applying the right amounts of new materials can be formulated. Following this intervention, the wing-blades regain usability, contributing to both environmental sustainability and cost-effectiveness.

However, to leverage these services effectively, considering the high initial technology investments, the development of a robust circular business model becomes imperative.

3. Circular Design

Indirectly, 3D vision adds to the circular design of products. Because it can reduce the likelihood of products with issues reaching the market, it contributes to product quality and longevity. But it can also add to circular design (optimization) directly: the 3D data captured during quality control processes can be used for design iterations and improvement. This data can help in aligning the product with circular design principles, such as repairability and recyclability.



	Characteristics for useful application
1. 3.	• Complex and expensive products in low quantities • Parts level (before assembly)
2. 3.	• Capital-intensive products • Products where wear and tear is likely to occur

Digital Factories

The PMC Digital Factories is dedicated to establishing secure and seamless information connections within a factory environment. The digitalization of factories plays a crucial role in facilitating this connectivity. The act of connecting information generates novel insights that can be leveraged to optimize factory operations, a process that encompasses three key levels: (1) integration of information, (2) interpretation and analysis, and (3) translation of insights.

Boosting connectivity in the manufacturing industry holds significant importance for a variety of reasons, such as labor shortages, sustainability imperatives, error identification, and the need for increased operational flexibility. There are many opportunities for the manufacturing industry to enhance its connectivity. Several factors contribute to the current low levels of connectivity:

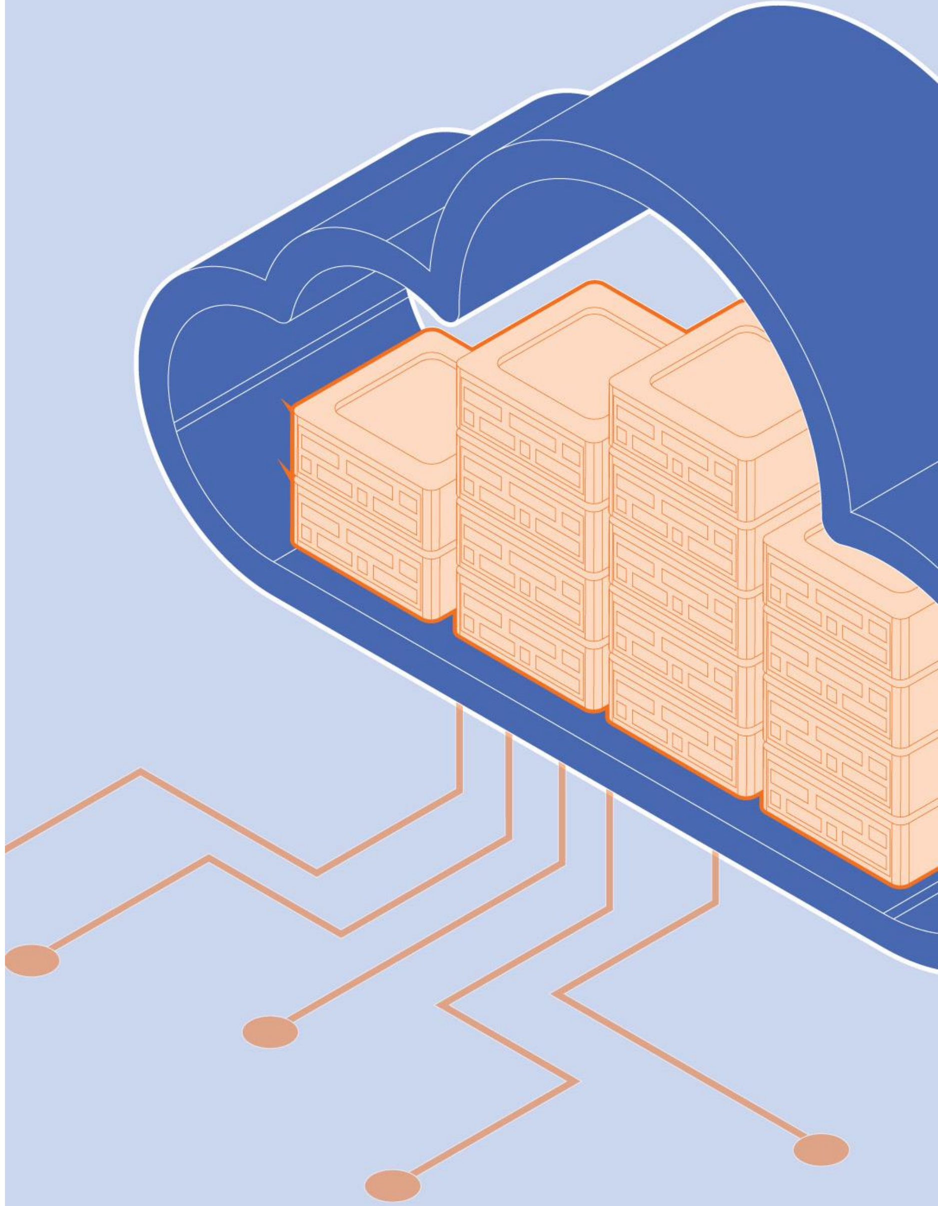
1. The manufacturing industry still lags in digitalization.
2. The presence of numerous non-integrated software systems (on average 10-20 different systems in a factory).
3. A lack of standard basic functions that are consistent across different factories.

Barriers/risks

The primary barriers to enhancing connectivity within an organisation are often rooted in the organizational dynamics rather than technological limitations. While the required technologies are available, the implementation within an organization is frequently challenging. Resistance to digitalization often arises as it necessitates a shift in working methods, and efficiency gains might inadvertently lead to workforce reductions, which is not the intended outcome for organizations. Furthermore, the lack of clear incentives to improve information connectivity within a company can pose a challenge. The positive impact on operational efficiency is not always evident upfront, and the initial investment in knowledge and equipment tends to discourage factories from making necessary changes.

Digital Twin of the factory

The application of digital twins within Factories primarily focuses on the digitalization of manufacturing facilities. A digital twin is a digital counterpart of a physical product, process, or asset. The objective of a digital twin is to simulate and replicate real-world factory operations, processes, and systems in a digital environment. This digital replica is created using various digital technologies, including sensors, IoT devices, computer-aided design (CAD) models, and data analytics. It facilitates the simulation and testing of various production scenarios, enabling process optimization, predicting equipment maintenance needs, and streamlining the manufacturing chain. The wealth of additional information supports specific process optimization and fosters innovative product concepts, particularly those that require seamless alignment between processes, such as modular design. Ultimately, digital twins play a pivotal role in supporting decision-making throughout the engineering and manufacturing phases.



Digital Twin

The application of a digital twin holds potential to improve in different ways the environmental performance and circularity of products. While the terminology of digital twins spans various context, our focus in this analysis is specifically on digital twins of manufacturing systems. These digital twins serve as catalysts in advancing key circular strategies:

1a. Reduce: manufacturing

The application of a digital twin for manufacturing systems marks a significant contribution to informed and sustainable practices. By capturing real-time information from production line, the digital twin enables accurate monitoring. The ability to detect or predicting issues directly allows for prompt intervention, thereby preventing defaults and minimizing production waste. The proactive approach aligns with the reduce-strategy, fostering efficiency and sustainability in the manufacturing process.

1b. Reduce: remanufacturing / refurbishment / recycle

Digital twins in the manufacturing systems can be extended to similar environments such as remanufacturing, refurbishment or recycling processes. By integrating digital twins into these manufacturing lanes, issues and material losses can be minimized, propelling these circularity strategies toward increased efficiency and economic viability. The comprehensive insights provided by digital twins make these strategies not only environmentally sustainable but also economically beneficial, enhancing the likelihood of their widespread application.

2. Repair

Digital twins could as well emerge as asset for the circular strategy of repair within the manufacturing system by by facilitating the early detection or prediction of issues within factory equipment. Armed with precise knowledge of the source of a problem, executing repair actions becomes more straightforward. Moreover, the predictive capabilities of digital twins contribute to issue prevention, reducing the occurrence of failures and optimizing maintenance efforts. This not only enhances operational efficiency but also prolongs the lifespan of machinery, aligning with the principles of sustainability.

3. Circular design

Information derived from digital twins about manufacturing processes can serve as a cornerstone for well-informed circular design. Empowering engineers to optimize product design with a focus on minimizing material and energy use. By facilitating engineers in identifying and evaluating design solutions, digital twins become catalysts for adapting products based on comprehensive insights, driving circular design practices.

	Characteristics for useful application
1a. 1b. 3.	• Product for which high-quality is required • Products with large quantity losses due to specific events; • Large quantity products (such as fast moving consumer goods).
2.	• Capital-intensive and complex machines

Data Ecosystems

The use of data is increasingly rising and digitization is nowadays part of the strategy of many organizations. However, organizing data flows is a challenging for many companies.

Data ecosystems are environments in which organizations can exchange data while ensuring confidentiality. Technologies that are being developed under TNOs Data Ecosystem Group focus on the sharing of data amongst multiple organizations in the supply chain. This stimulates effective collaborations and enables connecting ecosystems of multiple sectors. In the manufacturing industry, data ecosystems could help to optimize processes through knowledge of processes that take place in other companies and knowledge of specific product characteristics

To make this possible, all underlying systems must be able to exchange data easily. Only then operational processes can be optimized in order to make good business decisions and deploy AI applications. In addition, data sharing must be trouble-free and must comply with contractual and legal requirements, such as the General Data Protection Regulation (GDPR).

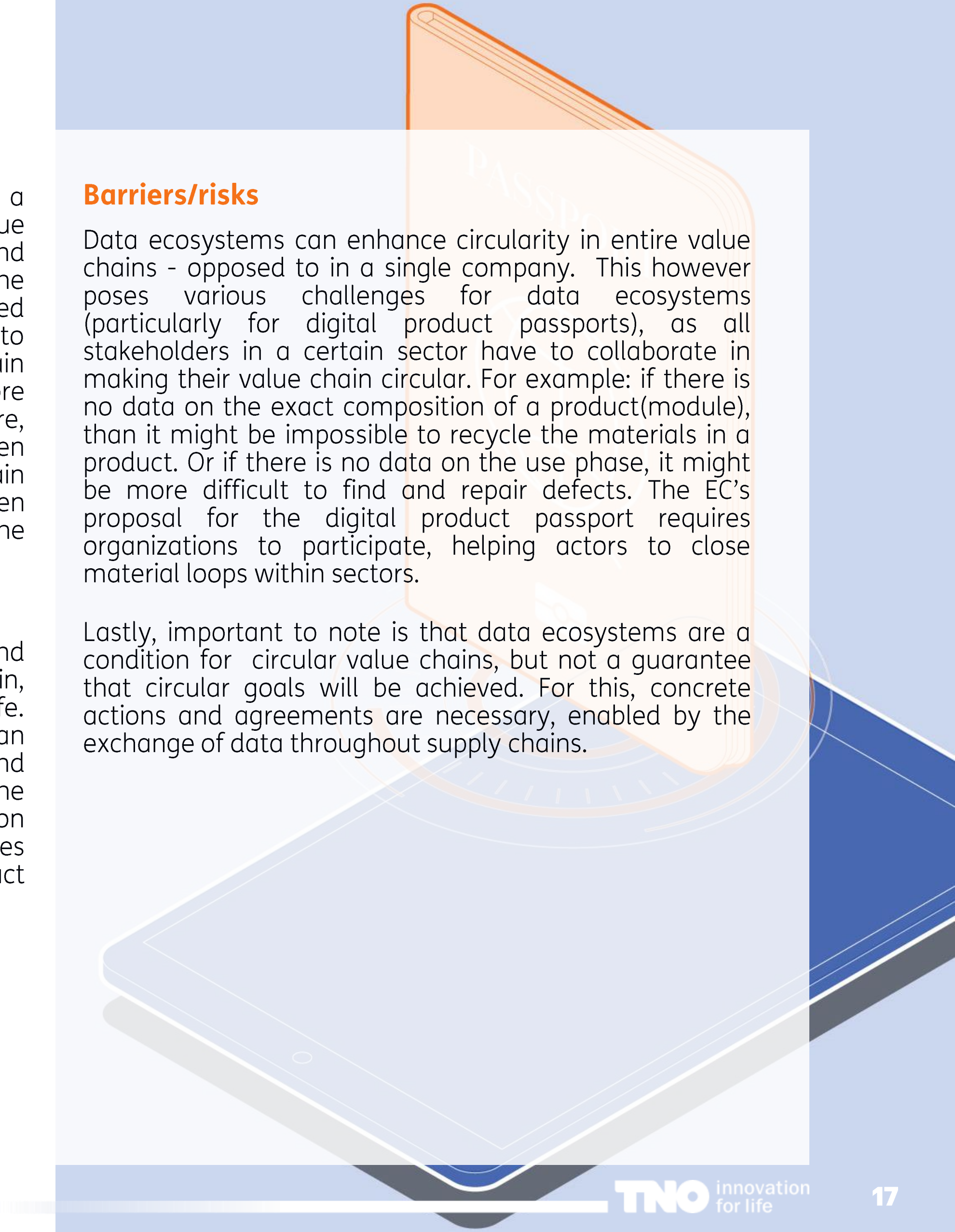
Privacy sensitive information or the fear of losing power to other organizations makes some organizations reluctant to share data. Novel technologies within data ecosystems help to reduce such barriers to share information and provide new opportunities to interact and utilize data. Exchanging data through *Collaborative data spaces* and *Digital product passports* provide opportunities and novel ways of utilizing data that enhances circularity as well.

Collaborative data spaces

Collaborative data spaces allow sharing data in a standardized way from one organization to another. Due to its standardization the process is more safe and efficient. An example of a data space in the manufacturing industry is SCSN (Smart Connected Supplier Network): a network that uses data standards to make the exchange of information in the supply chain more efficient. This allows companies to share data more easily, quickly, and reliably. Because of this, fast, secure, and interoperable exchange of information between companies can take place, resulting in higher supply chain productivity. This stimulates the connectivity between factories and also allows data exchange throughout the entire value chain.

Digital product passports

Digital product passports (DPPs) facilitate the sharing and use of product data in various phases of the supply chain, including the use phase and the phase after end-of-life. Different stakeholders throughout the value chain can access this data, which increases transparency and traceability. DPPs store information about how the product is manufactured, the different materials used on the product and the associated emissions. This creates opportunities in various R strategies to handle the product in a more circular way.



Barriers/risks

Data ecosystems can enhance circularity in entire value chains - opposed to in a single company. This however poses various challenges for data ecosystems (particularly for digital product passports), as all stakeholders in a certain sector have to collaborate in making their value chain circular. For example: if there is no data on the exact composition of a product(module), than it might be impossible to recycle the materials in a product. Or if there is no data on the use phase, it might be more difficult to find and repair defects. The EC's proposal for the digital product passport requires organizations to participate, helping actors to close material loops within sectors.

Lastly, important to note is that data ecosystems are a condition for circular value chains, but not a guarantee that circular goals will be achieved. For this, concrete actions and agreements are necessary, enabled by the exchange of data throughout supply chains.

Collaborative data spaces

Collaborating with stakeholders throughout the supply chain is crucial for a circular economy. Collaborative data spaces increase the connectivity between organisations, reducing errors and helping companies to better understand their resource usage and resource usage of supply chain partners. Through data spaces various circular business models can be supported, resulting in a variety of ways to operate more circular. This occurs mostly in production lines. Collaborative data spaces can therefore directly support the following R strategies.

1. Reduce: supply chain optimization

Data sharing among supply chain partners can lead to more efficient and sustainable practices, reducing waste and overproduction in the manufacturing process. For instance, with better connectivity, businesses can optimize inventory levels, ensuring that resources are used more efficiently. Also, by analyzing data from various partners in the supply chain, businesses can use predictive analytics to forecast demand more accurately. This helps in better planning and reduces the likelihood of overproduction or excess resource usage.

2. Circular Design

The sharing of data combined with increased collaboration between stakeholders (e.g. material experts, product designers and repairing companies) can result in better circular (modular) design of products. This is possibly strengthened by product data in the use phase: through tracking data of product lifecycles, user behaviour and waste, companies can find opportunities to better design products that have a longer lifespan, are more efficient, easier to repair, easier to recycle, etc.

Data spaces can help to increase the exchange of information among supply chain partners. Collaborative data spaces can therefore also (indirectly) support the following R strategies through increased connectivity of supply chain partners:

3. Repair / remanufacture / recycle / repurpose

Data sharing, in general, can improve company collaborations across supply chains. This can enable different supply chain partners to better deal with large amounts of industrial data, which could lead to better execution of various R strategies (such as repairing, remanufacturing, recycling). In addition, increased data sharing between different parties can facilitate more efficient reverse logistics, enabling the return (for repair), remanufacturing, or recycling of products and components.

	Characteristics for useful application
1 2 3	• Dependency on other organizations information to operate more circular or vice versa • Access to extensive and comprehensive data • Trust in supply chain partners, willingness to collaborate

Digital product passports

Digital product passports (DPP) can contain information throughout different phases of the supply chain. DPP’s can therefore support different various circular strategies, as explained below. Asset management and Enterprise Resource Planning will be fundamentally better with a DPP.

1. Reduce: resource consumption in product lifetime

DPPs provide manufacturers with detailed data on the product's composition and performance. This information can help in optimizing product designs to reduce resource consumption, energy usage, and waste generation during production.

2. Reuse

DPPs can include information on a product's condition, repair history, and suitability for reuse. This can support the certification of pre-owned products, making it easier for consumers to trust and purchase used items.

3. Repair

A DPP can provide information to repairers which makes it safer and more accessible to repair products and thus increases repair.

4. Refurbishing/remanufacturing

DPPs can support remanufacturing and refurbishment processes by providing insights into the original design, materials used and what happened to the product in its use phase, how to disassemble it, making it easier to reapply or reuse the product (components).

5. Repurposing

Information stored in DPPs can help individuals and organizations identify potential alternative uses or creative repurposing ideas for the product or its components. Asset management will be fundamentally better with a DPP.

6. Recycling

DPPs can provide guidance on how to disassemble and recycle a product efficiently, reducing the complexity and cost of recycling processes. Recycling materials becomes easier when information from earlier life-cycle stages of the product are available. Specifically for the alignment of secondary flows, digital product passports allow for the use materials from a certain product as input for a new product.

0. Circular Design (“0”, as it’s relevant for all other 6)

A DPP allows to gather information throughout the whole supply chain. Therefore information data from product passports can offer insights to designers and manufacturers about how their products are used and how they perform in real-world conditions. This data can inform design improvements and better align products with circular design principles, such as a longer product lifespan, repairability and recyclability.

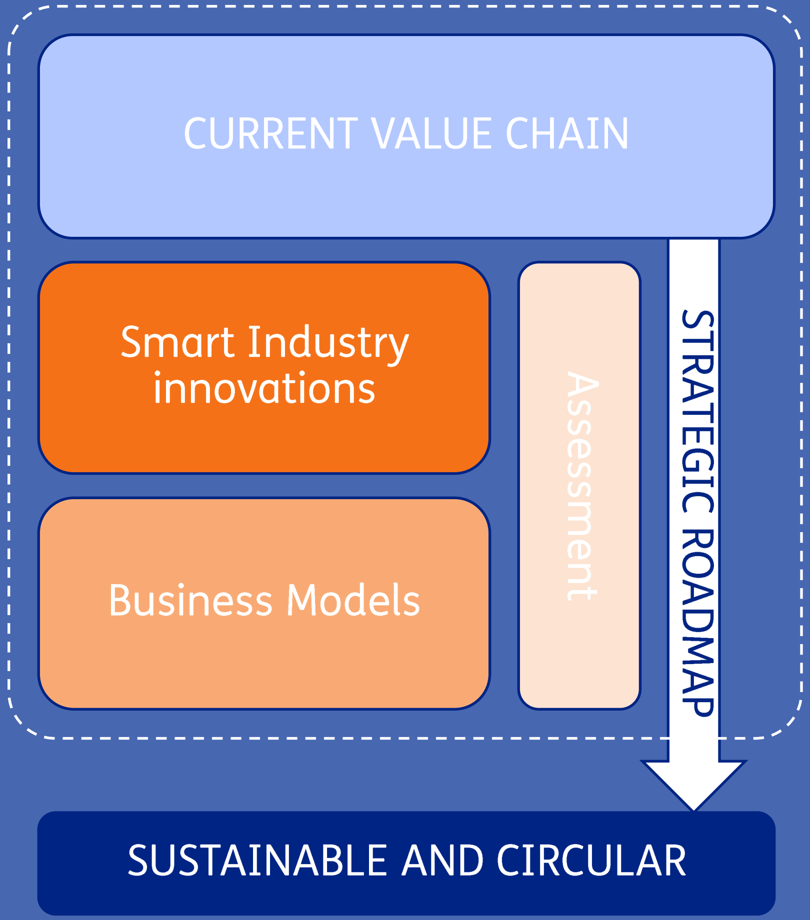
	Characteristics for useful application
1 2 3 4 5 6 7	• Dependency on other organizations (or consumers) information to operate more circular or vice versa • Product complexity • Access to extensive and comprehensive data

3. Strategic roadmap development

The previous chapters had a more general approach to identify the opportunities of certain SI-technologies to support a circular and sustainable economy. However, the actual implications of a technology are case dependent. A effective strategy will differ for each value chain. Therefore, in the following slides, we use a case study to make a first step to get a better understanding of the practical implications of how certain technology interventions enhance circularity.

The goal is to, by means of a case study, develop an approach to create in collaboration with value chain partners a strategic roadmap to effectively apply circular strategies, enabled by SI-technologies and new Business Models. The approach should not be limited to the circularity and sustainability effectiveness. Wider implications and responsibilities to allow implementation should be considered. Extensive assessments could be applied but are tried to be avoided to allow a fast iterative process.

The figure presents the concept of the approach. Identification of the current value chain and assessment of the responsibilities, material flows, impacts, interests and interactions allows to evaluate the implications of interventions. In this case study, we will specifically look at SI-innovations that could enable the circular value chain. But as well the knowledge about business models will play the role in the development of a strategic roadmap, which eventually leads to a sustainable and circular value chain.



Case study

Electric Vehicle Batteries

We use the case of electric vehicle (EV) batteries to increase the understanding of certain interventions on the circularity and sustainability of the value chain. The interventions are based on the SI-technologies that are discussed in this report. The choice for electric vehicle batteries is based on (1) its versatility to apply different interventions, and (2) the major role of batteries in the transition to sustainable transportation.

Use case context

Electrification of the transport sector is important to reduce its contribution to climate change and achieve carbon neutrality. EV-batteries play a crucial role in this transition. As a consequence, the demand grows rapidly and thus the demand for the materials used to produce the batteries as well. This rises some concerns, mainly for the critical raw materials (CRMs), such as Lithium, Nickel and Cobalt, that are needed to produce the batteries.

A more circular value chain is important to allow the use of EV-batteries while overcoming the concerns of material availability. We chose 5 interventions, based on the first part of this document, that are to improve the circularity of EV-batteries:

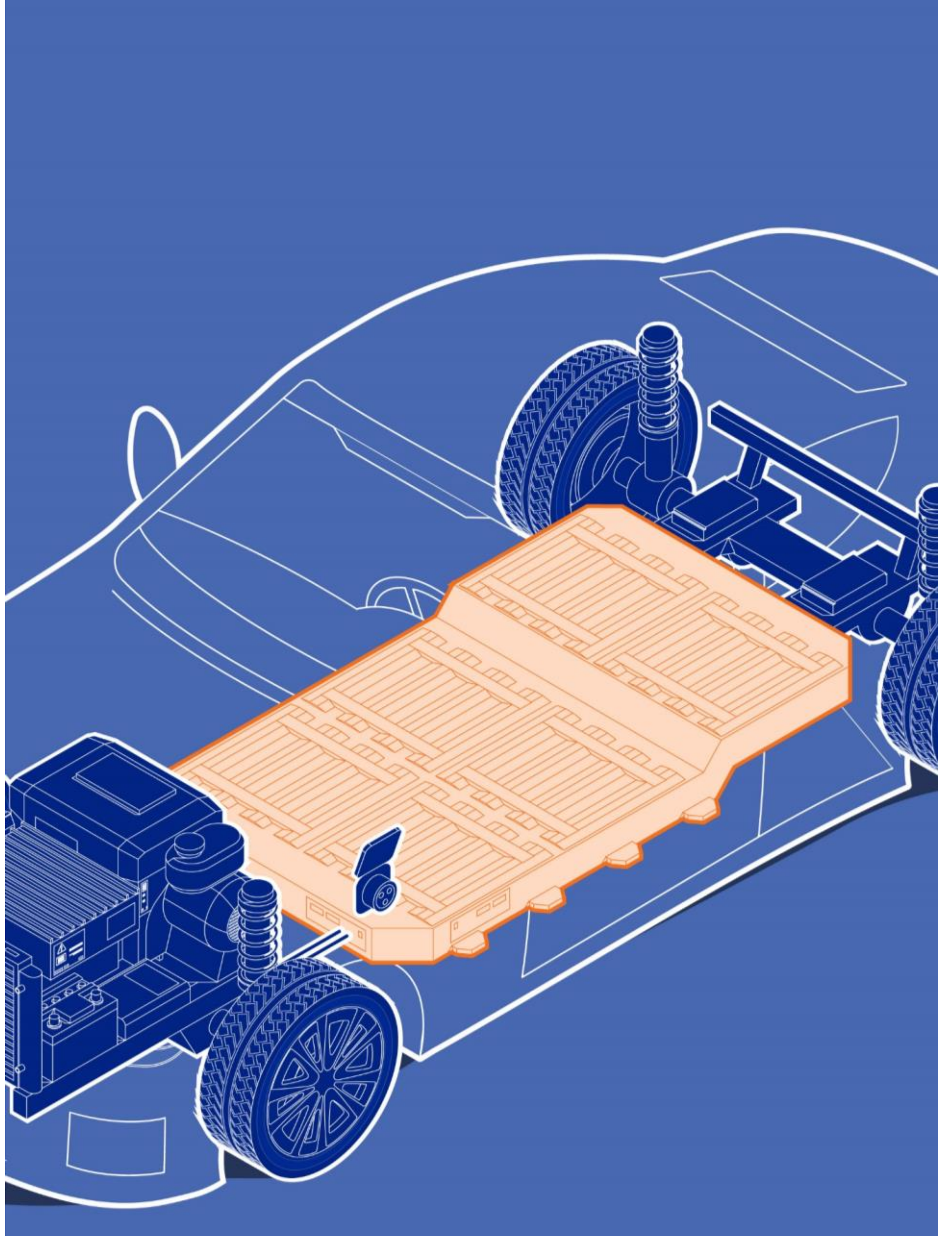
1. Introducing digital product passports (DPP)
2. Applying Zero Defect technologies during production
3. Operator support to increase & improve maintenance in the initial use phase
4. Flexible manufacturing system that allows for efficient remanufacturing
5. Using a digital twin for circular design; modular design

Scope

Since the CRMs are of main concern in this use case, we decided to focus on how the interventions effect the material flow of these CRMs in the batteries. Base on the implications of the interventions, scenarios are constituted to show the changes in the materials flows, those are compared to the scenario the business as usual (BAU). 2040 is selected as the reference years since implications of the interventions take time to be reflected in the material flows. In the appendix the methodology and assumption of the material flow analysis are described.

Notable characteristics

As mentioned, the demand for batteries is strongly increasing. Therefore, the amount of EV-batteries at the end of life is relatively small compared to the demand. Over time, the amount of batteries available for reuse or recycling will increase. Due to the growing market, you'll get some striking interactions in the system. Such as, a increase of lifespan reduces the share of secondary materials available.



Business as Usual | Scenario

To allow evaluation of the effects introducing SI-technologies, a Materia Flow Analysis (MFA) is carried out. First the Business as Usual (BaU) is constituted as a reference for the evaluation. The BaU scenario describes the CRM flows disregarding the interventions that can be applied to make the supply chain more sustainable, for Europe in 2040. The assumptions that go along with the assessment can be found in the appendix A.

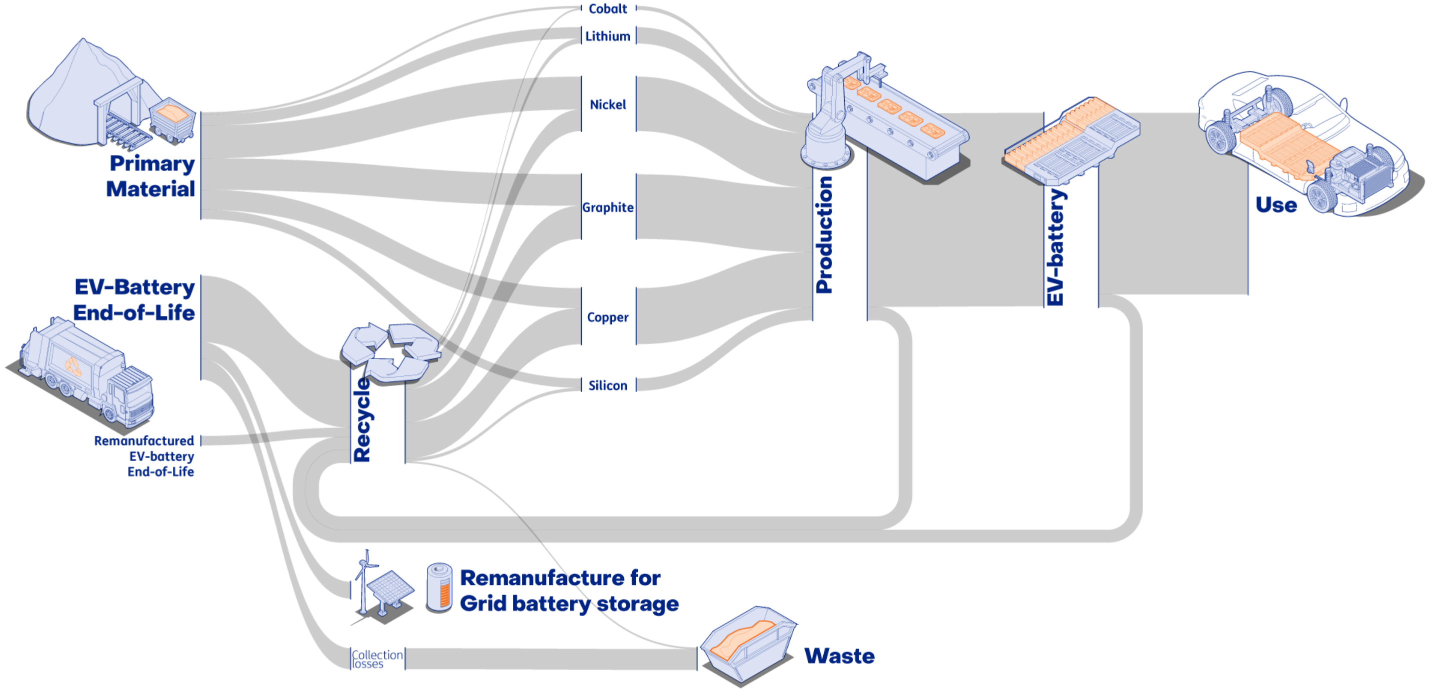
The MFA shows the CRMs that are required for the production of EV-batteries. The origin of materials is two-folded; primary materials extracted and secondary materials recovered from discarded EV-batteries. The amount of available secondary materials is in a growing market as the EV-batteries rather scares. You'll be limited by the EV-batteries that can be extracted from the 'urban mine' for the application of recycled materials. The overall alignment rate between the demand and secondary materials is 48%. Silicon and Lithium have the lowest rates, respectively 25% and 31%.

During the different processes, such as collection, recycling, production and assembly, losses of materials or products may occur. These are modeled as well in the MFA. It shows that some losses will lead to recycling, to reuse the materials. Losses of recycling or collection will result in waste, which leads to landfill, incineration or application as road foundation.

EV-batteries are in most cases discarded due to the capacity loss, which limits the driving range. Therefore, it is unfit for electricity storage within cars. However, for grid storage the batteries can still be applied. Remanufacturing for grid storage will give the battery a second life and avoids the production of new grid energy storage.

Material Flow Analysis

EV-battery | CRMs | Europe | 2040 | Business as Usual



Digital Product Passport | Scenario

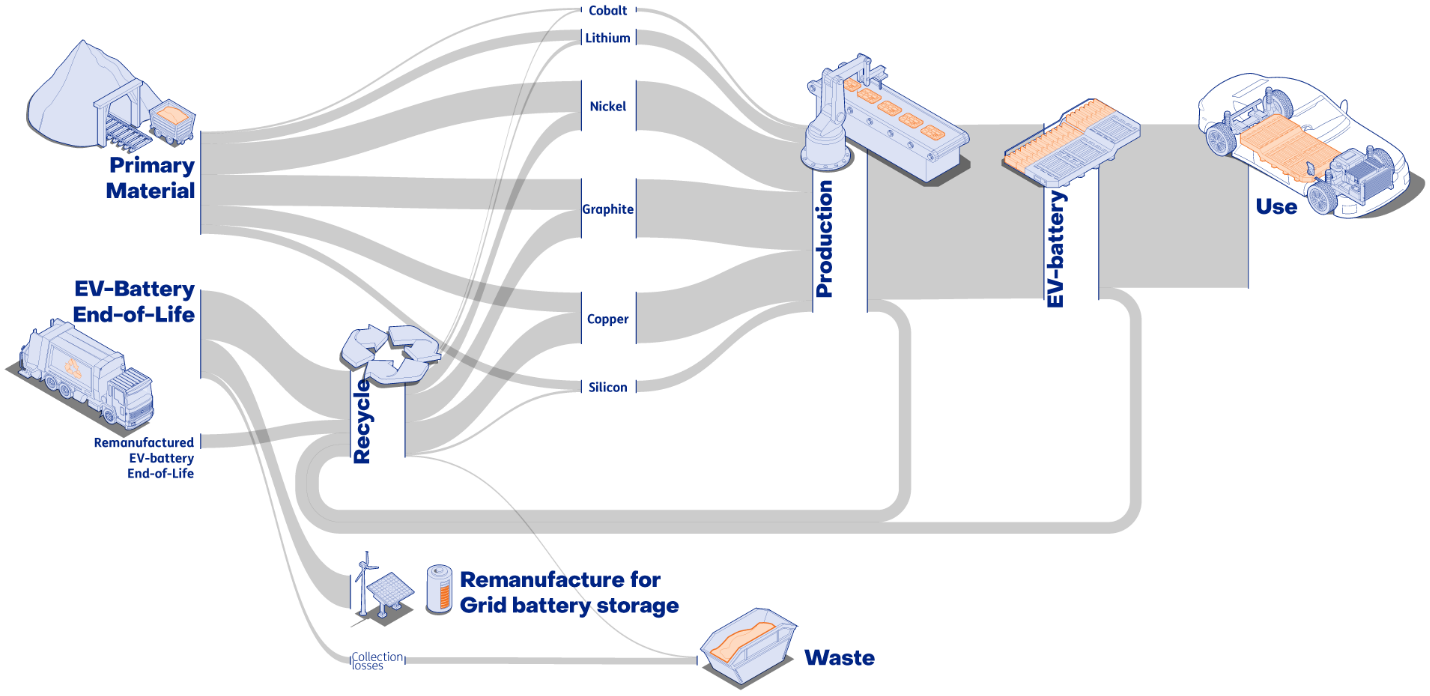
The introduction of a DPP allows for several circularity strategies to be carried out and thus changes the material flows of the CRMs. The information type documented is crucial for the implications of a DPP. The defined scenario assumes a passive DPP which documents the material content, battery properties and detachability. Consequently, the following implications are assumed:

1. Improved repairability increases the lifespan with 2 years[1]: The reluctance to repair EV-batteries due to safety requirements or unidentified defects can to some extent be overcome with a DPP. The information can simplify the problem identification and allow to better judge the safety of repair actions. It improves the repairability and, thus, the lifespan of the batteries.
2. Remanufacturing increase from 20 to 40%[2]: The DPP provides information on parts and their detachability. Therefore, a larger share of batteries can be given a second life for grid storage.
3. Collection rate improves from 80% to 93%[3]: The availability of information simplifies the identification and, therefore, the chance of correct sorting and collection of the waste stream. Consequently a larger amount of secondary materials becomes available, to substitute the primary materials.

All together, these effects reduce the overall CRM demand by 17%, a result of the increased lifespan. However, the alignment rate of secondary materials is negatively effected although the increased amount of batteries sorted correctly. Since a exploding market is assessed, the increased lifespan negatively effects the alignment rate, resulting in a 3%-point reduction. On the other side, there is a reduction of primary materials required, 12% overall. Specifically, the amount of primary cobalt demanded is reduced (23%), due to the increased collection rate

Material Flow Analysis

EV-battery | CRMs | Europe | 2040 | Introduction Digital Product Passport



Digital Product Passport | In-depth

Here we elaborate what the other consequences the implementation of a DPP in the EV-battery value chain might have.

Sustainability & Circularity

Widespread implementation of DPPs in the context of EV batteries can positively influence the product circularity across various dimensions, such as the collection, repair and remanufacturing rate, as elaborated upon in the preceding slide. By enhancing the collection rate of EV batteries, we can assure a larger share of materials into the recycling stream, mitigating the disposition of materials as generic waste. Consequently a larger amount of secondary materials becomes available, to substitute the primary materials. The lifespan increase, i.a. due to repair, contributes to a reduction in overall battery demand, thereby reducing the demand for materials allocated to EV batteries. Next to this consequences, there is a reduction of battery waste available in 2040. So, focusing on the implementation of the DPP will lead to improvements of sustainability and circularity on the long-run. The future-oriented benefits do not reduce the environmental impact and demand for materials in the present moment.

Increasing the lifespan of batteries reduces the total cost of ownership. In relation to the replacement of a battery, the costs for repair will likely to be relatively low. Furthermore, the driving range can remain to be similar. A consequence of the effects can be a larger demand for electric vehicles. Thus, a rebound effect of the DPP introduction could occur, which is not considered in the analysis.

Business processes

Optimally implementing and using a digital product passports can be quite challenging for an organization. Berger et al. (2023) identify four key barriers of adopting DPP:

1. Uncertainty of stakeholders, e.g. unclear what the role of the users will be.
2. Technological barriers, e.g. issues with the quality of the data or lacking IT infrastructure.
3. Reluctance to share information, e.g. no incentives to share data or privacy concerns.
4. Lack of clear legal requirements, e.g. there is sometimes a perceived lack of clarity in standards.

It is important to address such challenges. Part of the challenges can be tackled within an organization, such as adopting the needed technologies and IT infrastructure. However, some challenges would benefit greatly from policy interventions.

Policy

Clear policy is important to take away some of the barriers perceived by organization. For example, when a DPP for batteries is obliged an incentive is created to share information. Additionally, it can create clarity on the exact use of the DPP and enforce standards.

Such policies will become affective from 2026 onwards EV-batteries that are placed on the market need to have a DPP.

DPP policy is introduced for EV-batteries. These DPP should contain information like carbon footprint, bill of material, detachability and share of secondary material. Additional information can be added when a battery is being repaired. However, no additional in-use information is added.

So, although steps towards clear regulations are taken, there is still room for further developing and exploiting the use of a DPP.

Zero defect technologies | Scenario

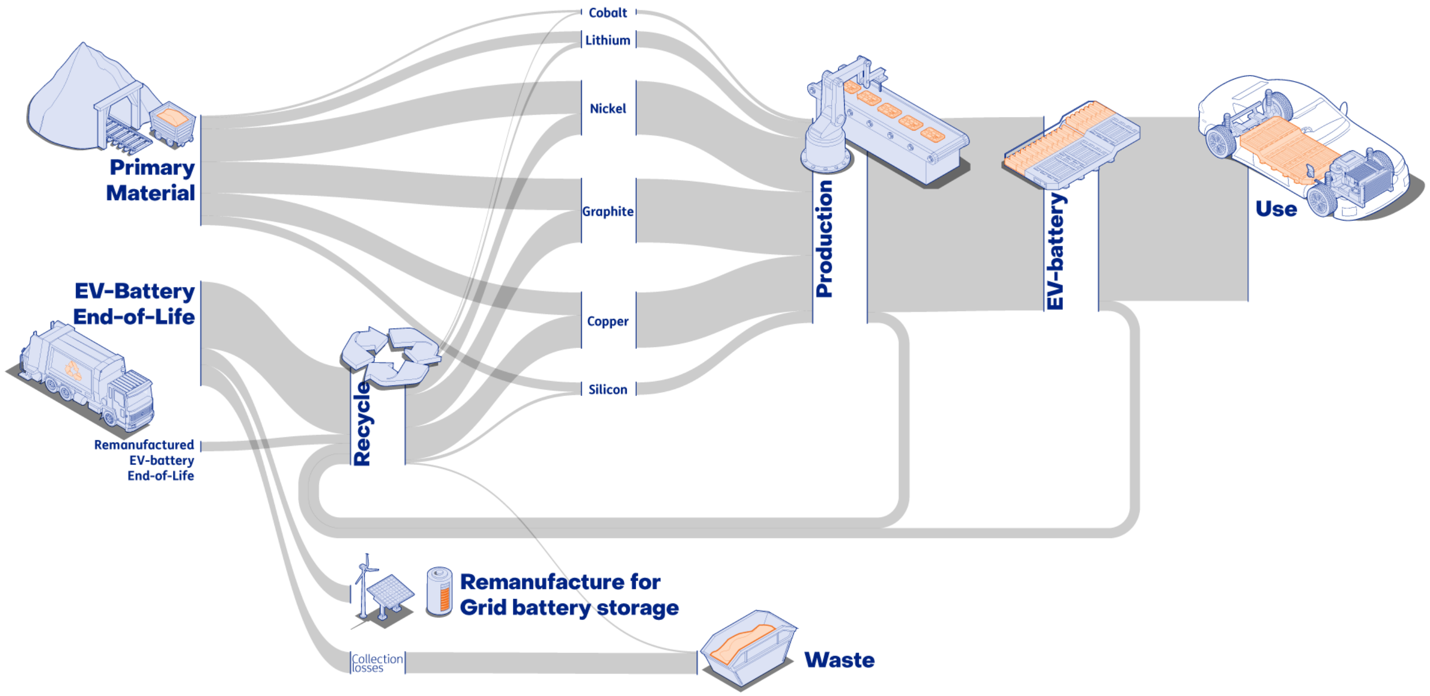
This scenario evaluates the effects of applying (additional) zero defect technologies in the production process. Material or product losses can be detected in time due to the application. The change in CRM flows are a result of the implications:

1. A reduction of product losses[1]: In time detection and intervention in the production chain reduces mistakes. For example, misalignment between production lines, assembly damage or mistakes in material measurements. However, most production lines for EV-batteries are assumed to be already advanced since the factories are recently build. Therefore, the reduction of production losses is assumed to be relatively low, from 6% to 5%.
2. A reduction of material losses[2]: Most material losses are not assumed to change in the situation since the losses are already minimal. Only cobalt has a relative large amount of losses, which are assumed to reduce by 5%-point, to 19%.
3. Improved product quality: The application of zero defect technologies could improve the battery quality, e.g. better inspections result into retrieving mistakes earlier. However, the effects on e.g. lifespan are assumed to be minimal.

Reducing the losses during the production by apply the zero defect technologies results in a limited change in the material flows. The production of EV-batteries are assumed to have relative low production losses. Therefore, the changes due to technology application are relatively small. Only copper has a relative high amount of losses, which are inherent to the production process. Consequently, the reduction of losses only highly effects the copper demand, reducing the primary material demand by 14%.

Material Flow Analysis

EV-battery | CRMs | Europe | 2040 | Zero Defect



Zero defect technologies | In-depth

Here we elaborate what other consequences the implementation of zero defect technologies in the EV batteries production line might have.

Sustainability & Circularity

Optimization of the production process will lead to small implication in the environmental impacts and changes in the material flows. The main incentive for the application of zero defect technologies is that changes will lead to short term benefits. Due to the small reduction of losses, the chances of rebound effects are relatively low for this particular application.

Business processes

Implementing zero defect technologies poses some challenges. Psarommatis et al. (2020) and Wan & Leirmo (2023) describe some main challenges:

1. Financial, e.g. high costs for implementation
2. Organizational, e.g. resistance to change in the organization
3. Technological barriers, e.g. lack of access to key technologies.
4. People and competences, e.g. lack of resources and experiences.

Zero defect technologies could be quite expensive and are therefore not accessible for every company. In addition, through reducing material losses and improving the batteries' quality, they might lead to significant (financial) benefits for companies that have implemented these technologies. This implies that they is a risk of **market inequalities**, as certain companies could have a significant competitive advantage.

In addition, it could be the case that operational processes for producing EV batteries (rapidly) become more complicated because of implementing zero defect technologies, potentially leading to a **skills gap**.

Operator support | Scenario

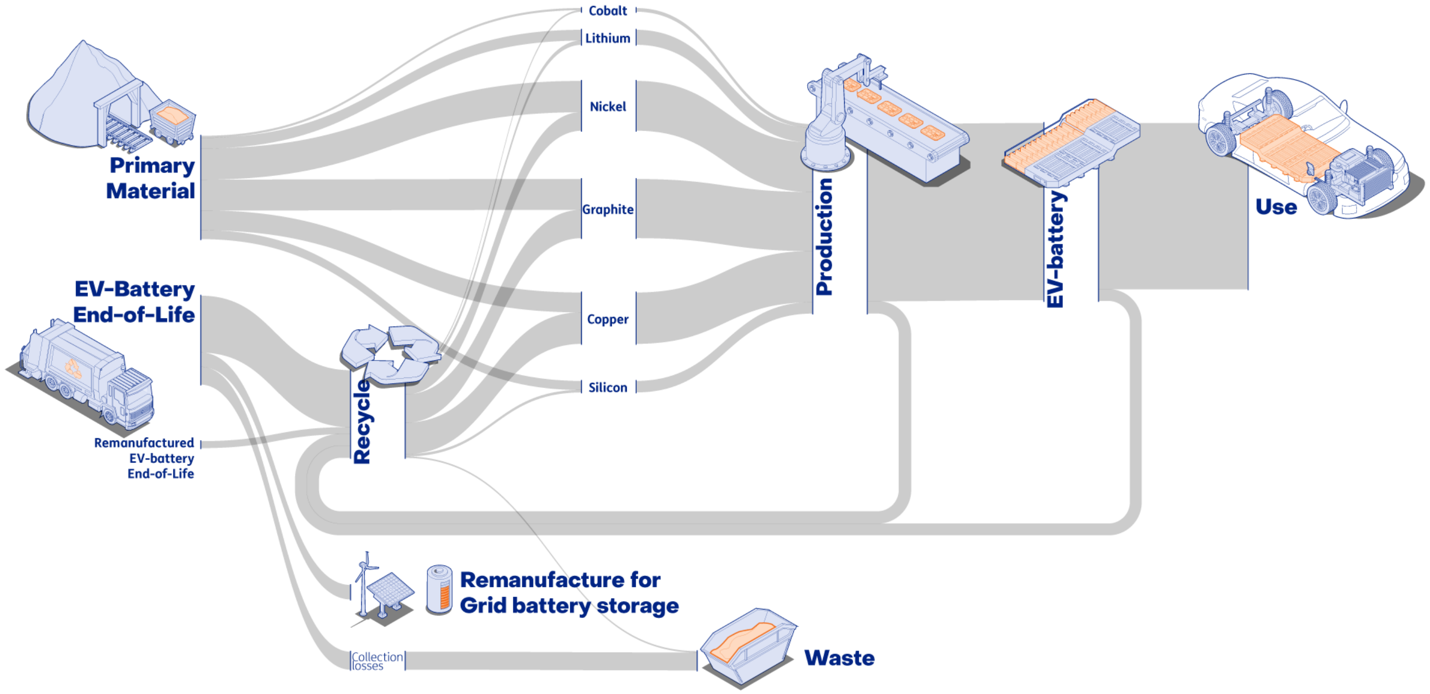
This scenario evaluates the application of the operator support concept using virtual, augmented or mixed reality technologies for repair and refurbish actions. The concept of operator support could have other applications as well. However, in this scenario the application is limited to repair since it is assumed that these effects are most significant. Introducing operator support to the value chain of batteries results in the following implications:

1. Increased lifespan due to increase of repair[1]: The operator support allows better problem identification, reduces safety risks and, thus, makes repair more likely. Consequently, it is assumed that the average lifespan increases by 2 years.

The consequence of the growing market for EV-batteries is that if you'll increase the lifespan of products, less materials will be available in the near future. Introducing operate support increases the lifespan, but reduces the share of secondary materials(3%-point), just as the amount of remanufactured batteries (22%). The overall demand for CRMs will be reduced with 17% and the amount of primary materials with 12%.

Material Flow Analysis

EV-battery | CRMs | Europe | 2040 | Operator Support



Operator support | In-depth

Here we elaborate what other consequences the implementation of operator support for repair of the EV batteries might have.

Sustainability & Circularity

Operator support positively impact the environmental performance and circularity of EV-batteries Increasing the repairability by operator support could lengthen the lifespan of EV-batteries, while making repairing more efficient and less resource-intensive. Operator support can already be applied at this moment, but is dependent on the information availability for successful implementation. Another limiting factor to allows cost-effective introduction of the technology is the quantity of EV-batteries in the stadium. It should be considered that improved repairability will lead to a reduction of the total cost of ownership, which allows rebound effect to occur.

Business processes

Adopting advanced operator support systems such as Augmented Reality can be challenging. Masooda & Egger (2020) identify the following challenges:

1. Technological, e.g. be able to integrate AR solutions with the current information technology system.
2. People and competences, e.g. users acceptance in terms of privacy and ergonomics of the application.
3. Organizational, e.g. lack of compatibility in the organization, for example, not in line with current safety measures or no common standards for IT-system integration
4. Challenging upscale, e.g. creating content relies on experts and is not intuitive or scale –up is difficult to the costs of content creation.

In order to have an actual effect on the lifespan of batteries, operator support either has to be accessible and beneficial to repairers (such as car dealers), or implemented in the business model of battery producers (shift to servitization/PaaS) – either because it is beneficial or because it is mandatory due to regulations. For this first point, an interaction between a car dealer (benefiting from repair work) and car manufacturers (having to deliver a product that can actually be repaired) is necessary.

Especially for batteries under warranty it could be economically feasible to repair batteries.

Policy

Obligations from the government could boost the repair rates of EV batteries through specific policies, like Right to Repair). It enforces producers to design for repair and provide the possibilities to repair the products. The technological implementation, such as operator support, could reduce the required efforts to successfully obey the law on a wider scale.

Labor market

As a secondary consequence, operator support can be a solution for scarcity on the labor market, enhancing skills for staff or providing opportunities for people with a distant from the labor market.

In addition, operator support could reduce the amount of accidents/complications for repairers, leading to **safer repairs** overall.

Remanufacturing system | Scenario

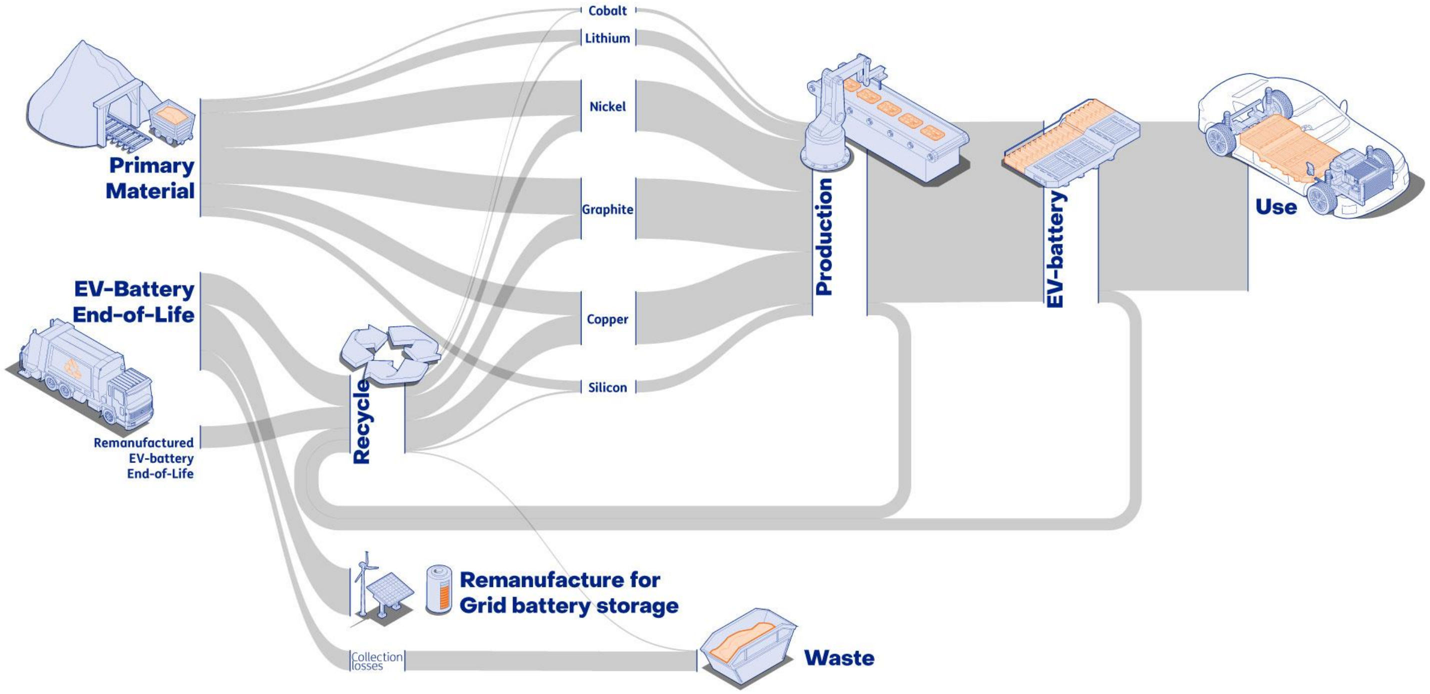
The variety of EV-batteries at the end-of-life in type, quality, design and amount limits efficient remanufacturing for reuse as grid battery. This scenario looks at a **flexible manufacturing system** that allows easily dealing with the changing demand for remanufacturing. The following implications are defined:

1. The share of remanufacturing batteries is assumed to be 60% instead of 20%[1]: The EV-batteries at the end-of-life vary widely in type, quality, design and amount. This poses barriers for remanufacturing or reuse as grid battery. A flexible manufacturing system that can easily deal with different designs, quality, type and amount of EV-batteries, allows to lower the barrier.
2. Lifespan of the second life application increases from 5 to 6 years[2]: Remanufacturing systems can help to optimally align the batteries and thus the quality of grid batteries increase, resulting in an extended lifespan.

A remanufacturing system leads to a increase EV batteries reuse for grid battery storage. Consequently, the amount of remanufactured batteries is assumed to triple compared to the BaU. The batteries available for recycling reduces and, therefore, the demand for secondary materials will increase with 18%. The longer lifespan of remanufactured batteries reduces the amount of remanufactured EV batteries available at the end of life. The positive effect, reduced demand for new grid energy storage, is outside the scope of the assessment

Material Flow Analysis

EV-battery | CRMs | Europe | 2040 | Introduction Remanufacturing System



Remanufacturing system | In-depth

Here we elaborate what other consequences the implementation of a remanufacturing system in the EV batteries production line might have.

Sustainability & Circularity

Investment in a remanufacturing system will lead to avoidance of environmental impact and material outside of the EV-battery system. Less new products to store grid energy, such as batteries, need to be produced. The avoided materials are not one-on-one due to the reduced battery capacity. Still, the avoided battery use can have a large contribution to reduce the overall demand for new materials.

Business processes

Enhancing flexible manufacturing can run into the following barriers identified by Sundarani & Qureshi (2017):

1. Financial barriers, e.g. high costs for obtaining and usage of flexible manufacturing systems.
2. Organizational, e.g. resistance to change within an organization.
3. Technical, e.g. the integration of different components.
4. Operational, e.g. difficult to handle problems.

Policy

Most circular economy or waste related policy don’t explicitly focus on other strategies then repairability (right to repair) or recyclability. Key performance indicators for policy-makers are mostly focused on recycling, e.g. by recycling efficiency. Also, in the new battery and battery waste regulation, remanufacturing is not subject for any of the defined measures.

Therefore, remanufacturing is up-to-now a consideration of just the economic interests. By enforcing waste collecting companies, e.g. ARN, to first consider the possibility of remanufacturing, this r-strategies can be stimulated.

Modular design | Scenario

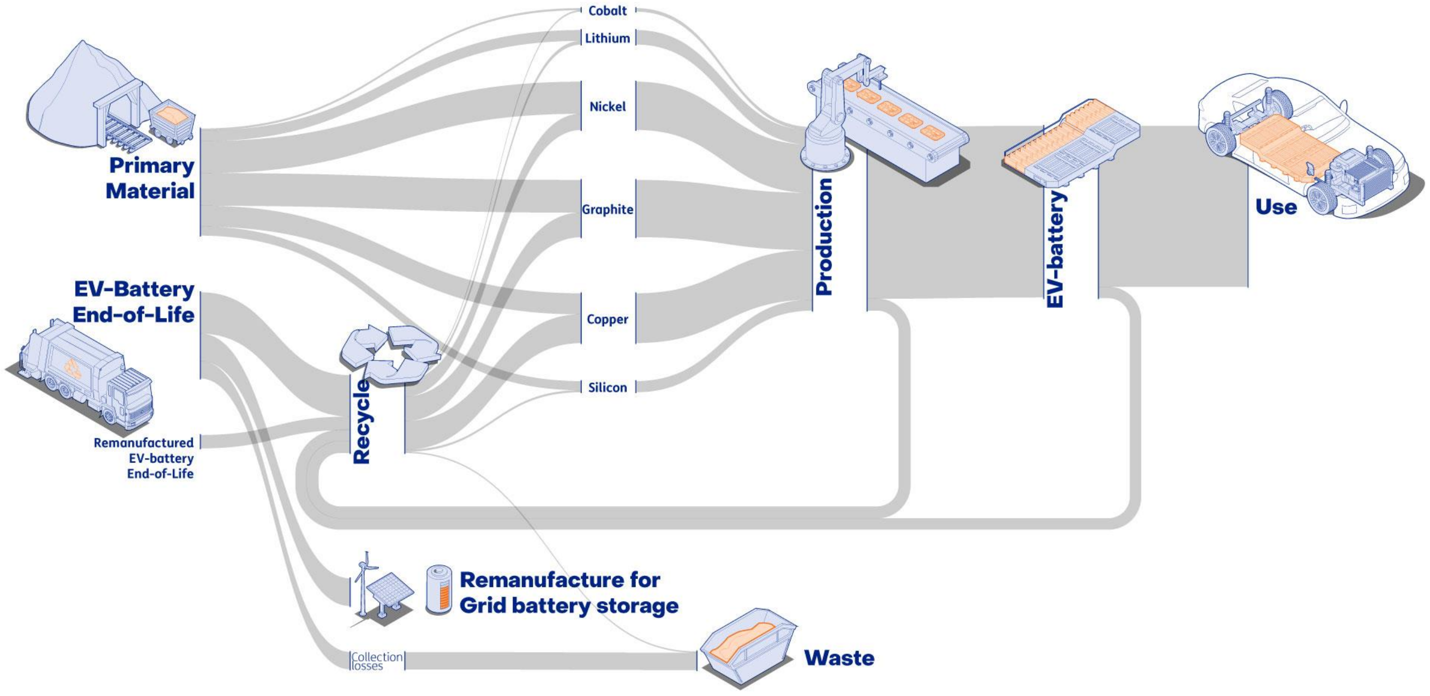
At this moment, EV-batteries are not primarily designed to be detachable and components to be easily replaceable. Allowing a modular design architecture could improve this, which requires alignment and coordination within the production. This scenario evaluates the implications of a modular EV-battery which is enabled by a digital twin implementation, resulting in the following implications:

1. Repairability increases[1]: since a modular designed product, can be easier disassembled in a safer way and component replacement is more straight-forward. As a consequence, similar to the scenario of DPP and operator support, the simplification of repair operations is assumed to increase the average lifespan by 2 years.
2. Remanufacturing increases from 20% to 40%[2]: the EV-battery for grid storage is assumed to increase since the individual battery cells can more easily be disassembled. Therefore , the share of batteries for reuse could increase.

A modular design architecture for EV-batteries could result into a reduction of primary materials with 6%, a result of the increased lifespan. To larger share of remanufactured batteries reduces the amount of secondary materials available for new EV-batteries. Consequently, the overall share of secondary content for CRMs is 42% instead of 48% in the BaU-scenario

Material Flow Analysis

EV–battery | CRMs | Europe | 2040 | Introduction modular design enabled by a digital twin



Modular design | In-depth

Here we elaborate what other consequences the implementation of a modular EV-battery design, enabled by a digital twin in the EV batteries production line, might have.

Sustainability & Circularity

Improving the repairability and remanufacturability because of the EV-batteries modularity will lead to a reduction of primary materials required. The effectiveness of the circularity strategy is substantial and could as well reduce the total cost of ownership. Therefore, it should be considered that rebound effect could occur.

Business processes

In the paper of Neto et al. (2020) some main barriers for organizations to implement a digital twin are highlighted:

1. System and technologies, e.g. IT infrastructure
2. Operational, e,g. standardization and clear implementation pathways.
3. People and competences, e.g. missing qualifications
4. Organizational, e.g. change-averse culture or difficulty to measure the potential benefits. Additionally, the fragmentation within an organization that makes it difficult to create a data flow.

However there are also drivers such as safety increasing for employees, pressure from competition or desire to acquire knowledge about the process.

Policy

Obligations from the government could boost the repairability of EV batteries through specific policies (think Right to Repair). Setting requirements for modular design, like ecodesign guidelines, could as well be a possibility, which could lead to companies having to connect better and invest in concepts of connected factories.

Combination technologies | Scenario

The introduction of SI-technologies are not isolated and impact each others effectiveness as well. In this scenario we have a look at the overall implication when all of the SI-interventions are applied. Combining them does not automatically mean that all changes can be added.

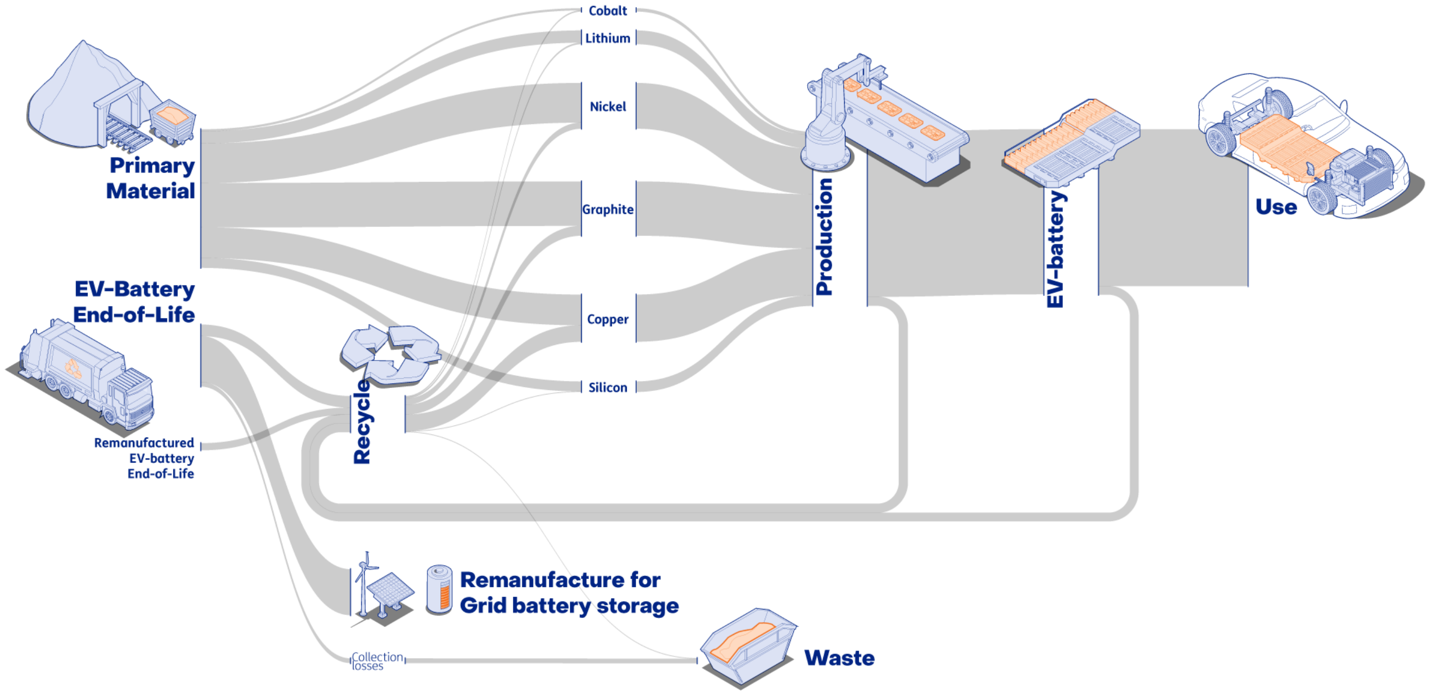
On top of the previously presented implications, the following main aspects impact the material flows:

1. The collection rate is assumed to change from 80% to 93%: due to the introduction of the DBP.
2. The collective lifespan increase is assumed to be 4 years: The increase can be attributed to the improved repairability by operator support, the DBP and modular design and the improved quality due to the zero defect technologies.
3. The technologies improve the remanufacturing rate of EV-batteries for grid storage: A large share of reusing batteries for this application avoids the production of separate grid storage batteries. The lifespan of reusing batteries is assumed to increase by a year due to the better quality of batteries by applying remanufacturing train. And the share of reused is assumed to be optimal, namely 80%[1].

The scenario, applying the different SI-technologies at once, shows a significant change in material flows compared to the BaU-scenario. The result is a 19% reduction in the overall demand for primary materials for 2040. Due to the increased remanufacturing rate, the amount of available secondary material significantly reduces. Consequently, the overall average share of secondary CRMs will be 20%, according to the assessment.

Material Flow Analysis

EV-battery | CRMs | Europe | 2040 | Combined scenario



EV-Battery scenario evaluation Combination technologies

Here we elaborate what other consequences the implementation of the technologies combined might have.

Sustainability & Circularity

Improving the alignment rate of secondary materials with the overall demand (share of secondary materials) does not necessarily stimulate other r-strategies, which keep the value of EV-batteries on a higher value, such as lifespan increase and reuse. Below the share of secondary materials for the combination scenario is compared to the BaU scenario, which shows that is significantly reduces. Furthermore, the focus on other r-strategies makes that the enforced share of secondary material for 2036 by the EU cannot be met for all materials. Therefore, the focus of the indicators it too limited. Especially when considering that the reduction in overall demand of primary materials is significant, a result of the lifespan increase.

Material	Enforced share of secondary material by 2036 (Battery & battery waste directive)	BaU scenario	Combination scenario
Cobalt	26%	42%	37%
Lead	85%	X	X
Lithium	12%	31%	11%
Nickel	15%	40%	13%

Also the remanufacturing possibilities due to the technological interventions significantly changes. The share of batteries reused for grid storage is assumed to significantly improve due to the efficiency of remanufacturing, which is a combination of available information and the technologies.

Business processes

Combining technologies can on the one hand make it more difficult to implement, since even more skills, capabilities and higher investments costs are required. On the other hand, the technologies can enhance each other and may reduce technical barriers for implementation and create a lot of value, which can be easier captured through the combination of technologies.

Policy

The state-of-the-art policies for EV-batteries show a significant focus on the recyclability and providing information to enable other circular strategies. The research shows that by extending the scope to drive multiple and higher R-strategies, the circularity performance can better be enhanced.

4. Conclusion

This report exists of two parts. In part one, we identified the interaction between circular economy strategies and several SI-technologies (based on the SI PMCs of TNO). In part two, we translated some of those technologies into scenarios and applied them to a use case of EV-batteries.

Some key insights for part one are as follows:

1) SI technologies can enable various circular strategies and some are even necessary for fully circular value chains in the manufacturing industry.
2) For an SI-technology to support several circular strategies, there are different drivers, challenges and target groups. Some examples of drivers are increased flexibility, safety, quality. Challenges can, for instance, be willingness of supply chain partners to collaborate, complex business models required for circular concepts or the high costs of implementing certain technologies.

For part two, some key insights are as follows.

Sustainability & Circularity

Smart technologies are an important mean to operate more circular. However, the implementation of SI technologies does not *guarantee* more circular supply chains. A circular strategy proves effective only when all other aspects are well-managed. For instance, resource optimization requires alignment of various supply chain partners to thrive. However, it's crucial to acknowledge that rebound effects may arise as well. Examples of unforeseen/rebound effects are as follows:

1. Sustainable/circular benefits are not evenly distributed over the supply chain, e.g. repair activities might lead to higher upstream emissions, however longer use can result in a lower overall reduction of emissions. Modeling/calculating impact (both material and energy) of the implementation of SI technologies for circular supply chains is therefore essential.
2. Efforts to increase efficiencies in supply chains might, paradoxally, result in more production, increasing consumption levels and offsetting the anticipated reduction in emissions.

It's important to find a balanced approach that considers all these factors for a truly effective sustainable strategy.

Business processes

So, far we mainly discussed the barriers for implementing certain technologies. We've identified recurring themes such as technological, financial, organizational, people and competencies, and operational challenges. Naturally, certain barriers are more closely tied to particular technologies, as seen in the reluctance to share information within the DPP scenario. Nevertheless, there are compelling (non-circularity related) motivations driving the implementation of these technologies. The primary drivers include the desire to remain competitive, achieve greater efficiency, enhance product quality, and foster a safer working environment. In that sense, circularity can be seen as an ‘extra win’.

Moreover, the adoption of these technologies, along with corresponding circular strategies, opens up opportunities to generate additional value in the form of services. Therefore, service-oriented business models play a pivotal role in capturing the added value these technologies bring. An example of such a service is offering repair and maintenance to customers. Alternatively, retaining ownership of a product becomes more attractive, facilitating easier regeneration after users decide to dispose of products, strengthened by possibilities to monitor a product during the use phase. This ownership retention allows for efficient remanufacturing, enabling the capture of value once again.

As we have shown in the CESI CVC KIP report 2023, proper implementation of such circular strategies has to be supported by suitable circular business models. Companies often face challenges in determining the most suitable circular strategy. This research therefore evolves around effective implementation of different circular business models in the manufacturing industry.

Policy

Lastly, we anticipate significant developments in circular economy policies for the manufacturing industry (such as CSRD, battery and battery waste regulations, CRM-act). It is crucial to thoroughly understand SI technologies are best implemented in order for companies to meet these requirements.

Follow up research: further roadmap development

The next step for CESI evolves around further exploring the **strategic roadmap**, i.e., back-casting to assess which steps (business investments, technology development, policy development, or otherwise) can or should be taken on the short and medium term to build a resilient circular economy in the Netherlands.

More concretely, we aim to enable companies in taking their investment decisions for future SI technologies, production techniques or business model innovations in order to build the most valuable and purpose-driven sustainable and circular product proposition. Future policies that are required for the implementation of these technologies or business model innovations are also included in the roadmap. Lastly, since the benefits for many circularity strategies will be harvested over a longer timespan, we will also evaluate the implications of sustainability/circularity performance indicators which create incentives via directives and legislation (such as CSRD, battery and battery waste regulations, CRM-act) for various circularity strategies.

Through a **use case** of a specific company/product/ value chain, we will develop an approach to create circular value chains enabled by a (few) SI innovation(s). We will develop this approach as follows. First, we evaluate the current value chain within this case study, e.g. by a material flow analysis (see figure), to determine what materials enter the system, are already reused or are disposed. Second, together with SI-innovation experts we will evaluate the extent to which the SI-innovations can enable a more circular value chain. For this, we will assess barriers, opportunities, risks and dependencies, and look into which business model innovations. Third, through combining SI and business model innovations, we will determine the most sustainable and circular system, while also highlighting any shortcomings and suggestions on how to overcome these.

The application to a concrete case allows us to develop a structural approach on how to incorporate SI innovations (and corresponding circular business models) in value chain designs. Furthermore, it allows us to review the incentives (e.g. created by legislations/directives such as CBAM and CSRD) to implement different circular strategies. Additionally, it provide us with insights in the SI-technologies which are inherent to be implemented to allow a circular value chain, inciting an SI research agenda for circular value chains.

To facilitate this, we will use our innovation overview and corresponding scenarios from this research. The method will outline a conditionality (and perhaps a sequence) of innovations for SI technologies in the manufacturing industry. This will enable us to devise a structured approach to overcome barriers in implementing SI technologies for various circular strategies.

Appendix A | EV-Battery MFA Model

By a MFA the implications of different SI-technology applications are evaluated. A parametrized MFA model is used, for which the Business as Usual (BaU) scenario is the starting point. Below the modelling assumptions for the BaU scenario are defined, afterwards the approach to evaluate the alternative scenarios is described.

The BaU-scenario

The BaU-scenario of the battery material flows in 2040 is constituted primarily by information from the executed literature research. Additionally, EcoIvent databases are analyzed to complement the information requirements. Only the relevant CRMs are considered in the MFA.

Geography

The material flows of EV-batteries within the Europe are analyzed. It implies that the assumptions are made accordingly. Assumptions about the EV-batteries at the end of life and demand for materials have a global coverage. Therefore, it is assumed that Europe has a share of 23%[6,7], which remains almost constant over time.

Lifespan

The literature study showed that there is a wide range in assumption related to the lifespan of EV-batteries, ranging from 6 till 18 years. Most literature refer to a lifespan between 8 till 12 years and, therefore, a average of 10[3] years is assumed to be the lifespan.

The wide variability in lifespan assumptions is as well applicable for the second application of batteries, reusing them for electricity grid storage. For the BuA scenario it is assumed that they can be reused for 5 years[4, 5].

Available EV-battery waste

The amount of materials that are at the end-of-life in 2040, are assumed to be the amount of materials that flow in the system at the start of the lifespan. Which means that if the lifespan of the battery is 10 years, inflow data from 2030 is considered. The amount of material inflow is retrieved from the critical mineral data set by the IEA1, material inflow for electric vehicles according to the Announced Pledges Scenario (APS) is used. Only data from 2022, 2025, 2030 and 2040 is available, data about the material demand in between those years are assumed to have a linear relation.

A share of batteries will be reused in the electricity grid for some years, which will be available as EV-battery waste after the reuse period. Therefore, the share of reused batteries is assumed by the additional lifespan as a second source of inflow materials for the system. So, the share of batteries that are reused are distracted from the EV-battery waste. Additionally, there is input flow of EV-battery reused. Which means that if the additional battery lifespan due to reuse is 5 years, the percentage of reuse for inflow from 2025 is taken.

Reuse

EV-batteries loose capacity, which is the main reasons thy are being abandoned. For electricity grid energy storage the capacity reduction is not directly a problem and, therefore, batteries are reused for the application. Reusing EV batteries allows to extend the lifespan. The share of reused battery is modelled from the EV-battery waste and assumed to be 20%[2].

Collection

Due to incorrect sorting, lack of knowledge about the battery, etc., EV-batteries are incorrectly treated at the end of life and not recycled The materials from the collection losses are not recovered. Data about the collection losses in the EU for EV-batteries is not monitored. Similar studies estimate the collection rate for a BaU of 2040 to be 20%[8], our MFA is modelled accordingly.

Recycling

The type battery recycling has high implications on the recovery rate of the critical raw materials. According to literature the most efficient type of recycling is the hydrometallurgical recycling process. It is assumed to be the most dominant recycling process for 2040[8] and, therefore, the recovery efficiencies are accordingly modelled.

Material	Recovery efficiency	Source
Cobalt	94%	8
Lithium	95%	8
Nickel	99%	8
Graphite	98%	9
Silicon	96%	10
Copper	99%	11

Appendix A | EV-Battery MFA Model

Material demand

The material demand for EV-batteries is modeled according to the IEA APS scenario[1]. The amount specified by the IEA is assumed to be the final amount of materials in batteries. Therefore, production losses are excluded from the demanded materials. The primary material inflow is the result of the material demand minus the secondary material available from EV-battery waste.

Production losses

The production losses occur on two levels, (1) materials/scrap lost during the production and (2) battery (components) lost during assembly due to mistakes or quality issues. These materials are all assumed to be recycled. The production losses are presented below.

	Production losses	Source
Cobalt	0,01%	Ecoinvent, almost 100% efficiency
Lithium	0,01%	Ecoinvent, almost 100% efficiency
Nickel	0,01%	Ecoinvent, almost 100% efficiency
Graphite	0,01%	Ecoinvent, almost 100% efficiency
Silicon	0,01%	Ecoinvent, almost 100% efficiency
Copper	24%	2
Complete battery	6%	Ecoinvent, according to NMC 811 battery

Constituting scenarios

The MFA for the different scenarios is created using a parametric model. The following variable are included:

- Reuse rate
- Collection rate
- Production losses
- Lifespan EV-battery
- Lifespan reuse EV-battery for grid storage

The material flow consequences of changing variables are modelled accordingly. For most variables this means just another destination of the materials. For example a improved collection rate make that more discarded batteries are being recycled. Consequently, the demand for primary materials reduce.

The consequences for the lifespan variables make that the amount of discarded batteries and the battery demand change. The amount of discarded batteries for 2040 is determined by the shift of the reference year for the inflow of materials. So, if the lifespan is 12 years instead of 10 (BaU), the amount of discarded batteries are retrieved from 2028 instead of 2030.

The second implication of the longer lifespan is the reduced demand for new batteries since no replacement is required. It is assumed that the additional created capacity is benefitted on for according to its lifespan. So, if the lifespan is 11 years instead of 10, the additional capacity of 2030 is distracted from the demand. A increase of more then one years follows the same line of thinking since the years before, the demand is already reduced. Since that is the case, the reference capacity is multiplied with the amount of times the battery capacity from that year is avoided. For example, 5 years lifespan increase avoids the capacity from 2025 five times. The effect of additional batteries for the grid storage is not considered.

The change in variables are defined for each of the scenarios and presented for each of the results. A literature study is executed to determine the effects of the different interventions. However, since most interventions are not yet in place, the quantification of effects are estimations. For most scenarios not literature information was available. Therefore, assumptions were made based on the developed knowledge with regard to the SI-technologies. The assumptions are evaluated with the SI-technology experts and battery experts.