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MSC INDUSTRIAL ECOLOGY

TOWARDS A FRAMEWORK FOR NAVIGATING CE METHODS IN THE TRANSITION TO A CIRCULAR ECONOMY IN ELECTRONICS

A case study on circular economy methods and lifecycle thinking

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Keywords
Circular economy, circular economy tools, circular economy strategies, circular economy methods, lifecycle management, circular lifecycle management

Abstract

In the face of increasing environmental challenges such as resource scarcity, biodiversity loss and water, air and soil pollution, the current consumption rate of resources is testing the earth's physical limits (Bansal and Song, 2017; Geissdoerfer et al., 2017; Esposito, Tse and Soufani, 2018). Of all products, electrical and electronic devices are especially challenging for sustainability considering their demand, resource usage and the challenges in waste management. In the EU 12.4 million tons of EEE is put on the market, of which 4.7 million tons of WEEE is collected. This is about 10.5 kg of collected e-waste per person, per year in the EU alone (Eurostat, 2020). Especially for small electronics the substitution rate is high and products are replaced before reaching their functional lifetime because of the introduction of newer, better performing models.

To address these challenges the concept of the circular economy emerged as an alternative to turn this single-use lifestyle into one in which resources are circulated (Geissdoerfer et al., 2017). Electronics also provide an especially interesting product group regarding the circular economy, not only for the challenges listed above but the development phase for electronics is also highly time-consuming when circularity is a requirement. Considering this industry, the transition to the circular economy requires the implementation of circular strategies in the day-to-day business as well as along the product lifecycle. Clear guidance on how to achieve this is however not always easy to find in academic literature. Every circular economy expert has a different area of expertise, creating a scattered range of guidelines, frameworks, indicators and approaches for designing, measuring and implementing circular economy principles in business. Business in practice therefore requires a navigation aid to select and properly implement circular economy methods for a particular business. This thesis therefore answers the research question *"How can appropriate circular economy methods be selected by OEMs to support the transition towards a circular economy in electronics?"*

This thesis studies six companies within the electronics industry on their use of CE methods to eventually develop a navigational aid for original equipment manufacturers in the electronics industry. The case comparison led to four distinctive groups on how companies select and apply CE methods as well as a set of generic insights. Together these were applied in the development of the Circular Economy Method Compass. The CE Method Compass is a holistic approach to navigating circular economy methods that offers original equipment manufacturers (OEMs) in the electronics industry guidance in the transition to the circular economy and the development process of circular products and services. The CE Method Compass summarizes a comprehensive overview of available circular economy methods over five categories of CE methods: differentiation, collaboration, physical architecture, consumer engagement, and evaluation and assessment methods. The categories hereby cover the development process from the initiation of a circular vision to the final assessment of a product or service. The five categories combined have the opportunity to enable the R-strategies, creating circularity. The CE Method Compass can furthermore be used by both companies that wish to enhance their circular economy strategy as by companies new to the circular economy. The CE Method Compass hereby supports the use of CE methods by OEMs in the electronics industry and has the ability to increase the circularity of the sector.

This is valuable because achieving circularity in electronics is a challenging assignment. The CE Method Compass hereby provides an overview of where and how circular value can be achieved. Overall, the CE Method Compass facilitates navigation and broad application of CE methods. The compass is however only a first iteration of such a navigational aid and future research is needed to develop it further.

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Glossary

The following terms and their definitions are used as such in the thesis. These terms are defined in the glossary to avoid confusion and ensure consistency within the research.

Circular economy
An economic system that replaces the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes. It operates at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, thus simultaneously creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations. It is enabled by novel business models and responsible consumers (Kirchherr et al., 2017).

CE methods
CE methods are the overarching term for the set of qualitative and quantitative (environmental) tools, toolkits, techniques, approaches, indicators, guidelines and frameworks that are strategically used to guide and/or assess particular activities and/or goals with the aim of making informed decisions in a circular economy.

CE principles
The principles of the circular economy are to eliminate waste and pollution, circulate products and materials (at their highest value) and it has a regenerative nature (Ellen MacArthur Foundation, n.d.)

CE strategies
CE strategies are considered to be recovery strategies such as the 9R-strategies by van Buren et al. (2017) and all closely related strategies such as maintenance, standardisation and part harvesting.

List of abbreviations

CE = Circular Economy

EEE = electrical and electronic equipment

WEEE = waste of electrical and electronic equipment

LCA = Lifecycle analysis

LCC = lifecycle costing

MFA = Material flow analysis

EEIOA = Economic environmental input output analysis

CBA = Cost-benefit analysis

C2C = Cradle-to-cradle

LCT = Lifecycle thinking

CBM = circular business model

EPR = extended producer responsibility

EOL = End-of-life

BMC = Business Model Canvas

PSS = Product service system

OEM = Original equipment manufacturer

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1. Introduction

"Waste is a design flaw"

- Kate Krebs

In the face of increasing environmental challenges such as resource scarcity, biodiversity loss and water, air and soil pollution, the current consumption rate of resources is testing the earth's physical limits (Bansal and Song, 2017; Geissdoerfer et al., 2017; Esposito, Tse and Soufani, 2018). This linear pattern of consumption, which still characterizes much of our current global economy, emerged during the industrial revolution. With increasing demand resources are extracted for the production of mass goods that are shipped worldwide by the press of a button, consumed and discarded. Of all products, electrical and electronic devices are especially challenging for sustainability considering their demand, resource usage and the challenges in waste management. In the EU 12.4 million tons of EEE is put on the market, of which 4.7 million tons of WEEE is collected. This is about 10.5 kg of collected e-waste per person, per year in the EU alone (Eurostat, 2020). Especially for small electronics the substitution rate is high, products are replaced before reaching their functional lifetime because of the introduction of newer, better performing models.

To address these challenges the concept of the circular economy emerged as an alternative to turn this single-use lifestyle into one in which resources are circulated (Geissdoerfer et al., 2017). Especially the industry needs to move away from the manner in which we treat the earth, from resource extraction to end-of-life. In academic literature on the circular economy, it is therefore already stressed that in order to decrease the impact of the current linear economy of production and use business needs to make this transition (Bansal and Song, 2017; Geissdoerfer et al., 2017; Esposito, Tse and Soufani, 2018; Planning, 2018).

The essence of the circular economy lies in the creation of an economic system that replaces the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes on the micro, meso and macro level. Hereby simultaneously creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations (Kirchherr et al., 2017). Considering the electronics industry, the transition to the circular economy requires the implementation of circular strategies in the day-to-day business as well as along the product lifecycle. Clear guidance on how to achieve this is however not always easy to find in academic literature. Every circular economy expert has a different area of expertise, creating a scattered range of guidelines, frameworks, indicators and approaches for designing, measuring and implementing circular economy principles in business. For example, to only define the circular economy as a concept, 114 definitions are already available[1] (Kirchherr et al., 2017). Business in practice therefore requires a navigation aid to select and properly implement circular economy methods for a particular business.

[1] The definition by Kirchherr et al. (2017) is used further in this thesis (see glossary)

1.2. Core concepts and research objective

Within circular economy (CE) literature there is a wide number of methods available to help guide the transition to a circular economy in business and support CE strategies. Such as, business models, for which the (qualitative) sustainable business model canvas tool can be used, as well as guidelines, taxonomies, and other quantitative and qualitative methods. There also already is a rich body of literature proposing methods based on case studies from business practice and meant for implementation in business practice. As well as literature on barriers to implementation of circular economy strategies. Such as the studies by Rizos et al. (2016) in business literature as well as the study by Perotto et al. (2008) in industrial ecology literature. A business perspective in academic literature is therefore not lacking. But firms are responsible for collecting and making sense of this information, asking for a navigation aid (Govindan and Hasanagic, 2018). This creates a risk of firms only implementing partial solutions in the shift towards a circular economy. Hereby risking internalization of a firm's strengths and optimization of individual parts of a product instead of the product lifecycle as a whole. Creating potential for the shifting of environmental burdens and causing products to be stamped as "circular" but in reality, only elements are. There is thus a lack of a comprehensive overview of applicable methods and a map to cover the relevant aspects, per particular field of business.

This thesis therefore looks further into what CE methods are available and how and what methods firms should select and implement through offering a navigation aid. This holistic approach towards CE methods is of value for the transition towards a circular economy in current business practices and for firms that wish to go circular. Contributing to current and future research by developing a general approach that eases and facilitates the shift towards a circular economy. This research is therefore relevant in the application of academic knowledge for the viewpoint of business practice as an end-user in the process of actual and timely implementation of circular economy methods in a holistic manner.

In order to narrow the scope of the research, the research is applied to firms in the electronics sector. Electronics provide an interesting product group since the development phase for electronics is especially time-consuming when circularity is a requirement. Electronics furthermore have a multitude of parts that are (often) not developed inhouse and therefore challenging to make sustainable, they frequently contain critical materials as well as permanent connections that hamper end-of-life processes (Tischner and Hora, 2019). Electronic products also often outdate before reaching their functional lifetime, creating a further challenge to fight obsolescence. Electronics as a product group will therefore provide a richness in data on the challenges in selecting CE methods that other products will not. Besides the development of electronics being of interest, electronic waste (WEEE) also is a global recycling issue as we generate 10.5 kg WEEE per person yearly (Bressanelli et al., 2021; Eurostat, 2020). Only 17% of WEEE was recycled in 2019 and critical materials are often lost in the process (D'adamo et al., 2016; Forti et al., 2020).

The core concepts on which this research is based are the circular economy, lifecycle thinking and management, circular value and supply chains, and circular economy strategies and methods. The objective of the research is thus to connect the available methods form literature with the methods used in business practice and its challenges to create a comprehensive overview that can support firms in designing, implementing and evaluating circular lifecycles.

The thesis is therefore relevant to the field of industrial ecology through its interdisciplinary approach of incorporating environmental factors with business and technology. Hereby supporting business in incorporating environmental factors into business practices and motivating a lifecycle thinking perspective within the ecosystem business operates. The integration of these factors is closely linked to the systems thinking approach typical for the field of industrial ecology. A systems thinking approach is central to this research as a circular economy cannot be achieved without industry efforts. Not only for more environmentally conscious business practices and products but also for supporting sustainable consumer behaviour through those products by, for example, supporting long-use and repair as fitting a circular economy. The navigation aid that is to be developed in this thesis will offer this interface and place business, technology and society into a circular ecosystem.

1.3. Research question

The research question and sub-questions are oriented at classifying existing circular economy methods in current literature to serve as the backbone of the research. As well as to understand the dynamics of decision-making by firms in selecting these methods for implementation. Consequently, the research question is:

"How can appropriate circular economy methods be selected by OEMs to support the transition towards a circular economy in electronics?"

To answer the main research question the following sub-questions are answered. Combined these will subsequently answer the main research question.

- What CE methods aiming at particular phases of the product lifecycle are available?
- How do OEMs select CE methods?
- How can a framework be developed to support OEMs in navigating CE methods?

The sub-questions hereby reveal the already available CE methods and how business in practice navigates them, through which the main research question is answered. To answer both the main research question as the sub-questions academic literature is used as well as the collected data as explained in the research design and methods that are discussed in chapter three.

2.2 Lifecycle thinking

To implement the principle of the circular economy in business, a circular value chain is needed. Commonly, we speak of a value chain in which the focal point is the end product and the chain is developed around the activities required to produce it. Every company occupies a place in the chain to provide inputs from upstream to downstream activities (Peppard and Rylander, 2006). In a circular economy however, a value network is more suiting. In a value network, value is co-created through collaboration with partners in the network (Peppard and Rylander, 2006). Activities revolve around the value-creating system instead of the company or industry itself. In which different economic actors (suppliers, partners, stakeholders, customers and more) co-produce value. The value network defines the way through which companies interact with suppliers and other actors to organize internal activities (Osterwalder and Pigneur, 2013). The network will define what CE methods are adopted, in what phase of the product lifecycle and what is needed from the network and its partners. Suppliers are therefore key partners and collaboration with them and other stakeholders is of importance.

In a circular economy as well as in a CE value network, it is important that CE methods are aligned to achieve circular lifecycles. Decisions that are made early-on will influence the number of options later in the lifecycle, calling for an approach called "lifecycle thinking" (LCT). When strategies are not aligned throughout the lifecycle environmental burdens are only shifted instead of resolved (Mazzi, 2020). This can have environmental, economic and social effects for other stakeholders, LCT directs attention to these tensions in the lifecycle (Mazzi, 2020). Designing circular lifecycles is therefore a puzzle in which all pieces need to fit with each other. Illustrating the need for a lifecycle thinking mentality. With a lifecycle perspective the totality of the system is considered in the analysis of a product with a long-term horizon and a multidimensional view (Mazzi, 2020). Lifecycle thinking offers a comprehensive analysis and leads to solutions for reducing impacts in an absolute way and not just a relative way (Mazzi, 2020). Essential for a circular lifecycle are therefore assessment methods to measure and evaluate the success of the envisioned design (Gheewala and Silalertruksa, 2021). Commonly used methods to do so are Life Cycle Analysis (LCA) and Material Flow Analysis (MFA). In addition, Life Cycle Costing (LCC), Cost Benefit Analysis (CBA), and Environmentally Extended Input-Output Analysis (EEIOA) and more are also used. Besides quantitative methods, qualitative methods also exist. Such as cradle-to-cradle (C2C), metrics on material flows, and recyclability and repairability assessments and indicators.

In addition to the need for alignment, timing also plays a role. In a circular lifecycle there is little space for "add-ons" later on. Multiple lifecycles therefore need to be envisioned and designed before taking products into production (Sumter, 2021). End-of-life solutions will be influenced by design decisions made in development, lifecycle design should therefore be considered in the early development phase (Gheewala and Silalertruksa, 2021). Lifecycle thinking furthermore affects the micro-, meso- and macro-level. At the micro-level individual processes and design choices are tackled. At the meso-level production lines and industrial sectors are considered. At this level there is room for industrial symbiosis and using waste/by-products of one system as feedstock for the other. At the macro-level international economies are considered and the lifecycle is evaluated on its circularity (Gheewala and Silalertruksa, 2021). Within these levels LCT affects several stakeholders. From designers and manufacturers to consumers and the market as well as local governments (Mazzi, 2020). In adopting an LCT approach both the different lifecycle phases as the different stakeholders throughout the lifecycle therefore need to be aligned (Mazzi, 2020). Overall, LCT thus directs attention to the need to envision the lifecycle as a whole to avoid and solve tensions between individual CE strategies. LCT is therefore a valuable method for firms designing circular products within the value network.

2.3 Circular economy strategies per lifecycle phase

2.3.1 Material sourcing and manufacturing

The materials that are chosen need to be suit for a circular lifecycle in order to close the loop. This also means that the material choices need to align with choices made later in the lifecycle phases, or the other way around. In material sourcing commonly used strategies by firms revolve around green procurement and fair sourcing, other methods such as energy recovery, material substitution and analysis methods can help inform on material selection (Kalmykova et al., 2018). Through energy recovery, residual energy can be used for the production of other goods and thus increase the energy efficiency of the material. Through material substitution unsustainable materials are replaced for more sustainable ones. Impact assessment methods can support in the identification of hotspots and help identify the materials that need to be substituted. Impact assessment methods are therefore also often used for green procurement as it allows comparison of goods. Making it possible to procure goods with the same primary function but with a lower environmental impact (Kalmykova et al., 2018). Firms can furthermore enter cross-sector partnerships to extend resource value and use by-products from industrial processes of one sector as input for another. Hereby creating mutually-beneficial relationships with nearby companies. This is defined as industrial symbiosis (Chertow, 2007). At the manufacturing level reproducible and adaptable manufacturing technology would be a scalable option where transparent and scalable technologies are used at other production sites using indigenously available resources and skills (Kalmykova et al., 2018).

2.3.2 Distribution and sales

During distribution and sales more efficient packaging design can benefit the environmental impact of the product (Kalmykova et al., 2018). Reducing the overall packaging benefits the space efficiency of the product as well as the weight during freight which is more energy efficient (Kalmykova et al., 2018). Using bio-based or end-of-life materials further reduces the impact of the distribution of the product. Redistribution of products is also an effective strategy to prolong the lifetime of goods. By reselling or reusing used goods fewer products need to be produced and the product lifetime is extended (Kalmykova et al., 2018). Impacts from distribution and sales however often do not compare to the impacts in other stages during lifecycle analysis.

2.3.3 Consumption and use

During the consumption phase of the lifecycle several circular business models can be put in place to ensure and/or motivate the circularity of the product as well as more sustainable consumer behaviour. Based on a review of several definitions, Geissdoerfer et al. (2020) define a circular business model (CBM) as a business model that cycles, extends, intensifies and/or dematerializes material and energy loops to reduce the resource input into and the waste and emission leakage out of an organisational system. Business models therefore often correspond with resource loops. To slow loops business models focus on long life products and prolonged use through life-extending services. Business models aimed at closing loops are focused at the end-of-life process to reuse materials through recycling. Geissdoerfer et al. (2018) also add intensifying and dematerializing loops aimed at intensified use and the substitution of products for services through optimization, digitization and the provision of services.

Through the product and the business model the consumer's behaviour also needs to be influenced in such a way that they perform the desired behaviour for a particular product and its intended lifecycle. Such as proper disposal, use of life extension services or communal care of shared products. In a circular economy the consumer is therefore an important part of the system (Wastling et al., 2018). This can be challenging, especially when the desired behaviour deviates from that of the established behaviour in a linear economy. Even when a consumer has a positive mindset towards environmental issues, this does not guarantee environmentally conscious behaviour or purchasing patterns (Luchs, 2010). Business models that resemble consumers of existing models are therefore more likely to receive consumer acceptance than those that do not (Mylan, 2015). To further achieve a target behaviour, interventions can be implemented within the business model to incentivize and motivate a behaviour change and lower burdens or provide the tools to make better consumption choices (Lammie et al., 2011; Michie et al., 2011), as further elaborated on in chapter four together with a full overview of business models per resource loop.

2.3.4 End-of-use

For the collection and disposal of products both the producer as the consumer play a role. The consumer is responsible for actually returning the product. Institutionalised consumer habits therefore need to be acknowledged and addressed by producers. Referring back to circular business models, alternative characteristics have to be introduced to reform habits (Mostaghel and Chirumalla, 2021). CBMs with a higher level of involvement of the consumer than with traditional sales motivate users to treat products responsibly during use and to give up after-use ownership by taking part in take-back schemes. This requires incentives from the company to enable them to reobtain ownership at end-of-use. In CBMs such as product service systems (PSS) that lease products or use the pay-per-use model this is easier as the product remains in the company's ownership and keeping track of products is thus facilitated as it is entangled with services as maintenance and repair (Mostaghel and Chirumalla, 2021). Nonetheless, this is still challenging to some degree in cases of shared products, as for example for Swapfiets or shared scooters which often get stolen.

Consumer responsibility is another aspect of CBMs that requires a shift in consumer behaviour. Depending on the architecture of the PSS, consumers no longer hold ownership of the product. Potentially creating a situation in which the user's incentive to treat the product responsibly decreases as the consequences are now shared by the consumer as well as the producer. Without proper consideration of consumer behaviour in the design of the PSS, this type of CBM thus do not necessarily require the user to treat the product responsibly and make use of preventative maintenance services from the provider. This shift in responsibility, causing service costs to be incurred by the company, also leads to a new focus of product designers on durability, longevity and quality, not only to accompany the business model as stated before but also to minimize costs (Tukker, 2015). In several CBMs the business model furthermore requires acceptance of a new financial paying scheme such as pay-per-use compared to more traditional sales. Nonetheless, this also has benefits to the consumer as charging schemes can be tailored to consumer needs, eliminating unnecessary costs to the consumer (Mostaghel and Chirumalla, 2021).

Research has however found that consumers appreciate take-back schemes more than product lease, sharing or pay-per-use models and is more probable to lead to behavioural change (Azjen, 2011). The study found that the payment scheme is of large influence on the acceptance of the business model. Companies offering CBMs should thus pay extra attention to the benefits of their payment method to the consumer, incorporating a one-time transaction and return scheme. The preference for take-back schemes for consumption goods by Dutch consumers might also be explained to the familiarity of the system as it is also used for household waste, bottles and electronics such as batteries. Lack of ownership and shift in responsibility were not identified as significant, which is beneficial for CBMs (Mostaghel and Chirumalla, 2021).

2.3.5 End-of-life

At end-of-life, there are several ways in which the value of the product can be retained longer. First of all, options should be explored in which the product can be used again or its parts. Options for maintenance, repair, reuse or repurposing should therefore be explored before recycling. If a product is then discarded and returned to a manufacturer, options for refurbishment and remanufacturing can be explored. However, the environmental impact of these options should be considered and weighed.

Maintenance, repair or upgrading of a product is not always necessarily sustainable. Per particular case the environmental impact of each step of the value hill (repair/maintain, reuse, refurbish, remanufacture, recycle) (Achterberg et al., 2016) should be evaluated to make informed decisions on the most sustainable options at end-of-use.

Another end-of-life option is cascading. By cascading, materials and components are used across different value streams (Kalmykova et al., 2018). This is often done with wood, where solid wood products are slowly cascaded into nutrients for the forest again. Nonetheless, in the current economy most products will be recycled at end-of-life. In a circular economy this is however a last resort.

2.3.6 Across lifecycle phases

Even though the product lifecycle can be divided in phases, these phases often overlap and are connected to each other. There are therefore also methods to help address more than one lifecycle phase or even the lifecycle as a whole, mainly covered through combinations in product design and business models. Regarding the physical product design, several methods can be combined (see chapter four) but few overarching methods exist regarding the lifecycle. To address multiple lifecycle phases, business model combinations also provide opportunities for circularity. Even though it is not often addressed, business models can be combined into portfolios to address several lifecycle phases and ensure circularity throughout a product's lifetime (Frishammar and Parida, 2019; Tunn et al., 2019). To further address multiple lifecycle phases cross-sector partnerships are often needed. Within the value chain a producer is not a stand-alone actor. Especially in a circular value network where collaboration and partnerships are key for producing circular products. To address more than one lifecycle phase collaboration throughout the value chain is needed where resources can be shared and shared value is created.

The Cradle-to-Cradle method is also a common approach that is used to address the product lifecycle in design to circulate resources (McDonough and Braungart, 2010). In order to qualify for the Cradle-to-Cradle certification several guidelines exist to ensure the quality of C2C products. C2C is however more of a vision towards circularity with a variety of underlying methods than a 'method' as it is defined in this thesis. Similarly, the Circle Economy Foundation summarizes methods to address multiple lifecycle phases rather than propose an overarching method.

2.4 Circularity in electronics

As mentioned earlier, circularity is particularly interesting in the field of electronics because of the pace of innovation and rapid substitution of products. Electronics furthermore contain critical materials and often have many parts and permanent connections while WEEE is still growing (Tischner and Hora, 2019). Electrical and electronic equipment however has a high reuse and recovery potential as a new resource (Bovea and Pérez-Belis, 2018). Especially for small electronics the substitution rate is high, products are replaced before reaching their functional lifetime because of the introduction of newer, better performing models. In the EU 12.4 million tons of EEE is put on the market, of which 4.7 million tons of WEEE is collected. This is about 10.5 kg of collected e-waste per person, per year in the EU alone (Eurostat, 2020). Bovea and Pérez-Belis (2018) studied 127 small to medium electrical and electronic equipment on the circularity of their design and where improvements need to be made. The results show that the main factors across all products that need to be improved in EEE are product life extension and product/component reuse. The Ellen MacArthur Foundation (2018) therefore has the following vision for circularity in electronics:

1. Electronic devices are loved for longer, by one user or many
2. Devices are a gateway to the cloud (for computing power and memory allocation)
3. Services are provided for circulation between different categories of users
4. Products and components are cascaded

To achieve this several recommendations are made to enhance the approaches that are currently taken by the industry. Namely, keeping products in use longer, component and material recovery, keeping products in the right place and smart use of residual value. To keep products in use longer, companies currently consider two design strategies. Repair, refurbishments and upgrades by the users and repair and/or refurbishment by technicians. Ideally, these strategies will one day lead to full repairability by the user but most importantly, that products, materials and components are kept at maximum utility as long as possible (Ellen MacArthur Foundation, 2018).

Regarding component and material recovery, components are being reused both in official refurbishment programs as through other platforms but standardization is lacking. Combined with the fast pace of technological development this hinders reuse (Ellen MacArthur Foundation, 2018). For material recovery, recycling is the main strategy so critical materials such as cobalt and chromium, and heavy rare earth elements can be recovered (Ellen MacArthur Foundation, 2018; Pan et al., 2022). However, in order for recycling rates to increase, collection is the first point of action (Sommer et al., 2015). Current collection rates are 65% in the EU, meaning that only 65% of electronics is brought to the appropriate collection points for recycling of electronics (Eurostat, n.d.). Collection rates therefore need to increase by, for example, incentivizing the consumer financially through trade-in options, rewards and potentially a deposit system as well as through improved infrastructure of collection points.

To ‘keep products in the right place’ the Ellen MacArthur Foundation also suggests that further logistical actions need to be taken regarding take-back systems and return logistics. The incentive for the consumer to return their products at end-of-life is low and reverse logistic processes are complex and expensive (Ellen MacArthur Foundation, 2018). The main problem for most producers is the value chain, making (brand specific) return streams difficult. Besides the risk of insufficient consumer participation, the infrastructure and logistical requirements for a take-back system are also restricting and unattractive from a business perspective. Making up 95% of costs of HP’s take-back program for inkjet cartridges for example. In order for take-back systems to be effective it is therefore necessary that the scope of individual take-back systems is expended to collective (national) systems to enable economies of scale and reduce cost burdens (Degher, 2002).

Information sharing through, for example, material passports and repair scoring would furthermore support manufacturers and consumers in understanding residual value of products as well as more time-efficient and effective end-of-life activities (Ellen MacArthur Foundation, 2018). Taking repair scoring as an example, OEMs should include repair scoring systems in their development process to assess the ease-of-repair and evaluate products on their repairability by both the producer as the consumer (Right to Repair Europe, 2023). This should also be communicated to the consumer to be able to evaluate a product on its reliability. But it also risks distrust in products through the perception that those products will also require a lot of repairs.

Another option is the implementation of circular business models such as access models. This type of business model has however not gained much popularity in the sector. At the moment, renting, sharing or leasing options are often higher in price than the purchasing price. Phones for example are often only leased once as they outdate and lose popularity before reaching a second user. For this business model to work, renting needs to be financially more attractive and suitable to the product group (Suppipat et al., 2022). For smart use of residual value, it is important for both users as manufacturers to see how different circular activities can reinforce each other for retaining value as long as possible (Ellen MacArthur Foundation, 2018).

But currently, the industry is far from reaching the 2050 goals for a circular economy set by the government. Current company policies are often insufficient to meet the 1.5 degrees Paris Agreement and for The Netherlands specifically the 2030 goals set by the government will likely not be met either with the current industry policies (Haanemaaijer et al., 2023). Overall, sustainability of electronics will thus be a combination of industry alignment, further and more active company integration of product life extension strategies and consumer participation. It is therefore again of importance to establish a larger value network through partnerships within the industry where resources can be shared (Peppard and Rylander, 2006).

2.5 Combining CE methods for circular lifecycles

Considering the examples in the literature review, Kalmykova et al. (2018) acknowledge that there exist different methods per phase of the lifecycle as well as different fields of expertise within CE literature but only categorize them and do not connect them. Literature on evaluation methods and environmental indicators is often also discussed separately and appears to be focussed within industrial ecology literature discussing them in deepening academic articles, such as the study by De Pascale et al. (2021). This does not necessarily mean evaluation methods are not discussed on other fields, here fast-track methods are often used to obtain a first assessment but better integration of methods is needed to design circular lifecycles. It however makes sense that these topics are discussed separately as these are deepening academic articles on particular CE methods. Without knowledge on the separate disciplines in the circular economy it is impossible to connect them to create the bigger picture. It is therefore more interesting to look at the body of literature in which connections between CE methods *are* made.

An interesting paper is therefore the one by Bocken et al. (2016) who categorize design strategies and business models for slowing and closing resource loops together and offer that the two interact. Moreno et al. (2016) combines the two as well and also state that more systemic approaches need to be adopted. But further connections are not made. Another interesting perspective is therefore that of Diaz et al. (2022) who combine circular product development with managerial factors that enable its implementation and developed a “CE implementation roadmap” for firms to use. The aim of creating a framework for business to use in practice, and the managerial factors that enable circular design strategies illustrates the acknowledgement that firms need more than isolated guidelines.

Bakker et al. (2014) looked into product life extension strategies for electronics using the environmental method LCA as well as dynamic modelling. Hereby combining product lifecycle considerations, circular economy and design strategies, and environmental methods. They end the paper by stating that designers need to know when to apply which strategies per product based on product characteristics and business constraints. For which the optimal product life scenario first needs to be established, after which business models need to be found to support these (Bakker et al., 2014). The paper thus combines different fields of expertise within CE literature and proves the need for integration of design and business models at the strategic level. Considering literature that takes the entire lifecycle into account, the study by Boorsma (2022) on remanufacturing provides an interesting perspective as well. Boorsma (2022) developed a 'circular product readiness' tool covering the product lifecycle from product development to use and end-of-life. Hereby combining several CE methods as well consumer behaviour and managerial considerations. Joustra et al. (2021) combines circular strategies over the lifecycle with design aspects for product and material integrity to explore recovery pathways and generate design solutions. Resulting in a framework that comes with several worksheets for (re)designing products for a circular economy, considering the product lifecycle, design and materials, but also stakeholders (Joustra et al., 2021; Joustra et al., 2022).

There is thus certainly literature available that combines CE methods over the product lifecycle. But the body of literature discussing CE methods separately is still significantly larger. It is therefore relevant to look further into how business can be guided in navigating the available CE methods throughout the product lifecycle to enable the implementation of several accurate CE methods at the appropriate phases of the lifecycle per particular product type.

2.6 Main take-aways

This is only a small overview of CE methods that exist in the literature. Together this is creating a scattered understanding for business to work with in designing circular products and services. Regarding the combination of CE methods, in both CE literature as LCT literature it has been offered that CE tools are not stand-alone methods (Bocken et al., 2016; Moreno et al., 2016; Niero and Hauschild, 2017; Mazzi, 2020). Current LCT literature does reveal its potential (Mazzi, 2020) but combining different CE methods has not been a focal point in CE literature yet. Creating a level of coherence in circular economy methods along the lifecycle can however be of interest (Corvellec et al., 2022; Niero and Hauschild, 2017). If lifecycle thinking is further integrated in CE literature for the purpose of combining CE methods over different areas of expertise, this has the opportunity to support business in designing circular lifecycles to avoid the shifting of environmental burdens. As also done by Bakker et al. (2014), Boorsma (2022) and Joustra (2021). Overall, there are a lot of CE methods available but there is a higher level of expertise needed to guide your way through it. Therefore, companies have a need to obtain guidance in what methods to use and when, calling for a framework to provide this.

3. Research methods

The following chapter expands on the research methods to execute the research. The methodological approach is discussed and the proceeding research design. Then, data collection and data analysis are discussed as well as practical and ethical concerns in regard to the research design.

3.1 Research design

Inductive research is perceived as the most suitable approach for this particular study. As the goal of the research is to build a framework that supports business practice in implementing CE methods an inductive approach leads to more extensive insights and interpretation of data from the interviews. The research is furthermore exploratory as it seeks to explore how firms can navigate and implement the available CE methods. Even though the research has participatory elements in the development of the final framework, the research is still theoretical research as it looks for basic principles and reasons for the situation in question.

3.2 Research strategy

For this thesis a literature review as well as a case study is performed. First, a literature review is performed to research the existing CE methods and categorize these by the end of the literature review to be used as the backbone of the research. The literature review furthermore helps answer sub-question one and two by providing knowledge on the currently available CE strategies and supporting methods as well as through existing case studies from business practice on the use of CE methods. Then, a case study strategy is adopted in which several cases are evaluated on their use of CE methods through semi-structured interviews. From the interview data and the literature review a framework is developed that is evaluated for improvements with every round of interviews. The final framework simultaneously provides the answer to sub-question three. Through the sub-questions the main research question is eventually answered in the discussion. The overall research process is shown in figure 2 below.

A case study approach is furthermore applied to facilitate the understanding of the logic behind the selection process of CE methods at each case company (Eisenhardt, 1989). The goal of the case study approach is thus to gather information from business practice on their experience with selecting CE methods. A multiple case study strategy is adopted as well in which data is gathered from multiple companies to analyse varying conditions of the research topic. Considering the breadth of available CE methods, having multiple cases therefore ensures the richest dataset. For this thesis a minimum of five cases is set as this number is perceived sufficient for this type of research (Yin, 2009). More cases can however be added if more data needs to be collected.

With this strategy the aim is to create an understanding from literature on what CE methods are out there and from business how they make selections from the available methods. To eventually understand the logic of creating circular lifecycles in practice and where improvements can be made to guide firms in accurately selecting and implementing them.

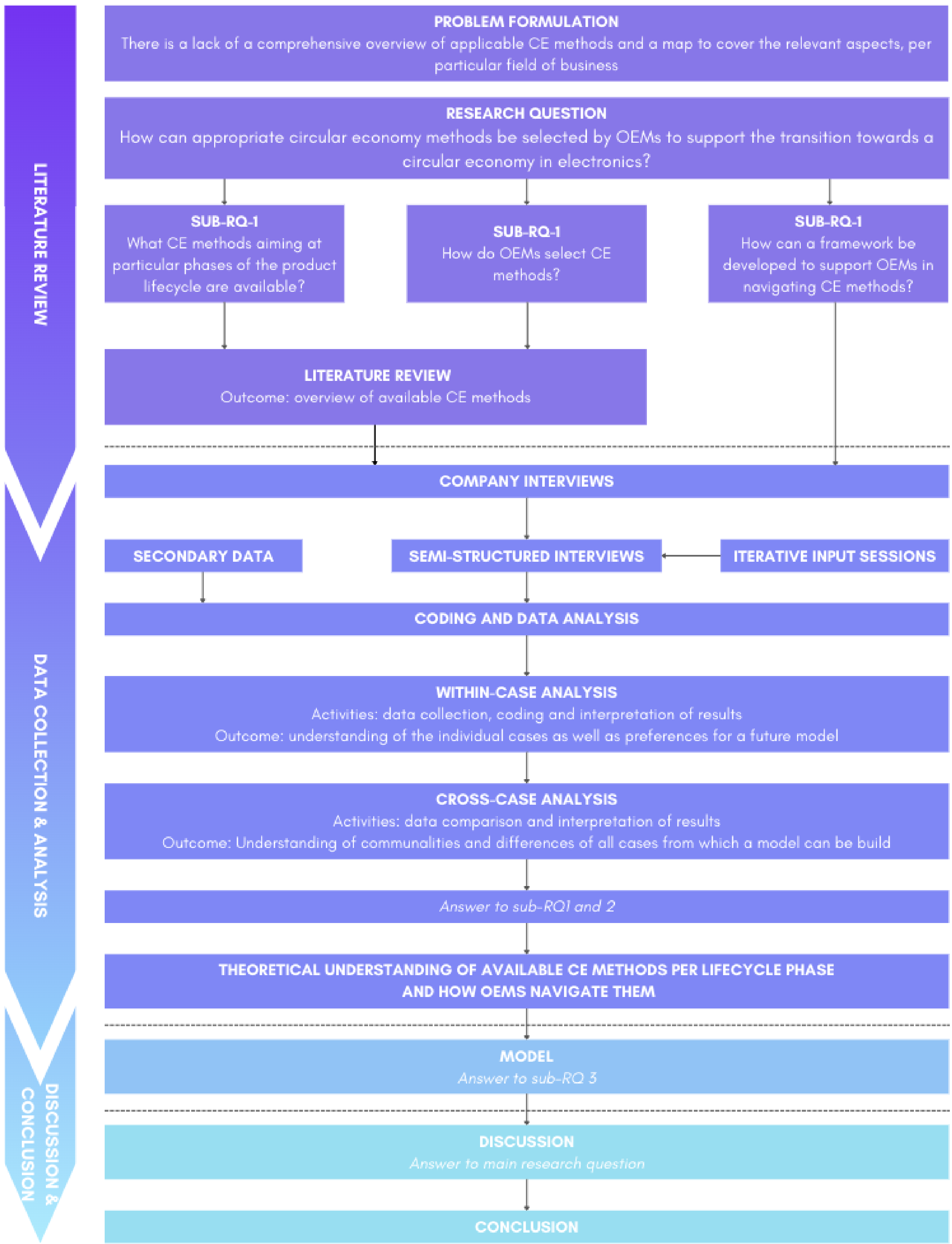


Figure 1: Research process

Table 1: Sampling criteria

Criteria for sampling case companies
Company is based in the EU or has an EU branch
Company must be specialized in electronics
Company must have at least one hour available for an interview or be willing to participate in a second interview
Company must produce at least a sustainable and preferably circular product

Table 2: Interview information cases

Company	Product	Function	B2B/B2C	Duration	Medium	Company size
A	Electronic and electrical appliances	Senior manager	B2B and B2C	1:05:00	Teams	Large enterprise
B	Renewable energy	Managing director	B2C	0:45:00	Teams	Start-up
C	Electrical appliances	Innovation and sustainability manager	B2C and B2B	0:55:00	On location	Large enterprise
D	Design agency	Senior sustainability design engineer & circular design engineer	B2B	0:45:00	Teams	Large enterprise
E	Lighting	Application scientist	B2B and B2C	1:10:00	Teams	Large enterprise
F	Lighting	Technical director & sustainability manager	B2B	0:55:00	Teams	SME

Table 3: Types of secondary data per case company

Company	Document type	Pages
A	Data from website	-
	Internal documents	125
B	Data from website	-
C	Data from website	-
	Internal documents	76
D	Data from website	-
	Internal documents	135
E	Data from website	-
	Internal documents	207
F	Data from website	-
	Internal documents	168

3.3.2 Sub-question 1: What CE methods aiming at particular phases of the product lifecycle are available?

The first sub-question of this research is primarily answered through the literature review. The literature review provides knowledge on the common and available CE strategies as well as knowledge on the available quantitative and qualitative CE methods. The first part of the literature review in chapter two provides the needed background information to understand the knowledge field within which this research is set. Then, the literature review serves to gain further knowledge on specific CE methods addressing specific phases of the product lifecycle. The literature review in total hereby provides an overview of the available CE strategies and the corresponding CE methods per particular phase of the lifecycle in academic literature. For the literature review a snowballing method is used to find articles. This is done by identifying a first set of academic articles using search keywords (including but not limited to the search keywords in table 5). Then, the references and citations from those papers are evaluated on quality and content and decisions are made to include or exclude the new papers. From the included set of papers, the procedure is repeated several times until data saturation occurs and a new search is started for which the process is repeated again (Goodman, 1961).

Table 4: Search keywords

Search keywords
Circular economy; Circular economy methods; circular economy strategies; circular economy tools; circular economy guidelines; electronics; circular electronics; WEEE; electronic waste; WEEE recycling, EEE end of life; circular economy business models; circular product design; environmental indicators; lifecycle thinking; lifecycle management; circular lifecycle phases; circular supply chains; circular value chains; value networks; cross-sector partnerships

The overview of CE strategies and methods in chapter two and chapter four serve as input for the interview guide, the coding framework in data analysis and in the development of the framework, which is expended on later in this chapter. Besides the literature review, the interviews also provide additional information on the use of CE methods. Through the interviews with case companies, it becomes clear whether the available CE methods in academic literature are in fact known and used in practice. The interviews furthermore show whether the literature review is lacking certain CE methods with which the overview needs to be extended.

3.3.3 Sub-question 2: How do firms select CE methods?

The second sub-question is primarily answered through the interviews with case companies. The interviews show the process of selecting CE methods in business practice. The goal of the interviews is to establish an understanding of what CE methods are known and used, the logic behind the selection process of CE methods, the challenges they face in this process and identify what would help them overcome those challenges. This information will show what minimal requirements needs to be included in the navigational framework and what the main points of attention are, hereby providing input for the framework. The topic of knowledge that the interviews contribute to was explored in the literature review, namely lifecycle thinking.

Company interviews

Prior to the interviews, an interview guide is developed as a guiding structure to the interviews (see appendix A). The interview guide exists of a set of open questions to support the expression of views by the interviewee. The interview guide therefore mainly functions to provide an outline of topics to be discussed and includes a set of probing questions to support conversation and gain a deeper understanding of the selection process for CE methods (Kvale and Brinkmann, 2009).

The interview guide is constructed using the overview from the literature review as a reference point from where on the interview questions are developed. The interviews start by providing an introduction of the research which is followed by an introduction of the participant. Then, introductory questions are asked to understand the position of the company in the value network and the level of integration of circular principles. Then, questions are focused on having an open conversation that is guided further into the process of selecting CE methods with each question to develop a deeper understanding of the logic behind this process. Finally, with every interview a (set of) preliminary framework(s) is presented to review the model on both intuitiveness as how it conveys information. With every interview the framework is improved and presented again in the next interview for further improvements.

After a list of potential case companies fitting the sampling criteria is drafted the companies are reached out to by email to ask for participation in the study and to set dates for the interviews. When participation is confirmed, each company receives a further description of the research, a time indication, consent form and the general topics that are enquired about. Interviews are either online via Teams, Zoom or Skype, at the company's office or at the university of Leiden or Delft. After the interviews the recordings are transcribed and coded together with any secondary data using the software program Atlas.ti. See section 3.4 for further description of the coding strategy.

Secondary data

Besides the primary data from the interviews, secondary data is collected to allow for data triangulation as well as to help answer sub-question two (see table 4 for an overview) (Yin, 2018). This provides information on the company prior to the interviews as well as additional information on the company's transition to the circular economy. Data is collected until there are multiple data incidents for a code and data triangulation is established (Eisenhardt, 1989).

3.3.4 Sub-question 3: How can a framework be developed to support business practice in navigating CE methods?

From the literature review, company interviews, input on the framework and secondary data, enough information is provided (after data analysis) to start building a framework of CE methods. As mentioned, with each interview new iterations of the framework are presented and developed further. After data analysis the last iteration of the framework is expanded further with the findings from the interviews to develop the final framework. The aim of the framework is to provide an overview of applicable CE methods per phase of the development process that addresses the necessary elements for a circular product and overcomes the challenges firms phase in selecting CE methods.

3.4 Data analysis

As mentioned, data is analysed during as well as after data collection to be able to refine the interviews and support the development of the final framework. The data is first analysed per case after which data is compared across cases.

3.4.1 Within-case analysis

In the within-case analysis the cases are initially analysed per case, hereby providing a rich knowledge base for comparison. The cases are first analysed based on prior company declarations and products regarding sustainability. The sustainability of the company is relevant background information to place the selection process of CE methods in context. Then, the cases will be analysed on the CE methods the firms have used before. When it is established what CE methods the companies are familiar with, cases are analysed on how they search for CE methods, why certain CE methods were chosen and the reasons for not selecting others and what challenges they faced in finding and selecting CE methods.

During the within-case analysis dimensions for differentiation are established based on recurrences in the codes. Which will provide the basis for case comparison.

3.4.2 Coding strategy

To analyse the data, the data is coded in 'Atlas.ti', a qualitative data analysis tool. Interviews are being coded in order to build data clusters and relate these back to the research questions. The coding criteria of Miles, Huberman and Saldaña (1994) are considered to build the codes. The interviews are analysed in a thematical approach to support interpretation of the cases (Saldaña, 2015). The first- and second-order codes are based on the existing categories in this thesis, as organized in the coding framework in table 6. As well as any new categories that arise from the interviews, indicated in *cursive* writing. As suggested by Gibbs (2007) the codes are therefore both driven by the data as the concepts in this thesis. See appendix B for an example of the coding.

Table 5: Coding framework

First-order codes	Second-order codes
Differentiation	Vision and strategy
	Business model
Collaboration	Identifying the right people
	Extending responsibility
Physical architecture	Product design
	Lifecycle design
Consumer engagement	Understanding behaviour change
	Designing for behaviour change
Evaluation and assessment	Impact assessment
	Concept evaluation
Use of CE methods	*Other methods*
	Reasoning for use of CE methods

3.4.3 Cross-case analysis

After the individual cases are analysed, cases are compared. From the dimensions that followed from the within-case analysis matrices are built. From these tables patterns are extracted from which theory is derived. Then, the cases are analysed in tables to find whether there are sensible groups based on these dimensions. Doing so will reveal the specific circumstances of the findings and how this connects to the cases (Miles, Huberman and Saldaña, 2014). The findings are then used to develop requirements, as well as any other relevant insights, for the development of the framework.

3.5 Practical and Ethical considerations

Like many studies, this research faces several challenges related to the conducting of interviews. Besides the needed early planning to schedule interviews considering the agendas of the interviewees, the research design also requires some ethical considerations. The primary concern is that of avoiding harm (Diener and Grandall, 1978). To address this concern, all information is anonymized to prevent leakage of sensitive information as well as identification of the interviewee or the company they work for, as emphasized by Bell, Bryman and Harley (2015). Another ethical concern is that of informed consent due to the open-ended nature of the interview and therefore absence of a predetermined list of questions in the interview (Diener and Grandall, 1978). Therefore, participants are to be informed at the beginning of the interview on the treatment of data.

4. Circular economy methods

This chapter builds upon the literature review in chapter two and dives deeper into circular economy methods. At the end of the chapter an overview of the available CE methods is provided in table 11 that is to be used further in this research as input for the interviews and coding framework. The identified CE methods are divided in five categories. Each of these categories exists of two subcategories. In total ten types of CE methods thus exist. It should however be mentioned that this is a subjective overview of CE methods that are found during the thesis research. There are a variety of other CE methods out there but within the timeframe of the research it is not possible to create an overview of all available CE methods. For visualisations of the separate CE methods discussed in this chapter see appendix C. See appendix D for an overview of all identified CE methods including those that were not selected for the research.

4.1 Differentiation

Differentiation involves the offering of a product, service or experience to the consumer that is unique and that competitors don't have, or that significantly lowers their costs. A successful differentiation strategy creates a competitive advantage and improves business performance (Sharp and Dawes, 2001).

4.1.1. Business model tools

As mentioned, a circular business model is a business model that cycles, extends, intensifies and/or dematerializes material and energy loops to reduce the resource input into and the waste and emission leakage out of an organisational system (Geissdoerfer et al., 2020). Business models can be divided in slowing, closing, narrowing and intensifying resource loops. Geissdoerfer et al. (2018) also add intensifying and dematerializing loops aimed at intensified use and the substitution of products for services through optimization, digitization and the provision of services. See table 7 for an overview of different business models corresponding to the identified resource loops.

Table 6: Overview of resource loops and circular business models

Resource loop	Business model	Author
Slowing resource loops	Access and performance (PSS) - Product oriented - Use oriented - Result oriented Extending product value Classic long-life Encouraging sufficiency	Bocken et al. (2016) Tukker (2004)
Closing resource loops	Extending resource value Industrial symbiosis	Bocken et al. (2016)
Narrowing resource loops	Reducing resources	Bocken et al. (2016)
Intensifying resource loops	Intensified use	Geissdoerfer et al. (2018)
Dematerialising resource loops	Dematerialisation - Optimization - Digitization - Services	Geissdoerfer et al. (2018)

To develop such a business model within a company, several business model tools exist in to help design and implement CBMs and facilitate business model innovation in a circular economy. An often-used method is the “business model canvas” by Ostenwalder and Pigneur (2010). The business model canvas (BMC) has been altered by several academic to also address sustainability. Similarly, the triple layered business model by Joyce and Paquin (2016) includes an economic, environmental and social layer as well but exists of three separate canvases and is therefore considered to be the most comprehensive. Together these layers create horizontal and vertical coherence within and in-between the three layers. Horizontal coherence allows for different types of value creation that facilitates a broader and more holistic view. Vertical coherence allows for alignment in-between the different levels. The purpose of these models is to provide a design tool that structures sustainability issues in business model innovation.

Focusing more on the ideation phase, the circular business model pattern cards by Pieroni et al. (2019) provide a method to sense opportunities and generate ideas for potential CBMs. The method exists of a card deck that showcases ‘patterns’ instead of specific business models. The cards can be combined and organized on the accompanying circular economy business model configurator poster to develop a business model portfolio. After completing this step, the CBM planningtool can be applied to create an actual business model and how it proposes, delivers and captures value over several use phases (Nussholz, 2018).

4.1.2. Vision and strategy development

In order to develop circular products a company needs a circular vision and a strategic aim of their product. Therefore, several methods exist to motivate CE thinking and help develop a more holistic view of the CE in organizations. A well-known and often adopted framework to achieve this is the RESOLVE framework by McKinsey and the Ellen MacArthur Foundation (2016). The RESOLVE framework represents six action areas that support the transition from the current linear economy to a circular one at the local, national, regional and global levels. Namely, regenerate, share, optimize, loop, virtualize and exchange. The RESOLVE framework is intended for both European economies as companies and aims to increase the utilization of physical assets, prolong product lifetimes and the use of renewable materials. Each action area furthermore reinforces the performance of the others (McKinsey, 2016). Similar to the RESOLVE framework, the key elements framework by Circle Economy (2021) renders the concepts of the circular economy and serves as a starting point to derive strategies and interventions by providing the core activities related to the CE as well as enabling elements that facilitate the transition to the CE.

For companies that are new to the CE and lifecycle thinking, the circular economy trend cards by Circit Nord (2020a) can support brainstorming on what the CE entails and what changes it might require. They can be used in the analysis of trend drivers and finding a company’s strengths and weaknesses as well as potential opportunities and threats. The method covers different topics of the circular economy, circular business models and raises specific questions on the CE to support team discussions. Similar to these trend cards, the circularity deck by Konietzko et al. (2020) provides a card deck on a collection of circular innovation principles and practical examples. These principles are organised according to the intended circular strategy outcome that they pursue (narrow, slow, close, regenerate and inform material and energy flows) as well as the perspective that is needed to operationalize the principles (product, business model or ecosystem). Compared to the trend cards, the circularity deck helps to specify and operationalize visions.

On a company vison level, the BECE (Back-casting and Co-design for the Circular Economy) framework was developed from the concept that effective implementation of CE principles requires systemic change and CE thinking in organizations. The BECE framework therefore helps to implement CE requirements in an organization by integrating back-casting and eco-design. Thereby empowering organizations to take a more holistic approach and embedding the concept into corporate decision-making. The framework further aims to bring operational and systems thinking together (Mendoza et al., 2017). This framework is therefore helpful in implementing CE thinking into a company and support vision development in a circular economy. The BECE framework exists of the following 10 steps:

1. Create an overarching CE vision
2. Analyse drivers and constraints
3. Add specifics to the CE vision
4. Characterize the product/service portfolio
5. Product/service selection and evaluation
6. Propose CE design and supply chain alternatives
7. Evaluate CE strategies
8. Devise CE scenarios and action plans
9. Validate CE scenarios and action plans
10. Implement and review

Once a clear vision and product strategy is established a tool such as the Sustainable By Design tool by Coffay and Bocken (2023) can be used identify and act on organizational barriers and drivers in business model innovation. The tool connects company culture, strategy and operations and helps identify barriers and opportunities at each level. The outcomes can be mapped on their feasibility and accuracy. The tool hereby helps connect the company to sustainability aims and provide direction for sustainable business model innovation.

Methods for differentiation thus mainly include methods that support company vision and product strategy development. As well as methods to differentiate the business and the product through the business model. Together this supports CE thinking which is necessary to have circularity as part of the core business and supports development of alternative ways of capturing value in a circular economy (Linder and Williander, 2017; Mendoza et al., 2017).

4.2 Collaboration

Collaboration is defined by the value network in which value is co-created (Peppard and Rylander, 2006). Activities revolve around the value-creating system instead of the company or industry itself. Where different economic actors (suppliers, partners, stakeholders, customers and more) co-produce value through collaborative partnerships.

4.2.1 Extending responsibility

Considering the increasing complexity of supply and value chains and the involvement of different parties throughout, collaboration has become an important strategy to achieve shared goals (Liao et al., 2017). CE strategies affects collaboration in three different ways. They motivate relational collaboration, advance operational collaboration and connect stakeholders to the network (Sudusinghe and Seuring, 2022). CE strategies such as repair, refurbish, remanufacture and resell/reuse for example encourage relational collaborations practices such as sharing, responsibility for product recovery, industry penalties and incentives, and long-term agreements (Jabbour et al., 2019). Braided into this is the concept of extended producer responsibility to motivate an internal drive for collaboration in the first place and eventually to create a collective responsibility throughout the value network (Jabbour et al., 2019).

On the producer side, extended producer responsibility (EPR) is an important aspect of selling products in a circular economy. The OECD defines EPR as an environmental policy approach in which a producer's responsibility for a product is extended to the post-consumer stage of a product's lifecycle including its final disposal (OECD, 2001). It should therefore thus be mentioned that EPR is a collective responsibility.

Where one producer's actions also benefit the industry as a whole, risking social loafing where individual actors expend less effort when present in a collective. The implementation of CE strategies however encourages collaboration and involvement of stakeholders that together have the opportunity to ensure environmental performance (Sudusinghe and Seuring, 2022). EPR as a policy approach calls for upstream producers to carry the financial and physical responsibility of recycling and incentivizes to incorporate environmental aspects in product design. EPR is an extension of the "polluter pays principle" and aims to internalize environmental costs into the market price. Even though EPR is not necessarily a CE method, its vision is required to achieve circular lifecycles and establish responsibility over this lifecycle as well as acknowledgement of the need for collaboration in a more holistic view of the circular economy.

EPR itself is an environmental strategy but it requires policy instruments for implementation. EPR can be implemented using administrative, economic and informative policy instruments, see table 8 below (Forslind, 2005). The different characteristics can be classified in five types of EPR. Namely, informative, physical, economic and owner responsibility and liability. Informative responsibility implies a responsibility to provide information about the product and its environmental effects. This can include manuals for repair up to material passports. This type of EPR is dependent on legal requirements and producer's goodwill. Physical responsibility implies that the producer is required to handle the end-of-life management of the physical product. Economic responsibility occurs when a producer pays the costs associated with the EOL management. Liability implies that the producer is responsible for all environmental harm a product produces in its lifetime. Finally, owner responsibility is a subset of all of the above when a producer remains ownership of the physical product through the business model (Forslind, 2005).

Table 7: Examples of policy instruments (Forslind, 2005)

Types of policy instrument	Type of EPR	Example
Administrative	Informative	Prohibition
		Regulations
	Physical	Take-back responsibility
		Recycling targets
Economic	Economic	Taxes
		Fees
		Deposit-refund systems
		Product disposal charge
Informational	Informative	Information
		Research and development
Agreements	Liability	Social contracts

4.2.2. Identifying partners and stakeholders

CE methods can help to identify potential partners that can fulfil the needed roles required throughout the value chain for a particular product. To help companies ideate to identify partners, the circular collaboration canvas was developed. The method integrates decision-making principles with a design thinking approach to stimulate collaborative ideation of circular propositions (Brown et al., 2021). The method exists of five 'topics' and provides questions to trigger ideation. The canvas is divided in challenges, resources, customers and collaborative partners of which the latter is split in two asking which partners are required and why those partners would join. In addition to the collaboration canvas, methods such as the co-creation and keystone activity scan by Circit Nord (2020b) can be applied to identify specific areas where co-creation is needed or beneficial. The method visualises the product lifecycle from raw materials to disposal and helps companies identify where they lack resources and need others to fulfil these roles and create shared value. The accompanying keystone activity cycle (Circit Nord, 2020c) can then be used to zoom in on the company's role in the value chain and their keystone activities to identify what, and who, are needed prior, during and post these activities.

Similar to these methods, the boundary tool helps visualize that full circular potential cannot be achieved without multi-stakeholder collaboration. But in addition, this tool also allows identification of potential partner mismatches in identity, relations, competences and activities (Circular X, n.d.). The tool furthermore supports multi-stakeholder alignment through five steps:

1. Defining a collective ambition
2. Mapping and negotiating the changing organizational boundaries
3. Exploring opportunities and tensions for aligning stakeholders
4. Defining first interventions
5. Developing a collaboration pitch

This tool thus also supports joint development and implementation of sustainable and circular innovations. Overall, collaboration methods thus focus on the one hand on the acknowledgement that a firm functions within a bigger ecosystem and on the other hand, methods focus on how a firm operates within the value network and the establishment of partnerships for joint value creation.

4.3. Physical architecture

The physical architecture of a product is defined by its technical design. Factors that affect the physical architecture of a product are the design requirements and strategies that are used as well as the lifecycle of the product that results in certain design choices and requirements.

4.3.1 Product design

In the design phase the chosen CE strategies are followed by design strategies. Taking the R-ladder of refuse, reduce, reuse, repair (including maintenance), refurbish, remanufacture, repurpose, recycle and recover as CE strategies, each strategy will require different design approaches. The design approach of enabling dis- and reassembly of a product in its design for example enables repair. For recycling however, a product should also be designed for mechanical disintegration to best enable end-of-life processes. Different CE strategies thus call for different design approaches, illustrating how design choices in the development phase will influence the lifecycle of the product.

Product designers also often use the distinction between slowing resource loops and closing resource loops for designing products (Braungart et al., 2008). Strategies that aim to slow resource loops are products focused at i.e., long-life, repair, maintenance and reuse. Design strategies to slow resource loops therefore exist of, designing long-life products and design for product-life extension (Den Hollander et al., 2017; Bocken et al., 2016). Within these strategies products should be designed for attachment and trust or reliability and durability in order to motivate a service loop of repair (Bocken et al., 2016). Within design strategies for product-life extension the product design should focus on ease of maintenance and repair, dis- and reassembly, adaptability and standardization (Bocken et al., 2016). Strategies that aim to close resource loops are products focused at i.e., design for recovery, remanufacture and refurbishment (Den Hollander et al., 2017; Bocken et al., 2016). Other academics also advise an overall design strategy, or design thinking approach, to design for systems change. This refers to thinking in complex systems at its entirety and within its parts to target key issues and find novel solutions (Moreno et al., 2016). In addition to design enabling CE strategies, design choices are also affected by the choice in business model. Business models have an underlying aim that needs to be supported by the design of the product (Bocken et al., 2016). A product that is to be subject to intensified use in an access and performance model for example needs to be designed to withstand this. Product design and business model therefore need to be integrated in order to be effectively circular.

But besides this needed integration, several methods exist to guide the product design process. Den Hollander (2018) for example developed ‘design for product integrity’ as a circular design approach to fight product obsolescence. In this approach product life extension is an addition to end-of-life processes to create, deliver and capture value from long or extended product lifetimes. Within this strategy design can be focused at resisting, preserving or reversing obsolescence. Design for resisting obsolescence is focused at long-use and can be achieved through design for emotional durability and design for physical durability. Design for postponing obsolescence is focused at extended use and can be achieved through design for maintenance, design for repair and design for upgrading. Design for reversing obsolescence is focused at recovery and can be achieved through design for recontextualization, design for refurbishment and design for remanufacture. Overall, design for resisting and preserving obsolescence are focused at slowing resource loops and design for reversing obsolescence is focused at closing resource loops. This particular method is thus mainly concerned with using products and materials as long as possible in the most valuable manner for a product.

Another well-known method is that of Design for X research, or DfX. Which entails a wide range of design strategies and is focused at the early design stage (Kuo et al., 2001). DfX research started from considerations of the environment in design such as design for recycling or design for lifecycles which later were expanded to a wide range of strategies and summarized into ‘Design for X’. Design for X is therefore a broad concept and can focus on the product, system and even ecosystem scope and often appears as part of other design methods (Kuo et al., 2001). On a product level some examples of DfX are design for manufacturing (DfM), assembly (DfA), variety (DfV), quality (DfQ), reliability (DfR), disassembly (DfD), maintenance (DfMa), obsolescence (DfO). On a system level DfX approaches cover design for supply chains (DfSC), logistics (DfL) and networks (DfN). On an ecosystem level design for recycling, sustainability (DfS), environment (DfE) and life cycle (DfLC) are considered (Chiu et al., 2011). Compared to the previous method this method is broader and to a lesser degree intended to guide the product design process. See table 9 below for an overview.

Table 8: Overview of circularity and design aspects

Resource loop	**Design strategies (Bocken et al., 2016)**	**Design strategies (Den Hollander, 2018; Sassanelli et al., 2020)**	**Design aspects**		
Overall approach	Guidelines for DfX				
Narrowing resource loops		Design for resource efficiency and conservation	Dematerialisation - Optimization - Digitalisation - Service	Cleaner production	
Slowing resource loops	Design for long-life	Design for sharing	Design for ease of maintenance and repair	Design for dis- and reassembly	Design for physical durability
		Design for standardisation and compatibility			
	Design for product life extension	Design for resisting obsolescence	Design for emotional durability	Design for physical durability	
		Design for postponing obsolescence	Design for repair Design for maintenance	Design for upgradability and adaptability	Design for dis- and reassembly
Closing resource loops	Design for remanufacturing, refurbishment and recycling	Design for reversing obsolescence	Design for reuse in manufacturing	Design for refurbishment	Design for recontextualization
		Design for recovery	Mechanical disintegration		

4.3.2. Lifecycle design

Besides the product itself, its lifecycle also needs to be considered and designed for. Through methods such as product journey mapping the use-life and different use-cycles are visualized. The method provides a horizontal timeline on which service touchpoints, product updates, expected repairs during use, return logistics and end-of-life activities can be determined (van Boeijen et al., 2014). In addition, the product journey can also be visualised over its lifecycle (including the use-life) where interactions with stakeholders, suppliers, network partners and consumers are visualized. By doing so, the service touchpoints can be matched to the involved partner. The product journey map hereby visualises the lifecycle and allows identification of necessary service activities (van Boeijen et al., 2014).

Similar to product journey mapping, the same can be done for materials. The purpose of material journey mapping is to explore implications of material choices at each phase of the product lifecycle (Circular Design Guide, n.d.). In a circular economy it is of importance that the impact of the chosen materials is considered across each lifecycle phase to ensure an ongoing cycle. In a material journey map all materials are considered. This includes raw materials, materials used during sourcing, production and treatment processes (coatings, finishes, bleaching agents etc.), to any materials needed during its use. The end-of-life phase is also included to map any materials needed to transform the material. By doing so, bottlenecks in material choices can be identified and addressed (Circular Design Guide, n.d.). Material journey mapping is however mainly a valuable method to visualize the material journey during the design phase. In addition to material journey mapping more quantitative methods such as MFA should be used to define the actual flow of materials and its implications.

To qualitatively view and score whether a product is indeed fulfilling its aim, the eco-design strategy wheel is a method to select and communicate strategies that minimalize the environmental impact of a product (van Boeijen et al., 2014). The method distinguishes between the conceptual level, product component level, product structure level and product system level. Most of these levels concern the product lifecycle but besides technical aspects the method also allows the ideation of new concepts where products are used more sustainably, such as through product sharing and strong product-user relationships. Complementary to the strategy wheel the eco-design checklist is often used to support the analysis of the product and enable identification of environmental conflicts within the product (van Boeijen et al., 2014). This method is however based on qualitative data and personal interpretations, and thus objective. Such methods are therefore mainly valuable in the early design phase but it is best accompanied by quantitative methods for verification of environmental impacts.

Methods addressing the physical architecture of a product thus take into account the technical design of a product to reduce the environmental impact and extend the product lifetime. As well as the 'journey' of a product during use to ensure a product is designed according to its envisioned lifecycle, including necessary service touchpoints.

4.4 Consumer engagement

Consumer engagement involves the shift from traditional consumption in a linear economy to sustainable consumer behaviour in a circular economy. This can be achieved through a variety of methods addressing the product, it's use and the business model by which it is put on the market. Sustainable consumer behaviour is key to circular economy in order to keep products in use for longer and close the loop at end-of-life.

4.4.1 Understanding behaviour change

Besides strategies focused at creating circular products, the use of the product is also an important element to consider for circularity to be achieved. In a circular economy the consumer is therefore an important part of the system (Wastling et al., 2018). Through the product and the business model the consumer's behaviour needs to be influenced in such a way that they perform the desired behaviour for a particular product and its intended lifecycle. Such as proper disposal, use of life extension services or communal care of shared products. This can be challenging, especially when the desired behaviour deviates from that of the established behaviour in a linear economy. There therefore exist several methods to influence consumer behaviour to that fitting a circular economy. Michie et al. (2011) identified nine types of interventions with the ability to influence consumer behaviour, summarized in the behaviour change wheel. These interventions can be applied for different ownership levels as well as to achieve a target behaviour during and after use. Interventions for products for which ownership is held by the consumer will be more product oriented. During use, interventions are best focussed at product attachment to prolong product lifetime and engagement in product life extension services. At end-of-use, interventions are best focussed on motivating reuse, correct disposal or participation in return logistics. While interventions for products for which ownership is retained by the producer will be more use-oriented. During use, interventions are best focussed on provision of information, product care, avoiding product misuse and engagement in life extension services. At end-of-use, interventions are best focused on contractual obligations for return of the product as well as motivating assistance in returning products to reduce operating costs (Wastling et al., 2018). The interventions are furthermore linked to policy categories and the source of the behaviour.

The behaviour change wheel identifies intervention functions and how behaviour can be influenced. Similarly, the SHIFT framework by White et al. (2019) explains how sustainable consumer behaviour can be motivated when the context leverages on the psychological factors: social influence, habit formation, individual self, feelings and cognition, and tangibility. The aim of both frameworks is to help understand behaviour change better, the context in which it occurs and how it can be influenced through the intended target of an intervention. These methods thus mainly focus on how consumer behaviour is influenced with regard to sustainability and is concerned with interventions external to the product itself. This is useful in addition to designing products that incorporate consumer behaviour into the actual product.

4.4.2. Designing for behaviour change

When behaviour is understood properly, other methods exist to design for behaviour change. Such as the EDD framework (Haines-Gadd et al., 2018), which identifies design factors that influence a consumer's tendency to use products longer. The aim of this framework is therefore to design for emotional durability, resulting in product longevity through behaviour interventions in the product. The framework exists of nine themes: relationships, narratives, identity, imagination, conversations, consciousness, integrity, materiality and evolvability (Haines-Gadd et al., 2018). In total the framework offers 38 strategies over all themes to create products with emotionally engaging product experiences. Then, when the product is designed, it's lifecycle can be mapped and the behaviour that occurs during each phase. One method to achieve this is customer journey mapping (van Boeijen et al., 2014). Similar to product and material journey mapping this method helps visualise the experience of the consumer with a product and supports identification of touchpoints where behaviour might be influenced through interventions, service or design. Combining both the customer journey as behaviour interventions, is the consumer intervention mapping tool developed by Sinclair et al. (2018). This tool visualises the lifecycle from development to disposal and combines this with intervention touchpoints at each level as well as how the intervention can be applied. These methods thus focus more on how a product is used and finding the right levers within the product itself or its use journey to achieve a target behaviour.

Methods to support sustainable consumer behaviour thus first involve the understanding of how behaviour change comes about and then focuses on how the technical design of a product or service can include behavioural nudges during use. As well as how the relationship with the consumer can be influenced through interventions already implemented in the business model.

4.5 Evaluation and assessment

Evaluation and assessment involve the quantitative or qualitative assessment of products and their environmental impact throughout the lifecycle.

4.5.1 Impact assessment

For the evaluation of products, a lot of environmental indicators are developed within industrial ecology literature to indicate and/or quantify environmental impacts. Environmental indicators can be used throughout the lifecycle of a product and help assess the environmental hotspots of a product. They furthermore support decision-making in the development process. Environmental indicators can address particular lifecycle phases and resource loops and can be qualitative as well as quantitative (Saidani et al., 2019; Helander et al., 2019).

Like the CE, these indicators can also be categorized at i.a. the micro- (products, materials and consumers), meso- (business, eco-industrial parks) and macro-level (city, region, country) (Kirchherr et al., 2017) (see table 10). At the micro-level indicators such as the Material Circularity Indicator developed by the Ellen MacArthur Foundation and Granta Design in 2015 can be used to identify additional circular value from materials. The Longevity Indicator by Franklin-Johnson et al. (2016) is used to assess the lifetime of mobile phones and the QWERTY/EE concept by Huisman (2003) can be used to quantify the recyclability and eco-efficiency for end-of-life treatment of consumer electronics. At the meso-level eco-efficiency and resource productivity can for example be assessed and at the macro-level methods such as LCA and MFA are often used. There are of course many more indicators available depending on the specific aim and industry. It should however be mentioned that no environmental indicator should be used as an absolute score. Environmental indicators serve as a method to assess environmental performance but require further investigation of specific hotspots and constrictions where improvements need to be made.

Table 9: Selection of environmental indicators

Lifecycle phase	Level	Indicator	Reference
Design and production	Meso	Value-based resource efficiency (VRE)	Di Maio et al. (2017)
	Micro	Product-level circularity (PLC)	Linder et al. (2017)
	Meso	Circularity index (CI)	Cullen (2017)
Use phase	Micro	Resource duration indicator (RDI)	Franklin-Johnson et al. (2016)
End-of-life	Micro	Circular economy performance indicator (CEPI)	Huysman et al. (2017)
	Meso	Recycling rate *(also determined by design)*	Haupt et al. (2017)
	Meso	Recyclability benefit rate (RBR)	Ardente and Mathieux (2014)
	Micro	Reuse potential (RP)	Park and Chertow (2014)
	Meso	Circular economy index (CEI)	Di Maio and Rem (2015)
Across lifecycle phases	Micro	Material circularity indicator (MCI)	Ellen MacArthur Foundation and Granta design (2015)
	Meso	Eco-costs value ratio (EVR)	Scheepens et al. (2016)
	Micro	Circularity potential indicator (CPI)	Saidana et al. (2017)
	Meso	EU resource efficiency scoreboard	European commission (2015)
	Meso	Zero waste index (ZWI)	Zaman and Lehmann (2013)
	Meso	MiPS analysis	Cahyandito (2009)
	Macro	Life cycle analysis (LCA)	Guinée (2001)
	Macro	Life cycle costing (LCC)	Moreau and Weidema (2015)
	Macro	Cost-benefit analysis (CBA)	Atkinson and Mourato (2008)
	Macro	Material Flow Analysis (MFA)	Brunner and Rechberger (2016)

4.5.2. Concept evaluation

Besides methods to assess the impact of products, there is also a range of methods to evaluate upon product concepts during the development phase. The main difference is that these methods should not be used to assess the environmental impact of products, materials or parts. Rather, they should be used to evaluate whether a design achieves its intended result. The disassembly map developed by De Fazio et al. (2020) for example is an intuitive method to identify whether a design has any features that hinder repair in a design for repair approach in the early design phase. Qualitative methods can also be used to help decide on an envisioned end-of-life process. Such as the recirculation strategy decision tree by Circit Nord (2023). This method asks questions about the product's materials and functionality and helps guide towards a suitable end-of-life option. Hereby providing a starting point for elements to consider in the product design to achieve the intended end-of-life or evaluate whether there are changes that can be made to achieve a more valuable end-of-life option.

The sustainable business model pilot canvas by Baldassare et al. (2020) can also be used to test whether a business model would work in practice in an intuitive manner. The aim of this method is to initiate brainstorming about alternative ways of capturing value and how this can be done over the lifecycle as well as to find out whether the idea can actually work in practice. It furthermore provides an opportunity to have stakeholders involved in a brainstorm setting and allows room for changes before actual implementation (Baldassare et al., 2020; Nussholz, 2018). Such methods thus also facilitate the involvement of value chain partners and stakeholders in the process. Once a final circular business model is decided upon, the circular rebound tool by Das et al. (2023) can be used to evaluate whether there are any potential environmental rebound effects of the business model. The tool provides an overview of circular strategies and their potential rebound effects as well as how these could be avoided. The business model idea is then mapped over the lifecycle and points of improvement are identified. During the design phase, the EDD framework mentioned earlier furthermore also functions as a method to evaluate whether a final design concept achieves its behavioral aim (Haines-Gadd et al., 2018). Similarly, the eco-design strategy wheel can also be used to evaluate upon new or existing products as well as to compare products in between (van Boeijen et al, 2014). The repairability index can also be used during the design phase and is an established scoring system for electrical and electronic equipment to evaluate upon the ease-of-repair of products to improve and facilitate 'design for repair' principles (Barros and Dimla, 2023).

Methods addressing the evaluation and assessment of products are thus mainly focussed at analysing and comparing the environmental impact of products throughout the lifecycle. This category however also includes methods to evaluate product ideas, concepts and/or products for redesign during the earlier stages of the development process. These methods are intended to more intuitively find whether a (design) solution achieves its circular purpose.

Table 10: Overview of CE methods

<table>
<tr><th>Aim</th><th>Focus →
↓ Target</th><th>Differentiation</th><th>Collaboration</th><th>Physical architecture</th><th>Consumer engagement</th><th>Evaluation and assessment</th></tr>
<tr><td>Smarter product and material use, and manufacturing</td><td>Refuse
Rethink
Reduce
Standardisation</td>
<td rowspan="3">Vision & Strategy
BECE framework

RESOLVE framework

Circularity deck

Key elements framework

Sustainable by design tool

Business model
Triple-layer business model canvas

Circular business model mapping tool

Circular economy trend cards

Circular economy business model pattern cards

Canvas Plus model</td>
<td rowspan="3">Extending responsibility
EPR

CSR

Finding the right people
Circular collaboration canvas

Co-creation and keystone activity scan

Keystone activity cycle

The boundary tool</td>
<td rowspan="3">Product design
Guidelines for DfX

Design for product integrity

Lifecycle design
Eco-design strategy wheel and checklist

Product journey mapping

Material journey mapping</td>
<td rowspan="3">Understanding behaviour change
SHIFT framework

Behavioural change wheel

Designing for behaviour change
Guidelines for DfX

Customer journey mapping

Emotional Durability Design framework (EDD)

Consumer intervention mapping</td>
<td rowspan="3">Impact assessment
LCA

MFA

LCC

CBA

EEIOA

Environmental indicators

Concept evaluation
Disassembly map

Recirculation strategy decision tree

CBM pilot canvas

EDD framework

Circular rebound tool

Eco-design strategy wheel and checklist

Repairability index</td></tr>
<tr><td>Extend lifetime of products and product parts</td><td>Reuse
Maintenance
Repair
Repurpose
Refurbish
Remanufacture
Part harvesting</td></tr>
<tr><td>Useful application of materials</td><td>Recycle</td></tr>
</table>

5. Findings: Within-case analysis

This chapter provides an analysis of the separate cases after which in the next chapter data is compared across cases. First, a short presentation of the company is provided, then the use of CE methods and reasoning for their use is discussed. The within-case analysis will thus show how each company implements and operates CE principles in their product and/or service offer through the use of CE methods. In chapter six the results of all cases are compared and the cases are differentiated. Together this provides the input for the development of the framework in chapter seven. See appendix E for examples of quotes from the interviews.

5.1. Case A: Electronic and electrical appliances

Company A is a global manufacturer of a wide range of electronics for both consumers, businesses, professionals in several industry sectors. Their priority business is however in the lifestyle product group. Considering the circular economy, company A has a group-wide sustainability initiative that is focused on 10+ priority issues to increase well-being for the consumer, society and the planet. Interviewee A is a sustainability manager and defines the product need and requirements for the European market.

Development process

When developing a new product, the product team existing of members from several departments analyses the product idea from a circular economy perspective to define circular needs and opportunities in a workshop setting. Together with recent laws and trends regarding the CE these are then translated into a programme of requirements for the product.

"So, based on the requirements it is decided that a product should be placed in a certain business model, and when we know that product will be returned to us then we want these two or four components to be easily accessible for reuse. Then you have a very clearly defined design brief based on the requirements for the engineering team".

Considering the use of CE methods, interviewee A was aware of several CE methods but they are not consciously applied in the development process. First of all, interviewee A felt that there was too much product variation in electronics in order to properly apply CE methods. Individual analysis of the product requirements is needed that cannot be achieved by 1-to-1 application of a method. Neither did interviewee A feel that CE methods has led to sufficient breakthroughs in the development process as many of the available methods overlap with previous work. Instead of CE methods, CE principles are therefore more often used at the development of more high-level sustainability guidelines. In the actual development process the company relies more on the expertise of the team members as well as in-house developed methods. The in-house methods are meant to facilitate product development within the group-wide guidelines. According to interviewee A, internal processes also further complicate the ability to apply external methods from literature.

"And considering a company, they all have their own design and development process and projects and templates. That is different for each company. And that is why you can't really just take a design strategy and apply it".

Regarding collaboration, company A has a wide value network with strong stakeholder involvement and social as well as environmental aims. They have also implemented a companywide green procurement protocol and only work with partners that fit their environmental compliance policy.

Insights for the development of the framework

Even though external knowledge and methods are used as inspiration in the development of in-house methods to keep up with CE trends. Overall, company A thus mainly relies on their own expertise to define the circular product 'needs' to which circular strategies are then matched to the product and decided upon by the team. Other CE methods are not consciously applied further in the development process. For the development of the framework, this means that the framework should not complicate development of internal methods, it should rather inspire to incorporate elements of CE methods. The framework should furthermore focus on methods that are generalizable across product groups.

5.2. Case B: Renewable energy

Company B is a Dutch start-up founded in 2021. They are a manufacturer in renewable energy products that are easy to install by the consumer themselves. Through making their product available to the consumer without needing technical support for installation company B's aim is to make sustainable energy accessible to all and increase household sustainability. Interviewee B is founder and managing director of the company and has a background in engineering.

Development process

During the development process company B had several conversations with experts and stakeholders, and prototyping sessions with potential consumers from which the learnings were translated into product requirements. Company B has not applied any particular methods to find or collaborate with partners and/or stakeholders. The main reason was because interviewee B felt that it was not necessarily difficult to identify the expertise they required, but rather that it was difficult to physically find partners with that particular expertise. Interviewee B felt that this is mainly based on a company's own network and their network's references, and that CE methods would therefore not support actual identification of partners. Company B has also collaborated with several potential consumers to test prototypes of the product. From these learnings the product was improved over several sessions. But no particular methods were used for consumer engagement or sustainable consumer behaviour.

"Yes, I do know them [methods] but not from [name company B]. I don't believe we really used those…there will probably be overlap but we did not consciously apply them."

Regarding the physical architecture of the product, company B partly outsourced the product design to a third party as they did not hold the expertise for sustainable product design inhouse. Hence, no CE methods were used that interviewee B was aware of. Instead, they mainly worked with product scenarios to iteratively generate different product concepts. Company B has however performed an LCA to evaluate the impact of their product but according to interviewee B *"it has not been in our DNA to keep performing those analyses and improving the product".* Because the company is still young, they are only just getting started on applying such methods. This was mainly due to budgetary constraints.

"Then we sat down with the design agency in several iterative sessions and we expanded the idea. They had a lot of expertise that we did not think of. And those sessions let to the final programme of requirements on the basis of which we started working."

Considering the use of CE methods, the programme of requirements was the 'read thread' throughout the process. Which was informed by collaboration with experts and consumers over several iterative sessions. The main reasoning for not applying CE methods was due to budgetary restraints for both applying the method as for executing the learnings from methods. Regarding the LCA for example, interviewee B knew prior to applying the method that the main impact would be in the materials but they currently do not have the budget to produce more locally and they struggle with the tension between sustainable materials and the required strength of the product.

Insights for the development of the framework

Interviewee B felt that a potential framework should support brainstorm sessions rather than guide them. As they would prefer to maintain a level of autonomy in applying the framework to their specific product development process. Interviewee B furthermore felt that such a framework should be easy to grasp and as straight forward as possible as not to be too time consuming in finding the right methods for the company. Interviewee B would also prefer a level of interaction with the framework to be able to store notes and thoughts.

5.3. Case C: Electrical appliances

Company C is a Dutch-founded manufacturer in electrical appliances and operates in over 100 countries. Company C furthermore has several subsidiary companies in other industries. The company has a group-wide sustainability strategy based on CSR principles that is implemented according to the triple-bottom-line throughout the company and their product offer. Interviewee C is the sustainability and innovation manager at the company in the Netherlands.

Development process

Company C mainly works in weekly to monthly brainstorm sessions with a team of people from several departments in which they evaluate upon the milestones for the specific phase of the process they are in. Company C works with an elaborate CSR strategy and five sustainable development goals on which they evaluate their progress per particular product. To guide this process, the company has internally developed a canvas tool covering their brand specific values, CSR strategy and the five SDGs to which they need to comply. The tool functions as a roadmap for the development process as well as for benchmarking products to previous products and their sustainability strategy. It furthermore facilitates communication between departments on shared sustainability milestones. Company C also collaborates with several partners, stakeholders and consumers during the development process. The firm has collaborated with several transport and packaging partners for example to improve the footprint of their products. All suppliers furthermore have to comply with a code of conduct of which compliance is ensured in randomised visits. They furthermore collaborate with their customers to improve the repairability of their product, research how they could motivate a return flow of products and also to ensure inclusivity of their product offer for people with disabilities. The company also has a repair service division that supports customers in extending the lifetime of their products.

"I think there is a lot in literature, but for the product group that we are responsible for, there a few elements that are very specific to those products. And then you have to be able to take something from the literature and be able to adjust it to the specifics of the company"

In addition to the internally developed canvas, the company also uses the R-strategies that are described in chapter two. As well as the triple-bottom-line, eco-design guidelines and the repairability index. According to company C their inhouse developed canvas tool provides sufficient space to apply external methods as well. Interviewee C was aware of several other methods but those were not applied, neither does interviewee C actively search for CE methods to apply in the development of products. Interviewee C furthermore felt that electronics are a difficult product to apply methods to due to the number of parts that they include. Interviewee C therefore felt that a lot of the methods they use will likely overlap with existing methods but they are not applied as such. Interviewee C also felt that methods need to reflect specific company elements that one-on-one application of generic methods does not allow. For example, instead of the disassembly map by de Fazio et al. (2021) the company had a graduation student develop a similar method specific to the company.

"I have been calculating the footprint of our organisation since 2018. Well, then you just know what the bottlenecks are"

Insights for the development of the framework

For a future framework, interviewee C would like to know what problem a method solves, the time consumption, what phase a method can be applied to in such a way that evaluation in an iterative process is still possible and the needed expertise that a method requires. In evaluating the iterations of the framework interviewee C found the framework to be very interesting but a process timeline or roadmap was missing on when to apply the methods as well as what methods can be combined.

5.4. Case D: Design agency

Company D is a worldwide design agency that consults in a variety of industry segments. Digital and strategic innovation in the pre-industrialization phase is their core business. They operate in over 40 countries and have between 700.000-800.000 employees. Company D designs a wide range of products for clients with a strong focus on sustainability and circularity. Interviewee D1 and D2 are both sustainability design engineers. It should be noted that company D is thus not an OEM but is hired on commission of OEMs and therefore strongly involved in their design process.

Development process

As company D develops products on commission by clients, they rely on the vision and strategy of the client regarding both the product as its sustainability and works towards complementing this. Company D therefore holds a broad internal expertise to support clients in all aspects of the circular economy. During the development process company D applies several CE methods. Both internally as externally developed. In selecting CE methods, the firm first looks to the scope of the assignment and where in the development process they are located. With a broad scope more high level and systemic methods are applied for exploration and with a narrow scope more specific methods are used for, for example, assessment. They hereby consider what CE methods they would benefit from at a certain phase of the development process. They then customize CE methods to the firm's needs at particular points in the development process. They hereby thus integrate internal and external knowledge of CE methods.

"So really the more complex the context, the less defined the tool. At this point it would just be about visualisation and the general design thinking principle. And the narrower we get to the definition of a product in a certain context, the best we will be able to define the tool we are using."

With this experience, company D has also internally developed a CE method that addresses the entire development process. The method integrates several CE methods that are 'customized' to company D's internal design process. Company D views this method as a "golden standard" and it is therefore the method that they apply to every design process. Dependent on the assignment they either go through the entire method or adjust it to the client.

"I don't think we come up with completely new tools, but maybe it's customizing them for our needs and also for the client need. I feel often times it's difficult to use methods and you can imagine if we are focusing on packaging compared to consumer electronics, then it is completely different. But even between the same category of products, if you're focusing on a very small product or a very deep product, then there might be some differences so often times I feel we cannot just use our off-the-shelf tools without some customization."

Insights for the framework

For a future framework or selection guide company D would like to know how complex a method is before they would be able to select it. In addition, they would also like to know the time it takes to execute it to inform on the costs the application of a method would inquire. They would also need to know where in the development process a method is supposed to be applied. In order to find new methods that would complement them in the particular phase of the development process for which they are consulting the framework. Furthermore, company C would like the overview to be visualised in such a way that it would inform them on what 'need' a method fulfils to inform on whether a method will serve the firm's specific purpose.

5.5. Case E: Lighting

Company E is a worldwide lighting manufacturer selling products in over 70 countries from their headquarters in The Netherlands. Their core business involves manufacturing of LED lighting, connected lighting and the provision of lighting services. They also produce lighting for IoT and provide products focused on energy efficiency. Their products are sold B2B as well as B2C. Interviewee E is an application scientist for human centric and circular lighting.

Development process

Company E has integrated a variety of CE methods, both externally as internally developed. Overarching to the sustainability strategy is their CSR policy and the R-strategies. From which over ten circular value spaces are developed to guide circular business model selection and product development. In addition, company E also has a specific sustainability checklist for product design to comply with the company's sustainability strategy and follows eco-design guidelines.

"A business model change is also required, so together with the client we look at the different frameworks for inspiration on the possible directions that we can go in."

Company E has also performed an LCA of their product offer and found that the use phase has the largest impact due to the energy use. Their sustainability strategy is therefore strongly oriented at increasing energy efficiency. In addition, they design products with a focus on repair, following 'right to repair' guidelines as well as design for upgrading, which is focused on allowing upgrades to increase energy efficiency without disposal of the entire product. They have furthermore invested in smart and connected lighting by using data to indicate the need for service. LCA has also shown the environmental hotspots and motivated more sustainable packaging design, cleaner production methods, green procurement guidelines and several internal as well as external scoring methods. Company E has also been running several pilots with clients and consumers to find what circular strategies are best fit for their product offer and in which areas to innovate, such as Light as a Service, refurbishment and remanufacturing.

"When I am making an improvement, how do I then quantify that a connection is more recyclable than the last? And which recycle method should I apply? Because when I talk to a recycler, they will show me all these fancy shredding methods and tell me that whatever product I provide them with, they will recycle it."

Regarding the methods that company E has developed internally, interviewee E felt that there is overlap between their approaches and the externally available methods. The main reason for developing methods inhouse was that the currently available CE methods are too high level and lack a certain actionability and (for some methods) quantifiability, that does not require expensive databases or high-level expertise. Interviewee E also felt that current methods are difficult to apply globally due to the differences in national laws and trends. Which complicates selection of the correct methods and circular strategies.

Insights for the framework

Company E's development process, or 'innovation to market' process is divided in several 'projects' such as exploration and advanced development For each project a different team is appointed that internally has a different process. Interviewee E therefore felt that the framework supports communication between the different teams and allows the process to go more efficiently. But it could be clearer as to what you deliver to the next team. Interviewee E therefore felt that the framework might be better suited for smaller companies.

5.6. Case F: Lighting

Company F is a manufacturing company in a specific range of lighting. They are based in the Netherlands and have about 50 employees. Their product portfolio is focused on achieving a Net-Zero impact, reducing energy use and finding more sustainable materials for manufacturing. Company F furthermore designs and produces products inhouse, that are primarily sold B2B. Interviewee F1 is the technical director of the company and interviewee F2 is both parttime mechanical engineer as parttime sustainability manager, both interviewees have been with the company for over fifteen years.

Development process

Company F is part of a wider business group and therefore follows the group's sustainability strategy, complemented with additional yearly sustainability goals developed by company F, which are quantified and evaluated upon after each financial year. They furthermore design and develop products inhouse for which they have also developed circular design goals. These design goals are based on the R-strategies that are executed through Design for X guidelines. In addition to the circular product design, company F also offers extended warrantees to lengthen the lifetime of their product.

"So together with the supplier we discussed that for the next delivery of parts they would also add two boxes without packaging. And like that we test it every time and when it gets here, we see that there is no damage and that is how we are reducing plastic use throughout our chain."

The company has been certified as Net-Zero (scope 1 and 2) since 2012 and mainly uses LCA as a method to compare product and material impacts. From these analyses several changes have been made. Together with suppliers they are reducing packaging in shipping and in collaboration with a material manufacturer as well as an injection moulding company a new material was developed out of waste products to reduce the carbon impact of the product. Company F also engages their clients in decision-making for sustainability to align expectations and requirements. Company F also has several partnerships for recycling. They pay a fee for proper disassembly of their product and separation in correct waste streams during recycling for both fixtures as batteries.

"It is difficult to choose a method. You see it as well with the R-strategies, which one fits your product and which one is dominant. What is also difficult is that you don't know what, for example, recycling will look like in 10 to 15 years because that is when we get our products back and we don't know what the chain will look like."

For the other impacts, company F struggles with several tensions. Mainly because their product lasts 10 to 15 years, making it difficult to forecast what the industry will look like as well as the fact that technology of their product will be too outdated by then for reuse. They furthermore struggle with the tension between the lower carbon impact of certain materials but the ethical implications that the mining of these 'more sustainable' materials imply. Different business models to place the product on the market furthermore does little for the main impact of energy use according to company F. These tensions make it difficult for company F to select the correct R-strategies from the start and the subsequent CE methods.

Insights for the framework

For a future framework company F mainly wanted to know how actionable a method was. Especially regarding time and costs management. In addition, company F would like to know how the methods interact with each other as well as across the different categories of the framework. Regarding the framework as a whole, company F mainly felt that the framework would be quite overwhelming to small firms and/or firms that are new to the circular economy as sustainability management is often a parttime job in addition to someone's core activities at the company. Attention should therefore be paid to structuring the framework and 'guiding' the user through the framework.

6. Findings: Cross-case analysis

The within-case analysis in chapter five described if and how each case company implements CE methods. The within-case analysis furthermore showed what each case company would require from a future framework of CE methods. The cross-case analysis can therefore be divided in two parts. First, a cross-case analysis is performed in which cases are compared on their similarities and differences regarding their use of CE methods. The cases are compared as shown in table 12. Then, those patterns are analysed to find the reasoning behind the use of methods by the case companies. The chapter will hereby present the requirements which the future framework will need to meet as well as other considerations that came forward from the input sessions during the interviews. The findings from the input sessions during the interviews are hereby combined with the findings from the cross-case analysis.

6.1. Dimensions for analysis

Based on the cross-case analysis, the cases can be differentiated on three dimensions: integration of CE methods, collaboration for a circular value network and lifecycle management. Through comparison on these three dimensions logical groupings are identified. These dimensions are meaningful for the development of the framework because they will reveal the generic and specific elements of the cases to account for. This will inform on the development of the requirements for the framework.

6.1.1. Integration of CE methods

All case companies showed a certain reliance on internal and external expertise in the use of CE methods. This dimension therefore differentiates companies that integrate existing CE principles and methods through customization to their individual development process. Companies that can be differentiated on this dimension either rely more on internal expertise or are aware of CE methods and apply these throughout the development process. Firms that score high on this dimension integrate existing CE principles in the companywide sustainability strategy and execute this through integration of CE methods. Thus, integrating internal expertise as well as adapting external knowledge to their specific context.

6.1.2. Collaboration for a circular value network

When comparing the cases, it was found that none of the companies used specific methods for collaboration. But collaboration was an apparent aspect of all company's their sustainability strategy. The case companies therefore also differentiate on their level of collaboration for a circular value network. Collaboration can either be more central to the company or more broad where all activities of the company are considered and accounted for through partnerships with suppliers, clients, consumers and external parties for joint development.

6.1.3. Lifecycle management

The case companies also differ on the integration of CE methods over the lifecycle. Regarding the use of CE methods this entails the breadth to which methods are implemented throughout the value chain. Compared to the first dimension, this dimension focuses more on whether methods are integrated over the value chain and lifecycle of the product to ensure circularity rather than *how* CE methods are integrated in the company. CSR and EPR efforts are also considered in this dimension. Companies that can be differentiated on this dimension tend to have a clear image of the main impacts of their products throughout the value chain and address these through CE methods. Besides direct impacts these companies also consider indirect impacts from their product and take actions to address these.

Table 11: Matrix of all cases

	Integration of methods	Collaboration within value network	Lifecycle management
A	HIGH: High integration of CE principles in CE strategy throughout group but strong reliance on internal expertise	HIGH: High level of collaboration throughout value chain as well as with external parties	HIGH: CE principles and methods implemented throughout product lifecycle, value- and supply chain for full circularity
B	LOW: Integration of CE principles in CE strategy but strong reliance on internal expertise	HIGH: Strong collaboration with consumers and suppliers central to the company	LOW: Disperse implementation of CE principles and methods
C	HIGH: Integration of CE principles in sustainability strategy and acknowledgement of overlap external and internally developed methods	HIGH: High level of collaboration throughout value chain as well as with external parties	HIGH: CE principles and methods implemented throughout product lifecycle, value- and supply chain for full circularity
D	HIGH: Integration and customization of CE principles and methods throughout development process	HIGH: Company D is a design agency and therefore reliant on the client's value network. However, they are strongly involved in consumer engagement and motivate collaboration by the client	HIGH: CE principles and methods implemented throughout product lifecycle, value- and supply chain for full circularity
E	HIGH: Integration and customization of CE principles and methods throughout development process	HIGH: High level of collaboration throughout value chain as well as with external parties	HIGH: CE principles and methods implemented throughout product lifecycle, value- and supply chain for full circularity
F	LOW: Integration of CE principles in sustainability strategy and acknowledgement of overlap external and internally developed methods	HIGH: Strong collaboration with consumers and suppliers central to the company	LOW: Disperse implementation of CE principles and methods

6.2. Comparison of cases

The matrix shows several similarities and differences between the cases through combining the three dimensions in regard to a 'high' or 'low' score. Resulting in eight possible combinations as visualised in table 13. When evaluating the combinations on their plausibility, four combinations are however considered unlikely. First of all, the three combinations with a low score on collaboration for a circular value network are eliminated. It is unlikely that a combination exists where there is a high level of integration of CE methods and/or lifecycle management without some form of collaboration in the value network. Either because collaboration is needed for a circular lifecycle, as indicated with a high score on lifecycle management. Or because collaboration is needed for, for example, joint development, as indicated with a high score on integration of CE methods. The combination 'low-high-high' is also eliminated as it is unlikely that a company with a strong value network and circular product lifecycle does not integrate CE principles and methods to some degree. The final categorization thus exists of four groups, as visualised in table 14.

Table 12: Possible combinations of scoring on dimensions for analysis (H=high, L=low)

Dimension	Scoring							
Integration	**H**	**H**	**L**	**L**	L	H	H	L
Collaboration	**H**	**H**	**H**	**L**	H	L	L	L
Lifecycle mgmt.	**H**	**L**	**L**	**L**	H	H	L	H

Table 13: Final groups of CE method use

BALANCED Integrated use and broad application of CE methods within a strong value network H-H-H A, C, D, E	CONFINED Integration of CE methods but applied centralized to the company H-H-L
LINEAR No participation in circular activities yet L-L-L	INTERNALIZED Little integration of CE methods applied only to area of expertise L-H-L B, F

Balanced use of methods: company A, C, D & E

The group 'balanced' is defined by companies that have a circular company vision and strategy and have implemented CE methods in their products and services. They are actively involved in collaborative activities for joint development, contributing to a strong value network. In addition, they also apply CE methods over the lifecycle of their product to ensure circularity. Overall, companies fitting this group have successfully integrated CE principles in their product offer as well as their daily operations in the transition to a circular economy.

The case companies fitting the balanced group are company A, C, D and E. Starting with company A, as a producing company, company A is the largest and most globally oriented of the sample. Over the years the company has developed into a highly autonomous company, including their own recycling scheme in their home country. Many activities are therefore organized internally. Considering their integration of internal and external expertise, the company therefore relies strongly on the internal expertise of the company to develop CE methods and hereby mainly uses CE trends and CE principles for high-level sustainability guidelines. But considering the implementation of CE principles and how the company's internal methods overlap with existing methods, company A is highly integrated. Regardless of the more autonomous structure of the company, company A collaborates with suppliers and third parties where possible. Not only for CSR activities but also for a strong value network. Overall, company A has been able to integrate CE principles and methods very broadly, addressing circularity throughout the product lifecycle and value chain.

Company C and E, both show a high level of integration of CE methods, as well as a high level of collaboration throughout the value chain and a broad implementation of CE methods to ensure circularity. These two companies are large companies as well and both actively look for new CE methods that could be relevant to the company. They have integrated circularity throughout the company and their value network. They do however both share the feeling that it is difficult to integrate existing CE methods into internal processes of the company. Both companies have therefore not only adapted existing methods to their context but have also developed methods internally, hereby both stating that these are strongly based on existing CE methods.

Even though company D is a design agency and not a producing company, company D does show a high level of integration and a broad implementation of CE methods to ensure circularity. Company D however does not have the same opportunity to collaborate in a value network as they design products for clients. They do however have a strong focus on user research and consumer engagement to ensure sustainable consumer behaviour. The company also advices on collaboration opportunities and motivates a circular value network. When taking the nature of the company in consideration, company D therefore best suits the balanced group.

For the framework this means that in order to enable a balanced type of company it needs to show where additional circular value can be achieved through CE methods without having to follow a step-by-step approach through the entire framework.

Internalized use of methods: company B & F

The group 'internalized' is defined by companies that are aware of CE principles but that do not have a clear circular vision and/or strategy and neither do they actively integrate CE methods in their product development process. The circular activities these companies do participate in are centralized to the company's area of expertise. As apparent in their strong level of collaboration with direct suppliers and customers. Overall, companies in this group therefore fail to capture circularity throughout the product lifecycle. Internalized companies are thus in the beginning of the transition to the circular economy. But activities need to be aligned and integrated further to create circular value.

From table 12 it is visible that company B and F both have a low level of integration of CE methods and maintain their circularity efforts more central to the company. They do however both show close collaboration with clients and suppliers to align sustainability requirements between the parties. The main explanation for this type of use of CE methods lies in the fact that both firms are SMEs and do not have a fulltime employee on the topic of circularity. They furthermore have a more limited (time) budget for both performing CE methods as for executing the findings of these methods. According to company B, they know where the main impact of their product lies but they do not have the resources yet to address this properly. Company F has the same experience. They too are aware of the main impact of their product but feel there exists a tension between the actions they are able to take and the limited impact these actions will have on the main impact of energy use during the use period. Their main reasoning for not applying CE methods is therefore time and budgetary constraints as well as the feeling that electronics are too complex to properly apply CE methods to every aspect of the product.

For the framework this means that in order to serve an internalized type of company it needs to provide a more structured approach to the selection of CE methods to create a clear circular vision and strategy and to select the appropriate CE methods within the constraints of the company. As well as to move circular activities from central the company to the value network.

Linear and confined

Two more combinations of a ‘low’ or ‘high’ score are identified. Namely, linear and confined. These groups were not identified through the cases but likely do exist and are therefore relevant background information for the development of the framework. The first, a linear use of CE methods, is defined by companies that are not (yet) involved in circular economy activities and score low on all three dimensions. This group is therefore best enabled by a framework that provides a step-by-step guide in the selection process of CE methods. The second group, a confined use of CE methods, is defined by companies with a clear circular vison and strategy and strong collaboration with direct partners. Confined companies are therefore very capable of creating circular value in autonomous production processes but hereby fail to expend their activities to the entire value chain in order to create circular product lifecycles. For this group the framework should provide guidance in extending circular activities to the value network.

The case comparison shows in what manner firms are using CE methods. Considering all companies, it is visible that the companies with a higher level of integration of CE methods and collaboration, and a broad scope also were more circular. Considering table 14, four groups can be defined of which two were identified in the research. These groups are relevant to the framework because they show how firms differ in applying CE methods and hereby inform on the needs that one group might have but the others do not, and how this distinction can be made in the framework. The following requirement therefore follows from the groups:

1. The framework, desirably, enables all four groups on how companies use CE methods
    a. By providing a variety of CE methods ranging from introductory to advanced methods
    b. By providing a navigational tool that can be used step-by-step as independently

6.3. Use of CE methods

in order to formulate a set of requirements for the framework it is necessary to not only look at logical groupings but also to dive deeper into the data and find why firms select and use methods the way they do. So, when considering the reasoning behind the use of methods of all companies the following patterns across all companies can be found. First of all, in regard to selecting CE methods, only company D and E actively searched for CE methods to apply to their development process. All other companies felt that CE methods did not provide sufficient ‘breakthroughs’, are too time consuming or did not feel they required the use of CE methods for guidance in developing a sustainable product.

In regard to the use of CE methods, all companies had a strong feeling that it is difficult to apply external methods within internal processes of the company. This includes the brand values, certain framing of processes as well as the structure of the company regarding the division of teams and departments that interact with each other, and the available CE methods. This was given as the main reason for not applying CE methods as well as for not actively searching for CE methods. A second reason for not being able to apply CE methods is that all companies felt that electronics are too complex to apply CE methods properly, or to the full product. According to the case companies applying CE methods to each part and material is too time consuming and that the methods therefore did not fit with the nature of the product.

As a solution, all case companies also developed methods inhouse. Most companies indicated to have incorporated the R-strategies in their sustainability policy. From which sustainability guidelines were drafted per relevant R-strategy as well as overarching more high-level methods. All companies hereby mentioned to be aware of several CE methods but that these were not directly applied or actively incorporated in the internally developed methods. All companies did however acknowledge there is a high likeability of overlap between the internally developed methods and the externally available CE methods and that the underlying principle of these methods are often used as inspiration. Instead, four out of six companies indicated to be more focused on circularity trends as well as environmental legislation within their industry to develop guidelines from, that are then incorporated into the sustainability strategy. Company C and D also indicated that they had developed an overarching method to guide the development process fitting their company. Company C developed a canvas tool that includes the company’s sustainability goals and milestones. Company D indicated to have developed a process-oriented tool as well but company D did actively incorporate existing CE methods.

The space between firms not actively searching for CE methods and the pattern of case companies incorporating elements of CE methods to adapt to internal processes hereby provides the design space for the development of the framework. It should however be noted, that a good method is meant to be adaptable to a company’s particular context. A method is impracticable if it cannot be customized to a particular context. The fact that all companies therefore adapt CE methods and/or incorporate elements of CE methods is as intended. Nonetheless, for the development of a framework this is relevant information. This finding shows that a future framework should not just provide an overview of relevant CE methods but it should inspire the integration of the underlying principle of a CE method. For example, some of the case companies did not perform an LCA using lifecycle analysis software or the known structure of an LCA, but they did have a very extensive calculation of a product’s footprint throughout the lifecycle in Excel. Even though this might not be recognised as a “CE method” it is still a “method” that incorporates the principle of LCA. As a future framework cannot change the nature of CE methods and the ease of implementation or adaptability for an organization, the framework should thus support the current approach by companies of integrating the underlying principle of a CE method rather than 1-1 application. The following requirements are therefore identified:

2. The framework should provide a comprehensive overview of CE methods over the product development process
3. The framework should allow and inspire adaptation of CE methods to the context of the user
    a. By providing information on the separate CE methods that considers that a method might meet more than one circular need depending on a company’s purpose

6.4. Insights from the individual input sessions

During the company interviews, input sessions were conducted for the development of the framework. During these input sessions all companies indicated they desired a process overview of all the CE methods in the framework to showcase at what moment in the development process a CE method is best used. All companies furthermore indicated that the framework should not be too overwhelming at once as this does not motivate the use of the framework. In addition, some companies would also like to know how complex a CE method is with regard to time and budgetary constraints. Two companies also indicated they would like to know how CE methods can be combined and one company would like a future framework to support communication between teams and department. How CE methods can be combined and how a future framework could support communication are important insights to note but are not considered in this research as these are out of scope. Instead, these are considered as future research opportunities and elaborated upon in chapter eleven. The following requirements are therefore used in the development of the framework:

4. The framework should provide a process overview of CE methods per phase of the development process
5. The framework should be structured in such a way that it gradually provides information as not to be too overwhelming at once
    a. By providing visual guidance through the different CE methods
    b. The framework should be structured in a visually appealing way to motivate its use
6. The framework should indicate the complexity of the separate CE methods

6.5. Requirements for the framework

To develop the framework several requirements and considerations are thus used as input. These are drawn from the cross-case analysis as well as from the feedback during the input sessions of the separate interviews. The framework should be able to fulfil the requirements based on the cross-case analysis while the considerations extracted from the separate interviews are used as input for the framework.

Requirements from the cross-case analysis:

1. The framework should provide a comprehensive overview of CE methods over the product development process
2. The framework should allow and inspire adaptation of CE methods to the context of the user
    a. By providing information on the separate CE methods that considers that a method might meet more than one circular need depending on a company's purpose
3. The framework, desirably, enables all four groups on how companies use CE methods
    a. By providing a variety of CE methods ranging from introductory to advanced methods
    b. By providing a navigational tool that can be used step-by-step as independently

Insights based on the input sessions during the interviews:

4. The framework should provide a process overview of CE methods per phase of the development process
5. The framework should be structured in such a way that it gradually provides information as not to be too overwhelming at once
    a. By providing visual guidance through the different CE methods
    b. The framework should be structured in a visually appealing way to motivate its use
6. The framework should indicate the complexity of the separate CE methods

The compliment of the requirements and considerations in the final framework is evaluated upon in the discussion in chapter nine.

7. Development of the framework

As explained in the research method chapter, the development of the framework is parallel to the interviews. This chapter discusses the different elements of the method that are developed before presenting the final method in chapter eight. Section 7.1. will discuss the framework as a method and section 7.2. will discuss how the framework can be used by companies.

7.1. The Circular Economy Method Compass

The framework developed in this thesis, the Circular Economy Method Compass, is to be a holistic approach to navigating circular economy methods that offers original equipment manufacturers (OEMs) in the electronics industry guidance in the transition to the circular economy and the development process of circular products and services. The framework is to provide a navigation tool in the selection process of circular economy methods. To achieve this the following choices are made in the development of the CE Method Compass.

To organize the identified CE methods in the CE Method Compass, the categories and subcategories of methods from table 11 are used. The framework thus exists out of a total of ten types of CE methods. As the CE Method Compass should not be too overwhelming at once, the user is to be gradually guided through the identified CE methods. To do so, the CE Method Compass is built up of four elements. A general overview of the CE Method Compass, an overview of CE methods per category based on table 11, information cards with additional information on each CE method in the compass and a process overview of all identified CE methods over a standard development process.

As mentioned, the CE Method Compass is developed for business practice, it therefore also includes a personalized project overview of CE methods and a matching personalized process overview. As expanded upon in section 7.2. This section will also shortly discuss how the CE Method Compass is best communicated to the end-user. In total, the CE Method Compass forms a selection guide for companies to choose CE methods over several categories, shape their personal CE method project and be informed on the timing of the use of the particular methods in the development process. See appendix G for all visualisations of the framework.

7.1.1. The CE Method Compass overview

To present the general overview of the compass the five categories of methods and their definition are combined. In addition, the compass also provides an overview of the R-strategies. Each case company indicated to be familiar with these and all companies applied them in the development of their sustainability strategy. Adding the R-strategies to the framework therefore provides a mnemonic and facilitates firms in deciding whether a certain method will fulfil their circular need. In order to incorporate the R-strategies into the framework they are used as the inner circle and 'base' of the framework (see figure 3). The R-strategies are categorized according to the circular goals used in table 1 in chapter two. Namely, smart product and material use, extend lifetime of products and parts, and useful application of materials.

Figure 2: General overview CE Method Compass

The CE Method Compass is read in an 'outside-in' manner, meaning that the framework starts with the most high-level CE methods in the category 'differentiation' and with every category the methods become more product-specific. When the five categories are combined, they have the opportunity to enable the R-strategies. The general overview of the compass therefore presents all five CE method categories and the R-strategies to illustrate the need to combine CE methods from each category to create circularity.

7.1.2. CE method overview per category

Per category the figure is divided in two parts to present the methods per subcategory (see figure 4). To illustrate that each method is of equal importance a circular visualisation was chosen in which equal cuts are possible. The circular visualisation furthermore allows space for adding new CE methods overtime as well as removing or replacing methods to stay up to date with the industry and literature.

Figure 3: CE method overview per category

Within the compass the aim of each method is described to inform the user on what purpose a method fulfils. Hereby supporting the requirement that the framework should allow and inspire adaption of CE methods. By providing the aim of a CE method, rather than the input and output for direct application, this allows for a more holistic approach to the separate CE methods and integration of the underlying principle of a method in existing internal approaches. In addition, the compass also presents the 'type' of method. A method can for example be a 'brainstorm tool' that facilitates and/or supports brainstorm sessions on a particular topic or a 'process tool' that guides the user step-by-step through a certain process such as vision building.

The overview of CE methods per category serve to gain familiarity with different CE methods and evaluate whether additional circular value can be achieved through the use of one or more of the presented CE methods. For a table overview and visualisation of the information on the separate CE methods discussed in the CE Method Compass see appendix F.

7.1.3. Information cards

For each CE method an information card is developed with a further description of the CE method, the needed expertise to apply the particular CE method, the development phase it is best used in, the R-strategies it enables and the original source of the CE method (see figure 5).

The information cards serve to gradually provide further information on the CE methods of interest to avoid the framework being too overwhelming at once. Hereby summarizing the primary information that is needed, based on the interviews, to be able to select a CE method. The information cards thus provide navigational support in the decision-making process for selecting CE methods that fit a particular company and their particular circular need.

Based on the input sessions during the interviews the following extra information is chosen:

- Further description of the method
- Phase of the development process
    - Based on the double diamond model by the British Design Council (n.d.).
- Complexity of the method
    - The complexity of a method is defined by a low, moderate or high level of required expertise within the field that the method is applied to as well as a time indication. Expertise as well as time is herein however subjective and only serves as an indication. Further research is needed to define the complexity of each method further as discussed in chapter eleven.
- R-strategies that the method enables
- Source

Together the CE method overview and the cards inform the user on the different CE methods that are available and supports selection of CE methods.

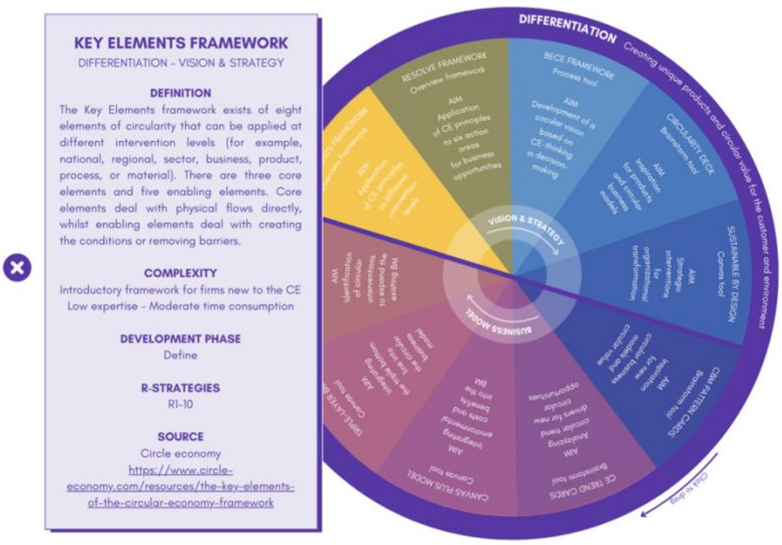


Figure 4: CE method overview and information card

7.1.4. Process overview

As several interviewees indicated they would prefer a process overview of the different methods this is also added to the framework. In this research it is however not possible to make academically correct and accurate connections between the methods. Neither is it possible to state whether methods are complementary. Therefore, the process overview is divided in the four phases of the double diamond method describing a general product development process (see figure 6) (Britsh Design Council, n.d.). Namely:

1. Discover: understanding the problem
2. Define: defining the challenge
3. Develop: answering a defined problem
4. Deliver: small-scale testing of different solutions

The double diamond method was known and preferred by most case companies and therefore selected. The different methods are then mapped according to the phase the author of the method recommends it to be used (see figure 7). When information on this topic is missing an educated guess is made by comparing the method in question to similar methods.

The individual methods are mapped on the four phases as described above. The figure can be followed in clockwise direction to cover the full development process. The colour of the individual methods hereby corresponds with the category the specific methods belong to. Central to the process overview is the general overview of the CE Method Compass to better connect the individual methods to their categories as well as to evaluate whether the methods a company has chosen indeed enable the R-strategies.

Figure 5: Double diamond method

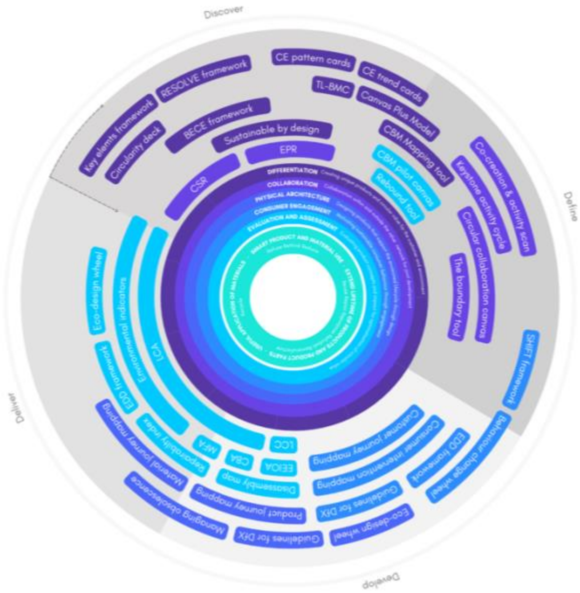


Figure 6: Process overview CE Method Compass

7.1.5. Accounting for the different groups of CE method use

From the cross-case analysis four distinctive groups were found on how companies use CE methods. The CE Method Compass should therefore account for these groups. In line with the requirement regarding the groups set in chapter six this is addressed through two elements.

First of all, through the selection of CE methods that are included in the CE Method Compass. To account for both companies new as more experienced in the CE, the CE Method Compass includes both introductory CE methods suitable to companies new to the CE, such as the linear and internalized group. As CE methods for which a company must hold more expertise, such as the balanced and confined group. The CE Method Compass therefore provides exploratory methods in each category of CE methods and specifying these as you move through each separate category of CE methods in the compass. For example, the differentiation category is divided in vision and strategy building which start with the key elements and resolve framework to gain familiarity with the circular economy, and it ends with implementing a circular business model. The CE Method Compass thus contains CE Methods that are suitable for each expertise level of the balanced, confined, linear and internalized groups.

Secondly, the CE Method Compass accounts for the different groups of method use through the way with which it is read. As mentioned, the CE Method Compass provides exploratory methods and these specify as you move through each separate category of CE methods in a clockwise direction. Internalized and linear companies can thus pursue all CE methods in a clockwise manner throughout the framework to go through a circular product development process. For these groups the CE Method Compass provides a step-by-step guide. While balanced and confined companies can choose a different starting point and evaluate per category of CE methods which of those methods suits their circular needs. They can thus choose to only implement the more advanced CE methods and thus use the CE Method Compass more independently.

7.2. Using the framework

7.2.1. Project overview when using the framework

As the CE Method Compass is developed for business practice, it's use in practice is also considered. For companies using the CE Method Compass it is of importance that a company is able to not only explore the available CE methods but also to select them. When using the framework, a company can therefore add methods to a project overview of the selected methods. This project overview is also translated to the process overview, highlighting the chosen methods over the development process. Hereby also facilitating the requirement that the framework should not be too overwhelming as it only shows the CE methods a company is interested in.

As visible in figure five, it is possible to 'add' methods through the information cards that a firm wishes to integrate in their development process to a project overview. When all five categories are placed on top of each other the selected methods are highlighted per category, as visualised in figure 8 for a non-existent illustrative example. This not only provides a narrowed down overview of CE methods but also illustrates whether a firm's choices might be concentrated in a certain category or whether a particular category is ignored. As mentioned, the project overview is further translated in the process overview by filtering out the CE methods a firm is not interested in and providing a tailored process for the firm, as also visualised in figure 8 for the illustrative example.

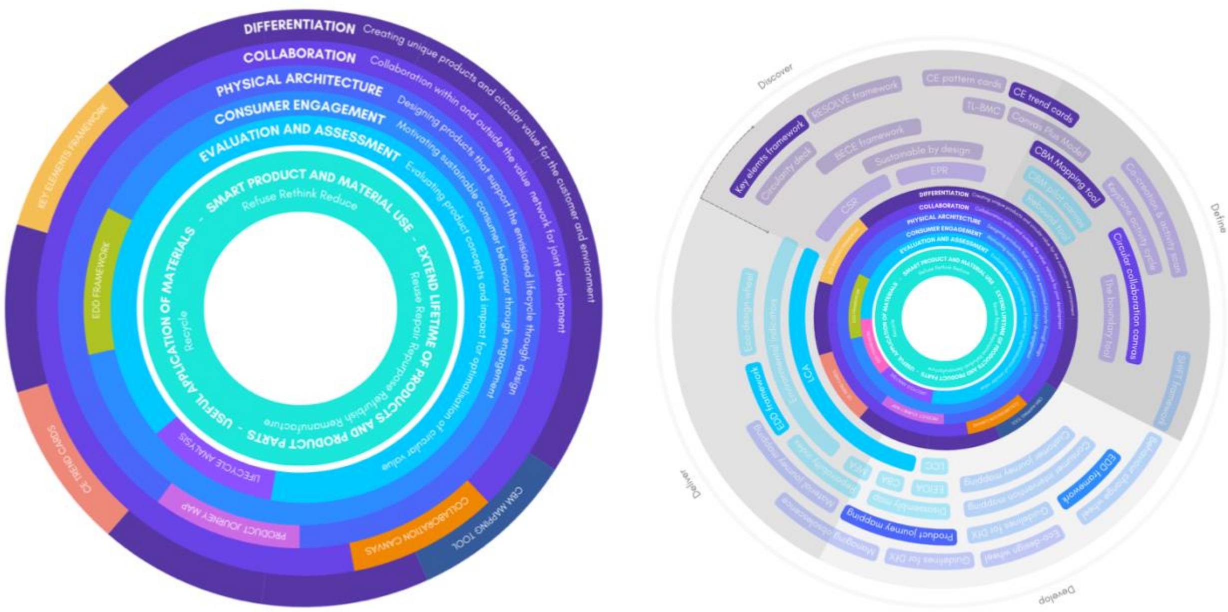


Figure 7: Project overview CE Method Compass

7.2.2. Communication of the framework

To access the framework by companies, it is best spread online. Because the framework has an interactive element to it through the ability to physically select methods and organize them in a project overview, a printable version of the framework is not possible. An online version of the framework furthermore allows easy changes in choices during the selection process. A website is therefore easy to access and through, for example, the creation of an account a company's choices can be saved and shared, allowing for easy communication. A web version of the framework furthermore allows the circular visual to be turned 360 degrees so the text does not have to be read upside down. Appendix H shows a possible visualisation of such a website as well as a link to a mock-up of the website.

8. Presentation of the framework

This chapter will present the final Circular Economy Method Compass. First, the CE Method Compass is presented. After which the CE Method Compass is applied to one of the case companies to serve as an example of how the CE Method Compass can be used in practice. For all visualisations of the framework see appendix G.

CIRCULAR ECONOMY METHOD COMPASS

A roadmap to circular economy methods

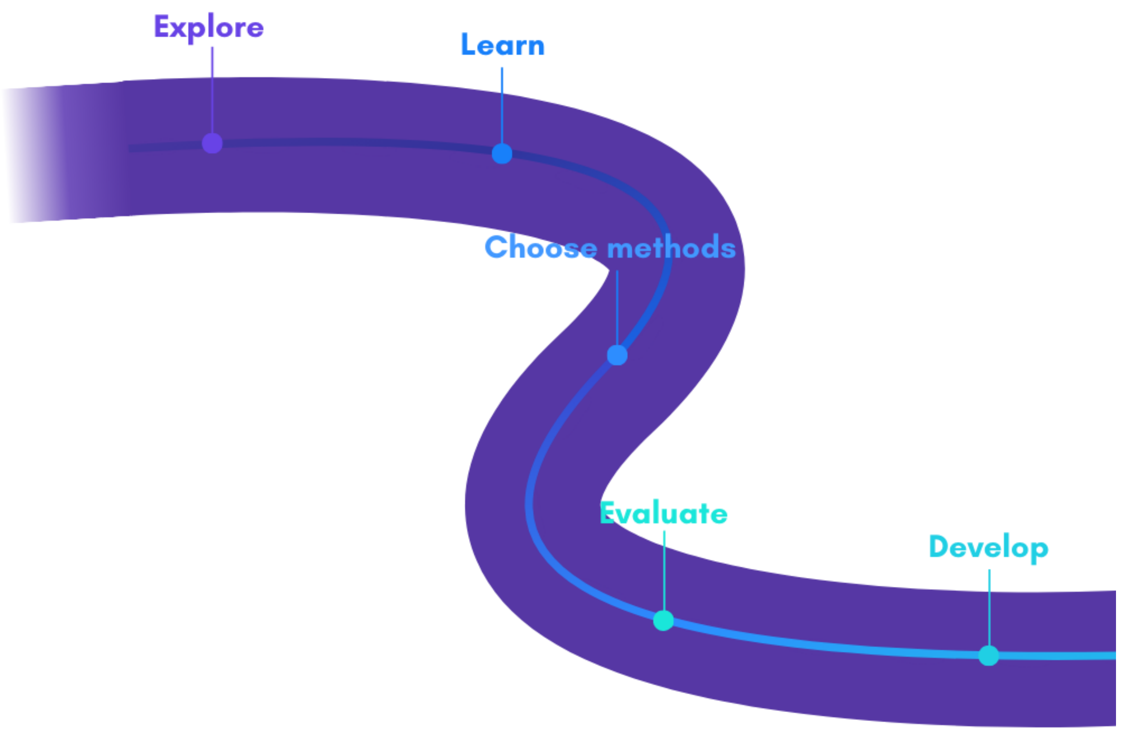
8. THE CIRCULAR ECONOMY METHOD COMPASS

The Circular Economy Method Compass is a holistic approach to navigating circular economy methods that offers original equipment manufacturers (OEMs) in the electronics industry guidance in the transition to the circular economy and the development process of circular products and services. The CE Method Compass hereby provides a navigation tool in the selection process of circular economy methods.

The CE Method Compass summarizes a comprehensive overview of available circular economy methods over five categories: differentiation, collaboration, physical architecture, consumer engagement and evaluation and assessment. The categories hereby cover the development process from the development of a circular economy vision to the final assessment of a product or service. The five categories together have the opportunity to enable the R-strategies, creating circularity. The CE Method Compass therefore exists of a general overview of all five categories and the R-strategies that illustrates the need to combine all categories to create circularity.

Per category the CE Method Compass provides an overview of the available circular economy methods and their aim. Per category of CE methods, methods can be selected and combined that are viewed as relevant to the company. After selecting circular economy methods in each category, it is possible to view a personalized development process of the selected methods in the recommended order of use, based on the double diamond method by the British Design Council (n.d.). A company is then ready to start their circular development process.

The CE Method Compass can be used by both companies that wish to enhance their circular economy strategy as by companies new to the circular economy. For companies that wish to enhance their circular economy strategy the CE Method Compass can be used to evaluate per category whether additional circular economy methods can be implemented to complement the existing strategy. For companies new to the circular economy the CE Method Compass can also be used as a step-by-step guide. By going through the circular economy methods in each category in clockwise direction a complete guide to circular product and service development is followed. Ensuring circularity is captured in both the company vision as the product.



5 CATEGORIES

The CE Method Compass identifies five categories. The categories function to categorize the different CE methods over the development process. Starting with high-level methods for vision building and moving towards product assessment methods.

Differentiation

Creating unique products and circular value for the consumer and the environment

Collaboration

Collaboration within and outside the value network for joint development

Physical architecture

Designing products that support the envisioned lifecycle through design

Consumer engagement

Motivating sustainable consumer behaviour through engagement

Evaluation and assessment

Evaluating product concepts and impact for optimization and circular value creation

10R-STRATEGIES

As each company indicated to be familiar with the 10R-strategies these are added as the central point of the Compass. The 10R-strategies are divided in three goals: smart product and material use, extending lifetime of products and parts, and useful application of materials. The five categories combined have the potential to enable the 10R-strategies.

Smart product and material use

Refuse - Rethink - Reduce

These R-strategies are focused on re-evaluating product and material choices for smarter application of resources

Extend lifetime of products and parts

Reuse - Repair - Repurpose - Remanufacture - Refurbish

These R-strategies are focused on avoiding obsolescence and creating products that last

Useful application of materials

Recycle

This R-strategy is focused on retrieving value from discarded products for new resources

8.2. THE COMPASS

The compass overview summarizes the five categories of CE methods and the 10R-strategies they together enable. The compass is read outside-in, starting with high-level CE methods at differentiation and moving towards more product specific CE methods at evaluation and assessment. In selecting CE methods it is therefore of importance to select a variety of methods from each category in order to create a balanced selection. A balanced selection of CE methods will ensure that the product and/or service will circulate as long as possible. After selecting methods the chosen methods should be evaluated on whether the envisioned R-strategies are met through the selected CE methods.

After selecting CE methods it is possible to view a personalized overview of the selected methods in as a personal CE method project.

8.3. DIFFERENTIATION

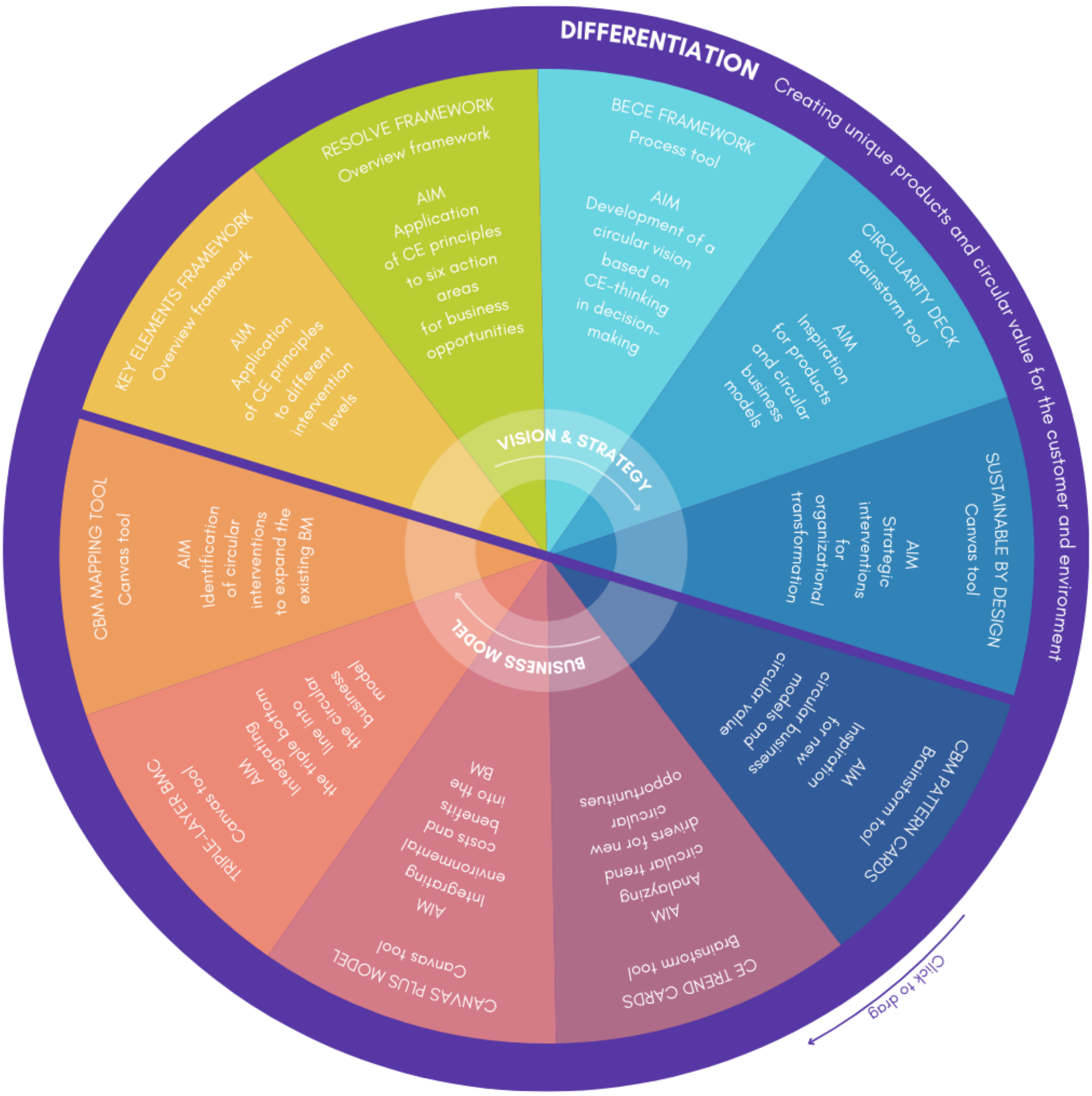
Differentiation involves the offering of a product, service or experience to the consumer that is unique and that competitors don't have, or that significantly lower their costs. A successful differentiation strategy creates a competitive advantage and improves business performance.

VISION AND STRATEGY

In order to develop circular products a company needs a circular vision and a strategic aim of their product. Therefore, several CE methods can be used to motivate CE thinking and help develop a more holistic view of the circular economy in organizations.

BUSINESS MODEL

A circular business model is a business model in which value creation is based on keeping economic value retained in products after use, and utilize that in the production of new offerings. CE methods can be used to develop and implement such a business model in an organization.



8.4. COLLABORATION

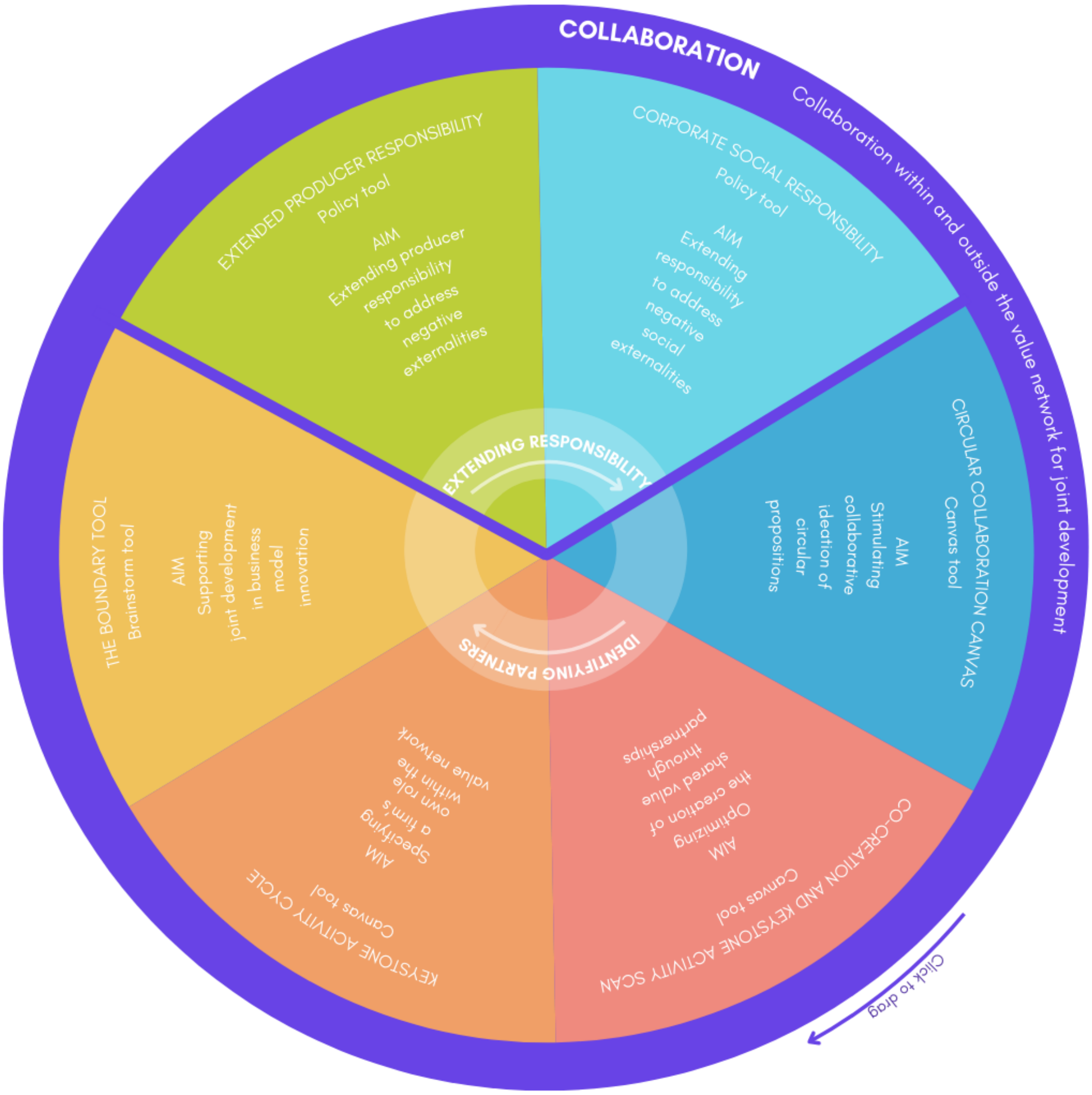
Collaboration is defined by the value network in which value is co-created. Activities revolve around the value-creating system instead of the company or industry itself. Where different economic actors (suppliers, partners, stakeholders, clients and more) co-produce value through collaborative partnerships. Client engagement is also considered in this category.

EXTENDING RESPONSIBILITY

Considering the increasing complexity of supply and value chains and the involvement of different parties throughout, collaboration has become an important strategy to achieve shared goals. CE methods can be used to extend the responsibility of an organization to the ecosystem.

IDENTIFYING PARTNERS AND STAKEHOLDERS

CE methods can support organization in identifying potential partners that can fulfil the needed roles required throughout the value chain for a particular product in joint development.



COLLABORATION

COLLABORATION WITHIN AND OUTSIDE THE VALUE NETWORK FOR JOINT DEVELOPMENT

8.5. PHYSICAL ARCHITECTURE

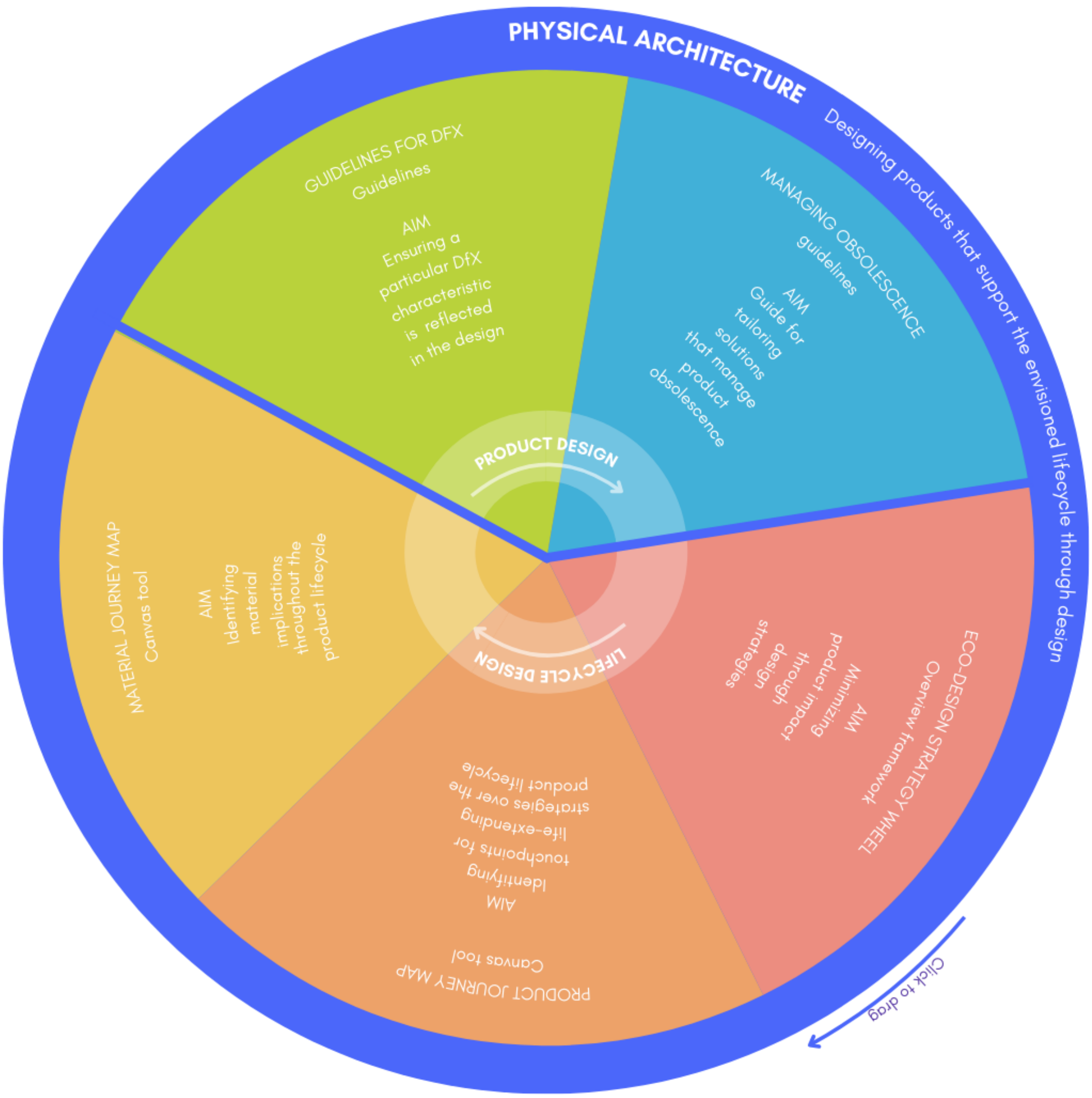
The physical architecture of a product is defined by its technical design. Factors that affect the physical architecture of a product are the design requirements and strategies that are used as well as the lifecycle of the product that results in certain design choices and requirements.

PRODUCT DESIGN

Each CE strategy requires a different design strategy and each design strategy calls for a different design approach. Together these will influence the lifecycle of the product. CE methods can be used to guide and support this design process.

LIFECYCLE DESIGN

Besides the product itself, its lifecycle also needs to be envisioned to ensure proper handling of the product throughout its lifetime. CE methods can be used to envision such a lifecycle and identify touchpoints where intervention might be needed.



8.6. CONSUMER ENGAGEMENT

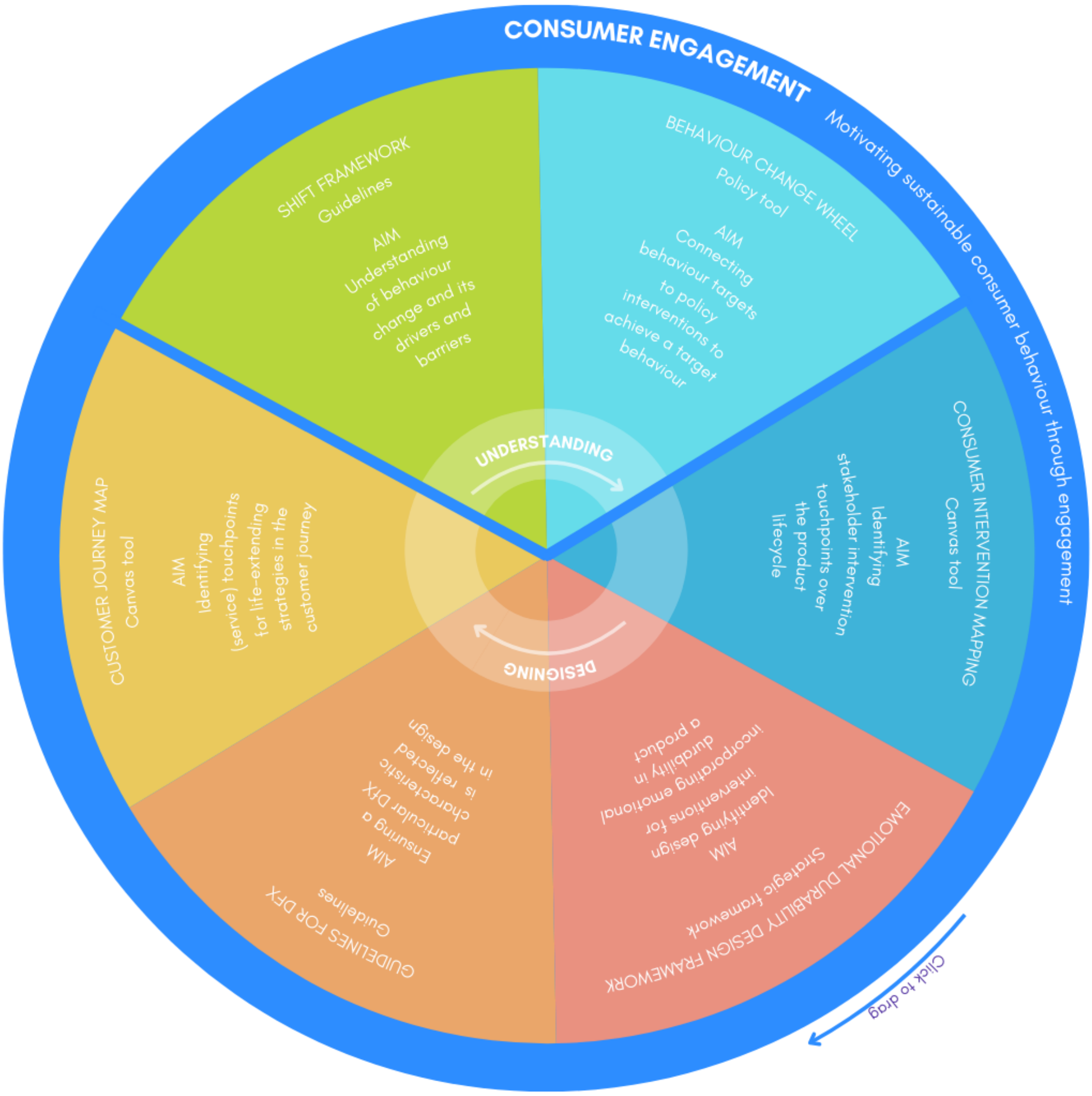
Consumer engagement involves the shift from traditional consumption in a linear economy to sustainable consumer behaviour in a circular economy. Sustainable consumer behaviour is key to circular economy in order to keep products in use for longer and close the loop at end-of-life.

UNDERSTANDING BEHAVIOUR CHANGE

Besides strategies focused at creating circular products, the use of the product is also an important element to consider for circularity to be achieved. CE methods can be used to understand how behaviour change comes about in order to design products that motivate behaviour change.

DESIGNING FOR BEHAVIOUR CHANGE

When behaviour change is understood properly, CE methods can be used to identify design and/or service interventions that have the ability to alter consumer behaviour for sustainability.



8.7. EVALUATION & ASSESSMENT

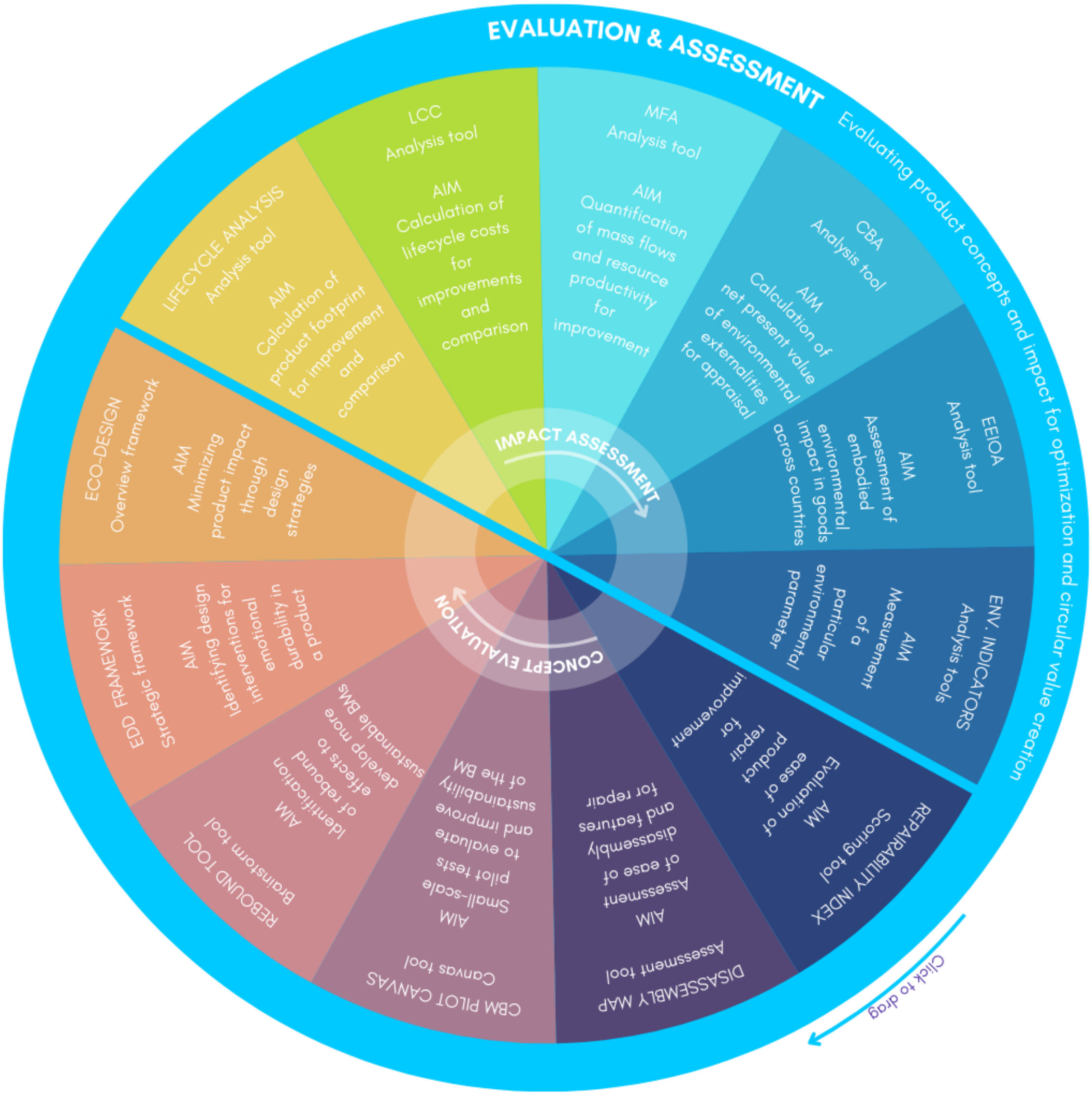
Evaluation and assessment involves the quantitative or qualitative assessment of products and their environmental impact throughout the lifecycle.

IMPACT ASSESSMENT

For the evaluation of products, several environmental indicators and tools are developed to indicate and/or quantify environmental impacts. These methods can be used throughout the lifecycle of a product and help assess the environmental hotspots of a product.

CONCEPT EVALUATION

Besides methods to assess the impact of products, there is also a range of methods to evaluate upon product concepts during the development phase to evaluate whether a design achieves its intended result.



8.8. ADDITIONAL INFORMATION CARDS

For each separate CE method an information card is provided with a further description of the CE method, the needed expertise to apply the particular CE method, the development phase it is best used in, the R-strategies it enables and the original source of the CE method.

The information cards serve to gradually provide further information on the CE methods of interest. Hereby summarizing the primary information that is needed, based on the interviews, to be able to select a CE method. The information cards thus provide navigational support in the decision-making process for selecting CE methods that fit a particular company and their particular circular need.

KEY ELEMENTS FRAMEWORK

DIFFERENTIATION - VISION & STRATEGY

DEFINITION

The Key Elements framework exists of eight elements of circularity that can be applied at different intervention levels (for example, national, regional, sector, business, product, process, or material). There are three core elements and five enabling elements. Core elements deal with physical flows directly, whilst enabling elements deal with creating the conditions or removing barriers.

COMPLEXITY

Introductory framework for firms new to the CE
Low expertise - Moderate time consumption

DEVELOPMENT PHASE

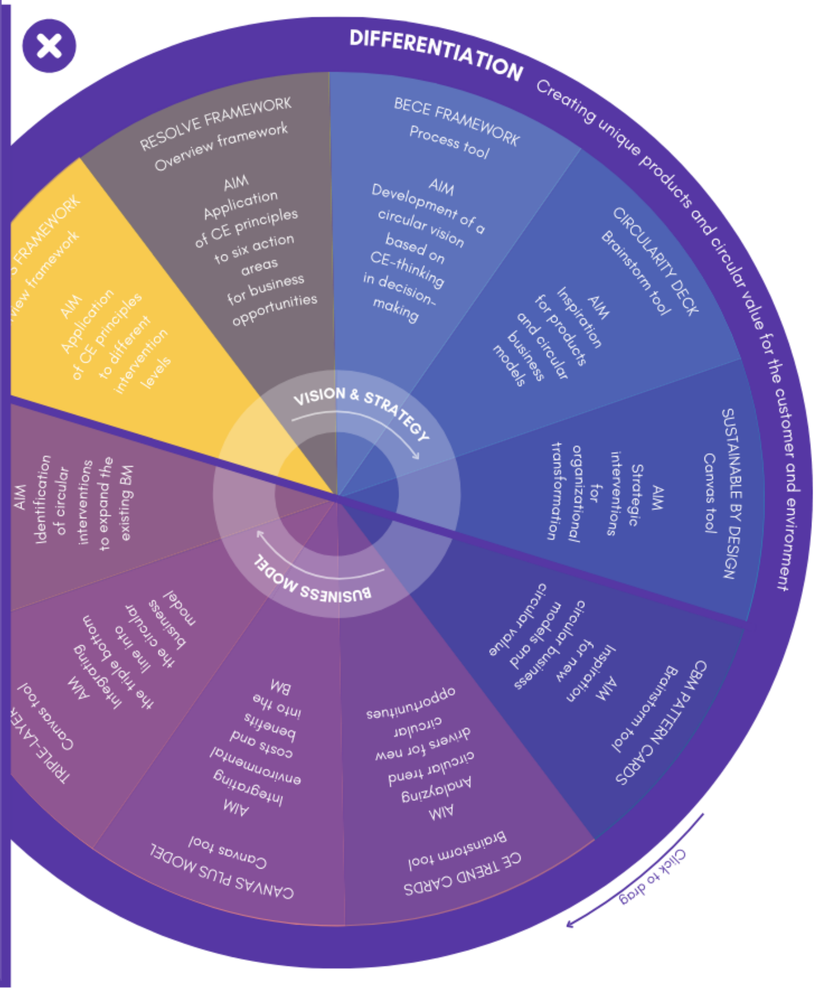
Define

R-STRATEGIES

R1-10

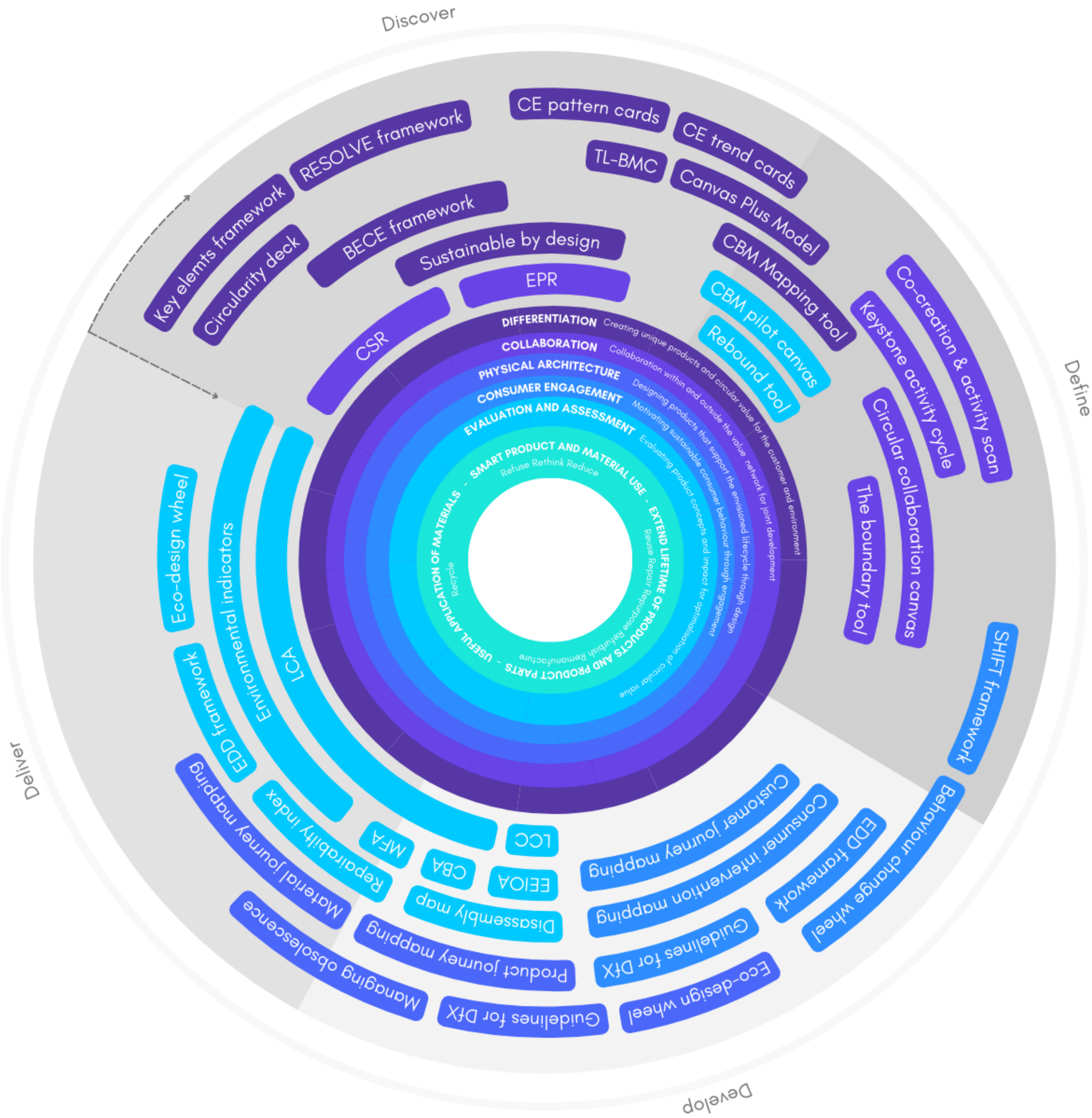
SOURCE

Circle economy
https://www.circle-economy.com/resources/the-key-elements-of-the-circular-economy-framework



8.9. PROCESS OVERVIEW

The figure below shows the CE Method Compass as well as a complete overview of all CE methods discussed in the CE Method Compass. The individual methods are mapped along each phase of the double diamond method by the British Design Council (n.d.). The figure can be followed in clockwise direction to cover the full development process. The color of the individual methods correspond with the category the specific methods belong to.

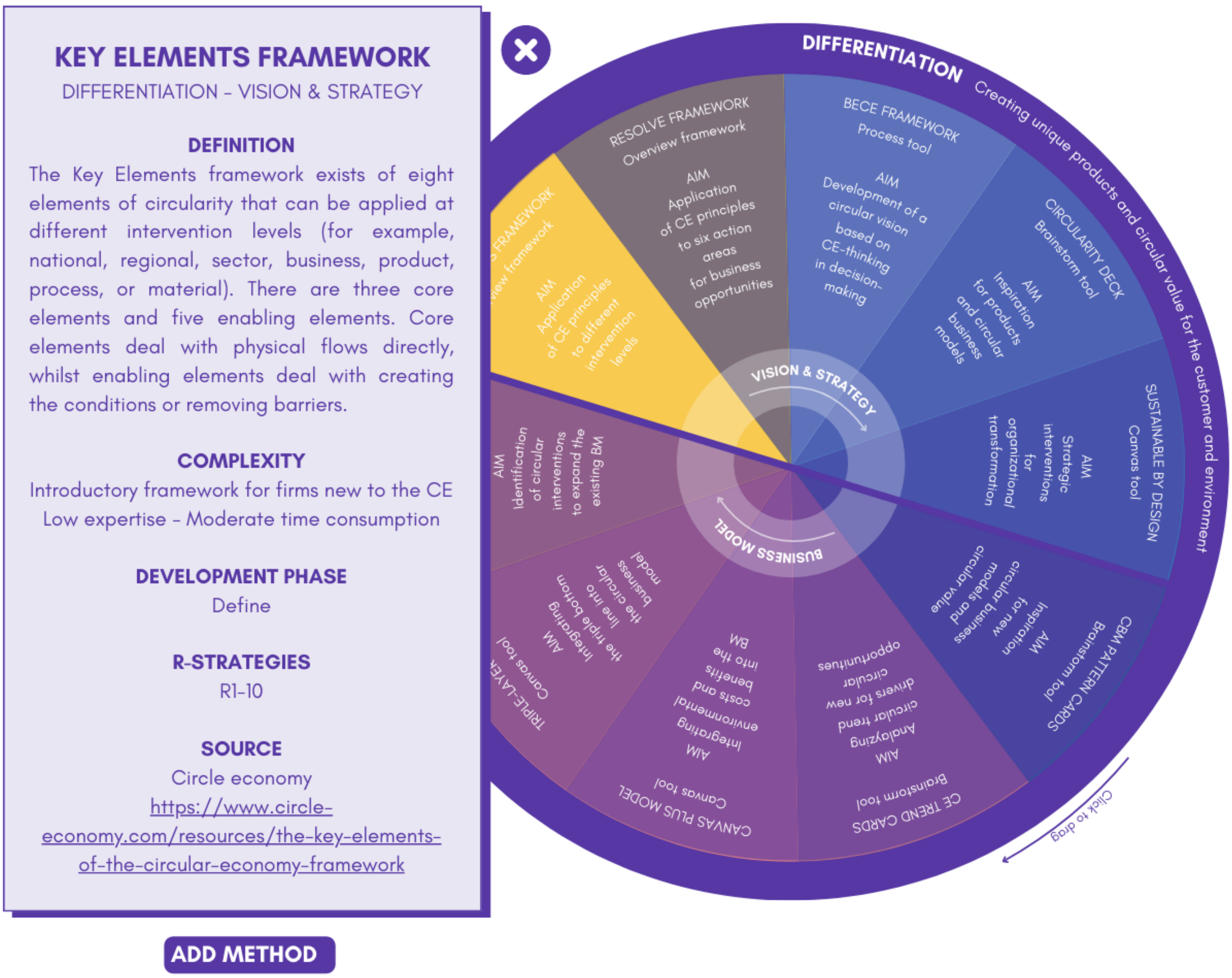


8.10. USING THE COMPASS IN PRACTICE

As the CE Method Compass is developed for business practice, it's use in practice is also considered. For companies using the CE Method Compass it is of importance that a company is able to not only explore the available CE methods but also to select them. When using the CE Method Compass a company can therefore add methods to their personal profile to summarize the selected methods. This project overview is also translated to the process overview, highlighting the chosen methods over the development process. To illustrate how the CE Method Compass is used in practice it is applied to company F as an example. The figures in this section thus represent the recommended CE methods for this company.

SELECTING METHODS

When using the CE Method Compass, individual CE methods can be selected by adding them to the company's profile via the additional information cards. There is no maximum of CE methods that can be selected but it is advised to select CE methods from each category to create a balanced selection.

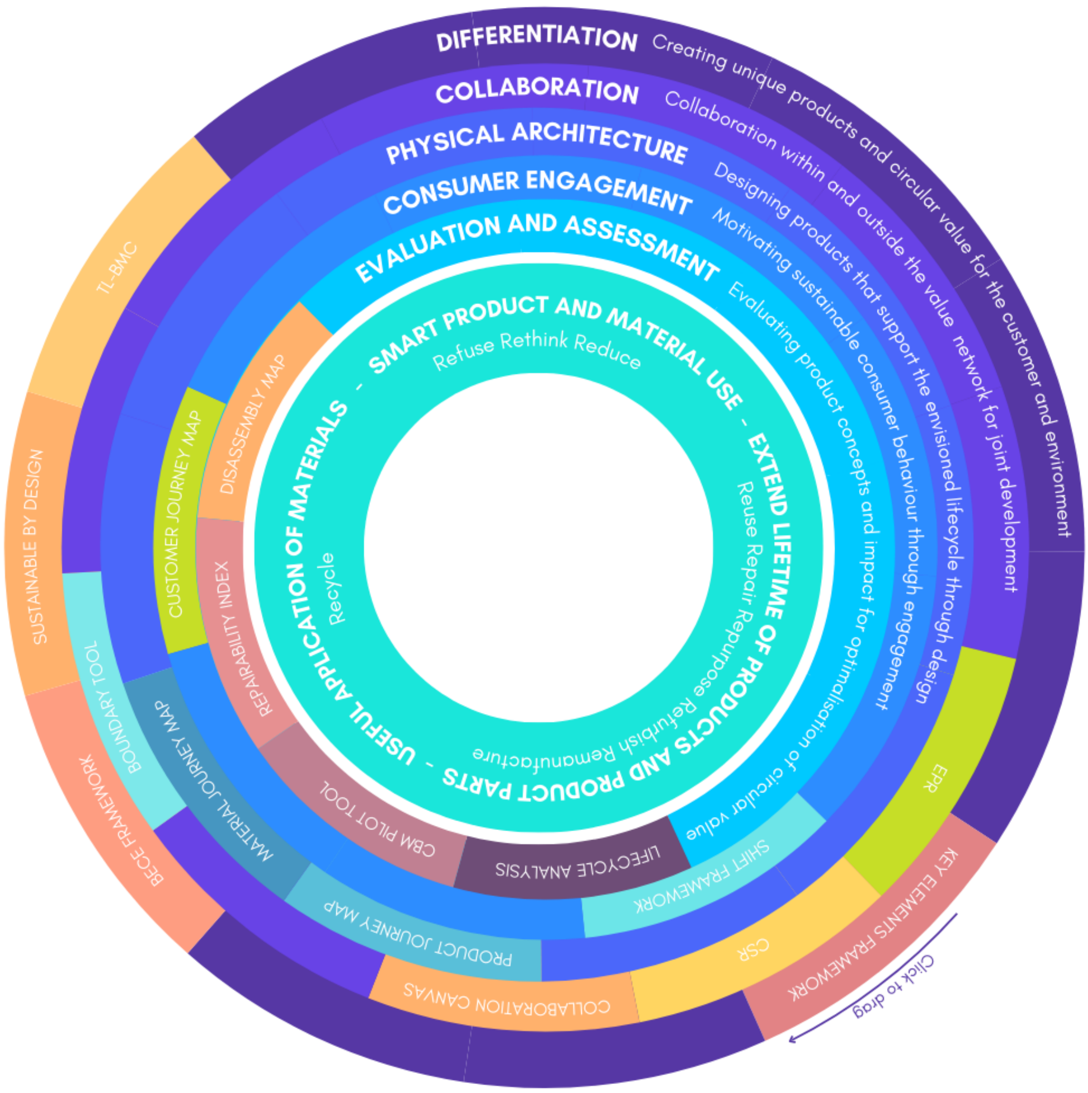


PROJECT OVERVIEW

The project overview below shows an overview of the selected CE methods per category of the CE Method Compass for company F. During this phase of the selection process, it should be evaluated whether the selected CE methods cover all five categories as well as the intended R-strategies. A balanced selection has the most opportunity to create circular value for the organization, client, consumer and the environment.

Company F is categorized as 'internalized'. They thus are aware of CE principles but they do not have a clear vision and/or strategy and CE methods are used centralized to the company. For this company it is therefore recommended to first select CE methods to gain more familiarity with the CE, such as the key elements framework, and then to develop a clear circular vision and strategy. Then, CBMs can be explored for new value creation. As collaboration is central to the company, collaboration activities need to be expanded through EPR and CSR activities. Then, the collaboration canvas and boundary tool can be used to find partners within the value network. For a circular product, they should also evaluate their product through the product and material journey map for potential touch points for life-extending strategies. As company F's products are sold B2B they could also explore service provision to their clients, such as a take-back service. For which the SHIFT framework is best suited to understand behavior change further. Then, the customer journey map can be applied to find touch points for possible services to circulate products. To evaluate the new circular product and services an LCA should be performed to assess the environmental impact. As well as the repairability index and disassembly map to ensure easy repairs.

By implementing these CE methods company F will be able to move from an internalized type of company to a balanced one with a clear understanding of the CE, a fitting vision and strategy and a circular product that is complemented through services.



PERSONAL PROCESS OVERVIEW

The below figure shows a personalized process of CE methods for company F. The selected CE methods are highlighted. The individual methods are mapped along each phase of the double diamond method by the British Design Council (n.d.). The figure can be followed in clockwise direction to cover the full development process.

COMMUNICATION OF THE MODEL

The CE Method Compass is best presented online for use in practice as this allows interaction with the framework and the creation of individual projects to select CE methods within for companies. Appendix H shows several illustrations of what such a website could look like. The following link can also be used to be redirected to a mock-up of the example website:

https://www.figma.com/proto/Zsu2V5VRQJB9fWZyFcGT0B/Thesis-website?node-id=7-22&t=6QSLTRl6YgYrtVdF-1&scaling=contain&page-id=0%3A1&starting-point-node-id=7%3A22

9. Discussion

This research aimed to answer the research question "*How can appropriate circular economy methods be selected by OEMs to support the transition towards a circular economy in electronics?*". In short, that question is answered through the development of the CE Method Compass.

The CE Method Compass is a holistic approach to navigating circular economy methods that offers original equipment manufacturers (OEMs) in the electronics industry guidance in the transition to the circular economy and the development process of circular products and services through CE methods. The CE Method Compass hereby provides an overview of where and how circular value can be achieved and where value might be left behind. Overall, the CE Method Compass facilitates navigation and broad application of CE methods and hereby has the ability to increase the circularity of the sector. This is valuable because achieving circularity in electronics is a challenging assignment, as discussed in the literature review.

In this chapter the research outcome is discussed regarding the requirements stated earlier in chapter six as well as its contribution to literature and its purpose for practice. Some important footnotes of the research outcome are discussed further as well. Such as the generalizability and transferability of the CE Method Compass both within as outside the electronics industry.

9.1. Meeting requirements

As the CE Method Compass is developed in collaboration and with insights from business practice it needs to be discussed how the research outcome succeeds in meeting the requirements set in chapter six.

The CE method overview together with the information cards provide a comprehensive overview of CE methods. Looking at the insights from the input sessions during the interviews the categorization of the CE methods and the provision of information cards, rather than all information being in one figure, also facilitates the gradual provision of information. Together with the project overview of CE methods and accompanying process overview this facilitates that the CE Method Compass is not too overwhelming at once and the user is guided through the process of selecting CE methods. Hereby meeting requirement one (provide a comprehensive overview) and five (the future framework should provide information gradually).

Through presenting the aim of the CE methods, the CE Method Compass does not imply that direct application of a CE method is needed. Which all of the interviewees considered a drawback for the use of CE methods. Instead, it reveals the underlying purpose of the method which supports integration into internal methods and processes. Hereby meeting requirement two (allow and inspire adaptation of CE methods to the context of the user). Considering requirement four, the desire for a process overview of CE methods, the process overview in the CE Method compass self-evidently fulfils this. By meeting these requirements, the research outcome succeeds in gradually presenting information in such a way that companies are able to incorporate CE methods into internal processes throughout the development process.

As mentioned, the framework should not only meet generic findings but also serve specific findings of the cases. Hereby desirably enabling all four groups of how companies use CE methods found in the research. On a practical level this means that the CE Method Compass can be used by both companies that wish to enhance their circular economy strategy (confined and balanced) as by companies newer to the circular economy (internalized and linear). This is accomplished by simultaneously providing a step-by-step guide by going through all CE methods in the compass in a clockwise manner, as an independent framework for companies more familiar with the CE.

On a theoretical level this requirement means that the CE Method Compass must contain both CE Methods that are suitable for companies that use CE methods in a linear manner and in an internalized manner. As well as CE methods that can be used by companies more experienced in the field of circularity, such as balanced and confined companies. The framework has accomplished this through providing exploratory CE methods in each category and specifying these as you move through each separate category of CE methods in the compass. The CE Method Compass is therefore relevant to both companies new to the CE as companies that are more experienced in circularity. Through meeting these requirements, it is ensured that the CE Method Compass overcomes the challenges in business practice regarding the use of CE methods and is able to create value for different companies in the electronics industry.

Two insights from the research could however not be addressed in this study as these are considered out of scope. Nonetheless, these are relevant findings and therefore important to discuss shortly. First of all, all case companies indicated they would like to know how methods can be combined. As mentioned before, in this research's timeframe it is not possible to make academically correct and accurate connections between the methods as this is a separate study itself. Neither is it therefore possible to state whether methods are complementary. Instead, the CE methods in the compass are therefore organized in their recommended order of use. By doing so, the requirement of a process overview of the CE methods is facilitated without making faulty assumptions. It would however be interesting for future research to study how CE methods can be combined and to what degree they are complementary as discussed in the next chapter.

The second insight that is considered out of scope in this research is the desire for a future framework to facilitate communication between teams and departments. Communication structures and the needed deliverables of each team and/or department is considered a separate study as well. The CE Method Compass however does facilitate communication between teams and departments by showing what CE methods have been integrated. Hereby providing more background information on what has been done and how certain choices have been made. The process overview furthermore illustrates where in the development process the next team joins in. To develop distinctive deliverables per development team future research is however needed. But overall, the research outcome has succeeded in meeting the requirements set in chapter six.

9.2. Theoretical implications

As discussed in the beginning of this thesis, there is a large body of literature on CE methods, but the available literature that provides an overview of CE methods or that combines CE methods over the product development process is significantly smaller. Literature on how business practice than uses those CE methods is even scarcer. Considering the previous body of literature, the thesis builds upon the work by Bocken et al. (2014), Boorsma (2022) and Joustra et al. (2022). Bakker et al. (2014) combines different fields of expertise within CE literature and proves the need for integration of design and business models at the strategic level. Boorsma (2022) developed a 'circular product readiness' tool covering the product lifecycle from product development to use and end-of-life, focusing on remanufacturing. Hereby combining several CE methods as well as consumer behaviour and managerial considerations. Joustra et al. (2021) combines circular strategies over the lifecycle of composites with design aspects for product and material integrity to explore recovery pathways and generate design solutions. All papers combine different areas of expertise regarding CE literature and relate these to the product lifecycle, illustrating the need for these combinations in CE methods. The thesis hereby supports earlier work on offering CE methods over the product lifecycle. But it is an addition in offering navigational support through CE methods, for which a higher level of expertise is needed to guide your way through it. As expressed by Corvellec et al. (2022), Kalmykova et al. (2018) and Niero and Hauschild (2017), creating a level of coherence in circular economy methods along the lifecycle is of interest.

Regarding the CE Method Compass, the research outcome is strongly based on academic insights regarding the overview of CE methods. For the research an extensive literature search for both generic CE methods as CE methods specific to electronics was conducted. From the total overview the CE methods were clustered, resulting in ten types of CE methods. Which could be related and organized into the final five categories of CE methods: differentiation, collaboration, physical architecture, consumer engagement, and evaluation and assessment. The overview of CE methods strongly represents the available CE methods in the literature. Regarding the CE Method Compass as a method itself however, it is only weakly related to academic insights. As little is known on how companies navigate and select CE methods few other academic methods are out there to relate the CE Method Compass to. The CE Method Compass is therefore mainly similar to the Circulator by EIT (n.d.) in offering exploration of CE methods and the option to 'mix' CE methods. The circulator however is only applied to circular business models while the CE Method Compass covers a wider range of CE methods. The CE Method Compass is also similar to the Circular Design Project by Franconi et al. (2016) which provides an overview of Design for X strategies and also has the option to 'add' strategies to a personal project. But this framework too only focuses on one of the CE methods addressed in the CE Method Compass. The CE Method Compass is therefore a contribution to the literature in providing a comprehensive overview of CE methods in one space and navigation through them. As well as its research to how companies use CE methods.

Considering the generalizability of the CE Method Compass, both the electronics industry itself as industries outside electronics need to be considered. For the electronics industry itself, the CE methods included in the CE Method Compass are not specific to one type of electronics. The companies that were interviewed were also not focussed in a particular type of electronics. But it might be considered that adjustments need to be made to be able to actually serve all electronic and electrical appliances. A manufacturer of consumer electronics might, for example, have a larger interest in the SHIFT framework than a manufacturer in medical equipment. However, both companies are able to use and benefit from the CE Method Compass. It could therefore be interesting to research further whether the CE Method Compass might be bias towards certain product types or whether other CE methods need to be added for particular EEE products. But overall, the CE Method Compass can be applied throughout the electronics industry.

Regarding other industries, most of the CE methods that are included are generic methods that are applicable to electronics. The CE Method Compass was however developed based on the challenges in the electronics industry. Electronics are a very specific product type regarding its physical architecture and the potential complications for circularity. Because the CE Method Compass was developed for this industry it therefore considers the product development process of electronic products in an extensive manner that other industries might not touch upon. But regarding the CE Method Compass as presented in chapter eight, removing the electronic-specific environmental indicators would result in a generic framework of CE methods for technical products. Considering the five categories of CE methods and R-strategies, these are applicable and relevant to a variety of industries. Additional CE methods can furthermore be added to the compass or current CE methods can be removed if considered necessary to adapt to a specific industry. It is thus expected that adapting the CE Method Compass to apply to other industries will not be complicated as CE methods can easily be added and removed from the framework. But for non-technical products, such as food products, more research is needed on what CE methods are best suited. The structure of the CE Method Compass can then be maintained and the separate CE methods can be adjusted for other industries. The CE Method Compass' validity can however not be claimed beyond the electronics industry. Future research is therefore needed to explore the transferability of the framework to other industries.

Considerations for how the CE Method Compass might develop overtime were also accounted for in the development of the compass. As research within the field of the CE is expanding quickly the CE methods discussed in the compass risk becoming 'outdated'. The CE Method Compass therefore offers the opportunity through the circular visualisation to add and remove CE methods from the framework to maintain up-to-date. The CE Method Compass is therefore adaptable to both different industries as to the passing of time.

To summarize, the main theoretical contribution of this thesis lies in making a first step in researching how firms navigate, select and implement CE methods. As existing literature tends to empirically focus on the separate CE methods in theory, rather than their integration in practice. As expressed by Mazzi (2020) this is valuable information as it informs on how business can be guided further in the transition to the circular economy.

9.3. Practical implications

Regarding the impact for business practice of the research outcome, the research has highlighted that the navigation and selection of CE methods requires a higher level of expertise from companies. This creates a risk of firms only implementing partial solutions in the shift towards a circular economy. Hereby risking internalization of a firm's strengths and optimization of individual parts of a product instead of the product lifecycle as a whole. The CE Method Compass therefore has the opportunity to advise and support organizations and teams in not only navigating CE methods but also in selecting CE methods over the development process to ensure circularity of a product and/or service. Organizations can use the CE Method Compass to either initiate circular product development or to identify potential for additional circular value through CE methods. The CE Method Compass is therefore not only valuable to companies new to the CE but also to companies more experienced in the CE.

The CE Method Compass furthermore places business in a circular ecosystem. Hereby recognizing the need for business to acknowledge they are not a stand-alone actor. Not only in the value network but also regarding the consumer. A circular product should not only be produced in an environmentally (and socially) conscious manner but it should also support and motivate sustainable use of those products. The CE Method Compass hereby has the opportunity to connect business to the environment and society. A commitment to circularity is therefore a boundary condition to retrieve the most value out of the CE Method Compass. Circularity is a concept that needs to be integrated in every aspect of both the company, their product and their services. It is not straightforward, unchallenging or undemanding. The CE Method Compass should therefore not be mistaken as effortless. But with proper use the CE Method Compass has the opportunity to enhance circularity in the electronics industry through the integration of CE methods. Overall, the CE Method Compass supports navigation of CE methods, structures the development process of circular products and services, and advises business on how the current CE strategy can be improved through the implementation of CE methods. The CE Method Compass is therefore a first iteration in supporting and structuring the navigation of CE methods as there is yet to be a complete overview of available CE methods out there.

To summarize, the CE Method Compass can be used as a navigation tool in the selection process of CE methods to either initiate the circularity of a company and their product offer or to enhance it. Hereby offering guidance for original equipment manufacturers within the electronics industry in the transition to the circular economy.

10. Limitations

As no research is without limitations, this thesis also has several. Firstly, an important note is that of the generalizability of the findings, as this is difficult in case study research (Merriam, 1995). Even though several cases were analysed as well as multiple data sources allowing more robust results, more research will be needed to ensure the generalizability and transferability of the findings.

More specific to the research is the need for further exploration on whether the four groups (internalized, confined, dispersed and balanced) distinguished in this thesis hold in a larger sample and if there might be other groups. As well as whether there are other dimensions on which the cases can be differentiated.

Considering data collection, interviewee bias also needs to be considered. For example, both a founder and a managing director were interviewed. This type of interviewee presents the most accurate data but they are also most vulnerable to interviewee bias. As information could be framed more positively, focusing on the strengths of the company. Furthermore, it needs to be noted that not all CE methods a company uses can be mentioned in a 45-minute interview. In reality, it is thus possible that companies use more CE methods than discussed in the interview. Another possibility is that certain internal methods were perhaps not recognised as CE methods and therefore not mentioned in the interview. Even though this was considered in the interview questions through framing method-oriented questions in different manners throughout the interview it should be considered that it is possible that companies in reality operate more CE methods than apparent in the interviews. Another aspect influencing this issue is the interviewee's background at the company. Interviewees with several positions were interviewed. Of which some will be more knowledgeable and experienced within the field of CE methods than others. A longitudinal study should therefore be performed to observe an actual product development process to more accurately identify all CE methods used.

Regarding the CE Method Compass, the developed framework is subjected to the time and scope of the thesis. It is therefore only a first iteration of a navigational tool in the selection process of CE methods and needs further development. Furthermore, the CE methods discussed in the CE Method Compass are only a small portion of the available CE methods. Future research is needed to evaluate whether there might be more appropriate recommendations of CE methods for the CE Method Compass.

Even though the CE Method Compass was developed in collaboration with the case companies, user tests with the final CE Method could be performed to improve it. As this study did not observe an actual development process it is unknown what improvements could follow from application of the CE Method Compass in practice. Testing the compass with OEMs would therefore benefit future iterations as well as validation of the outcome.

11. Future research

While the present study has provided a first step in navigating CE methods it has also unveiled new opportunities for future research. Starting with recommendations based on the case study design, a wider sampling frame is needed to ensure transferability of the findings (Merriam, 1995). Future research is therefore needed to test the four groups on how firms use CE methods found in this research and to develop these further. A wider sampling frame will also allow more accurate findings on the needs of each group in regard to the proposed CE Method Compass. Secondly, as the findings cannot be expanded beyond the cases analysed in this study, it is necessary to explore if the composition of the three dimensions for analysis indeed leads to a higher level of circularity. Or whether more dimensions exist on which the cases can be differentiated.

More specific to the research context, it would be interesting to research whether, how and which CE methods can be combined. This is considered outside the scope of the thesis as this has the opportunity to be an elaborate study on its own. It would however be highly interesting to find how CE methods can be combined over the product lifecycle and whether different CE methods are complementary. This information could be used to advise companies in the transition to the circular economy and in the development of circular products and services. It would furthermore be an interesting addition to the CE Method Compass proposed in this thesis.

Several interviewees also indicated they would like to know how complex a CE method is in order to be able to select it. This requirement is therefore addressed on the information cards through an indication of the needed expertise and time consumption. But as explained in chapter seven this only serves as an indication. Future research is needed to address the complexity of a method more accurately.

Another aspect that is considered outside the scope of the thesis is how the CE Method Compass could facilitate communication between teams and departments. The CE Method Compass has the opportunity to support communication by showing what CE methods have been integrated and providing background information on how certain choices were made. But more research on communication structures is needed to accurately develop clear deliverables per category of CE methods in the compass. Studying this further could also be interesting to find whether different company sizes would benefit from a different formulation of the compass. Studying communication structures further would be interesting for the proposed framework as then the development process can be structured further and efficiency is increased throughout the process.

Regarding the overall CE Method Compass, future research is needed on the generalizability and transferability of the framework to other industries. Likely, different CE methods will be required for different industries. As well as potentially different categories to cover the development process and/or product lifecycle.

Lastly, this thesis only starts to research the topic of CE methods. More research is therefore thus needed on how CE methods can be combined and navigated further. The CE Method Compass is only a first iteration in doing so and is meant to be expanded and developed. Future graduation students and researchers are therefore very much invited to use this framework as inspiration and develop it further to provide an accessible framework that supports companies in navigating, selecting and combining CE methods as well as structuring and guiding the development process of circular products and services in the transition to the circular economy.

12. Conclusion

This study explored how OEMs can be guided in navigating the available CE methods throughout the product development process to enable the integration of CE methods. In order to achieve this, it was researched how companies navigate, select and operate the available CE methods by analysing multiple case companies. As a result, four groups were found on how firms use CE methods. From these findings a navigational framework is proposed, the Circular Economy Method Compass. This study hereby provides a starting point on not only understanding how firms apply CE methods in practice but also provides a first iteration of navigation tools in the selection process of CE methods.

Regarding the first sub-question in this research, *"What CE methods aiming at particular phases of the product lifecycle are available?"*, the literature review provides an overview of the available CE methods aiming at particular phases of the product development process. Which can be categorized according to five categories of CE methods: differentiation, collaboration, physical architecture, consumer engagement, and evaluation and assessment.

Regarding the second sub-question, *"How do OEMs apply CE methods?"*, the multiple case study performed in this research has shed light on how different companies use CE methods. Four distinctive groups were found of which two were identified in the research. It was found that a firm's use of CE methods is defined by the integration of internal and external expertise, whether they actively collaborate for joint development in the value network, and to what extent the product lifecycle is addressed through CE methods. When firms combine these three dimensions for the use of CE methods a balanced application of CE methods can be achieved.

Regarding the third sub-question, *"How can a framework be developed to support OEMs in navigating CE methods?"*, the multiple case study has shown the generic and specific elements to consider in the development of such a framework. All companies found it difficult to integrate external CE methods within their internal processes. This was the main reason for firms to not actively search for CE methods or to apply them. Some companies furthermore felt that current CE methods did not provide sufficient breakthroughs and are too time consuming to apply, for which the complexity of electronic products also was a factor. It was therefore found that all companies instead developed internal methods, hereby using CE methods as inspiration and mainly focussing on CE trends and environmental legislation. Apparent in all companies was the application of the R-strategies to develop these internal methods, which were therefore integrated in the CE Method Compass as well.

To answer the main research question, *"How can appropriate circular economy methods be selected by OEMs to support the transition towards a circular economy in electronics?",* the CE Method Compass is developed. The CE Method Compass is a method to navigating circular economy methods that offer OEMs in the electronics industry guidance in the transition to the circular economy. The CE Method Compass hereby supports OEMs in selecting CE methods by motivating broad integration of CE methods over the product development process and offering the opportunity to enhance the current circular strategy of a firm as well as to guide the development of circular products from the initiation of a circular vision to the evaluation and assessment of products and services.

To conclude, the thesis proposes a first iteration of a method that supports OEMs in navigating and selecting CE methods to initiate or enhance the development of circular products and services in the transition to a circular economy. The thesis hereby sets the starting point for further development towards this goal.

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Appendix A

Appendix A1: Interview guide case companies

Introduction

Is it alright with you to record the interview? There are various possibilities with regard to anonymity and non-disclosure that we can discuss at the end of the interview. Thank you for participating in this interview. Prior to this interview we had contact via email in which the subject, key elements and goal of this interview and research was explained. I hope everything is clear, and if you have any questions during the interview, feel free to ask.

General information

- Could you introduce yourself?
- Could you describe the product your company offers?
- Is your product sold as B2C or B2B?

Sustainability level

- How does your company define the circular economy and what role does it play to your company?
- What sustainability measures have you generally taken in your product offer?

CE methods

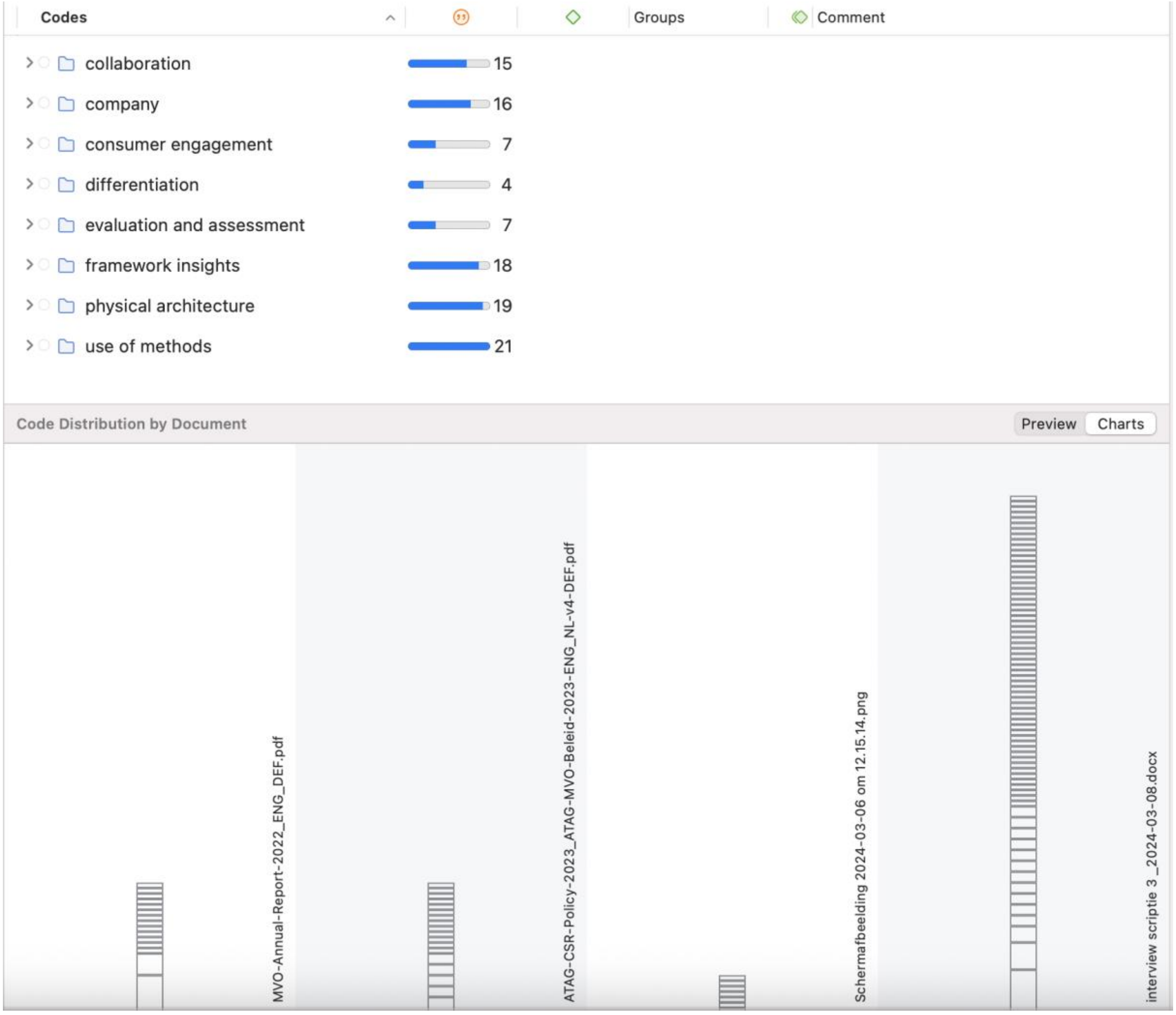
- What makes your product circular?
- Did you have certain circular strategies set for your product?
- What actions did you take to get to this result?
- Did you use any specific CE methods in this process?
- What aim did you want to achieve through the use of these methods?
- Could you walk me through the process of how you searched for these methods?
- Could you tell me why you selected these methods?
- What did you find challenging in searching and selecting methods?
- Is there a certain type of method that you preferred during specific phases of the development process? (guidelines, frameworks, card decks, brainstorms)
- Are there particular aspects of electronics that you find more difficult to address through CE methods?

CE framework

- What would you need to support the use of CE methods internally at your company?
- What would you need on an external level to support the use of CE methods?
- What would you need to ease the development of circular products?

Appendix B

Example of coding



Appendix C

Visualisation of methods discussed in chapter 4

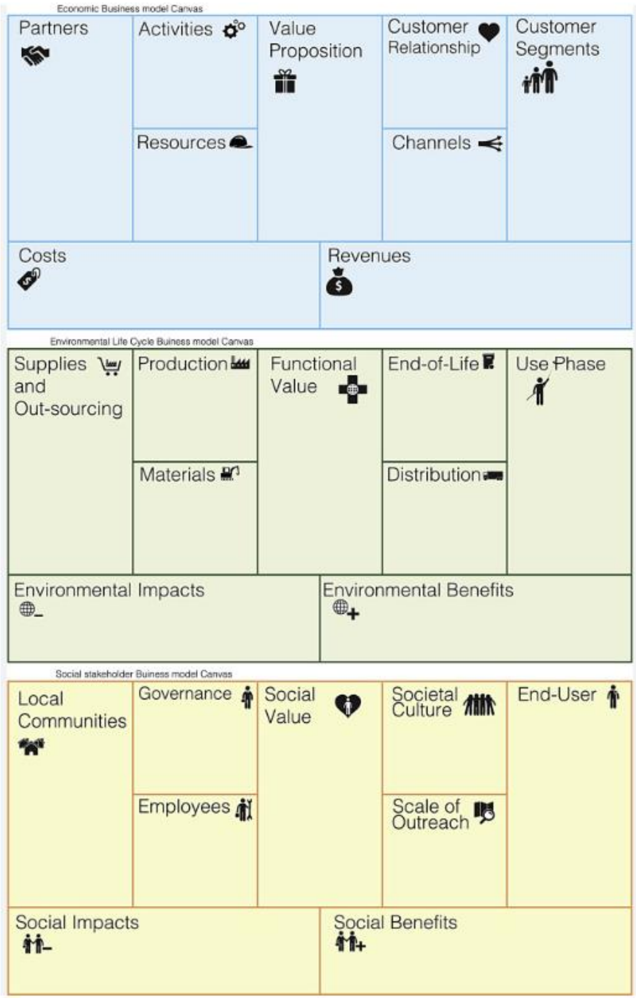


Figure C1: Triple-layered business model canvas (Joyce and Paquin, 2016)

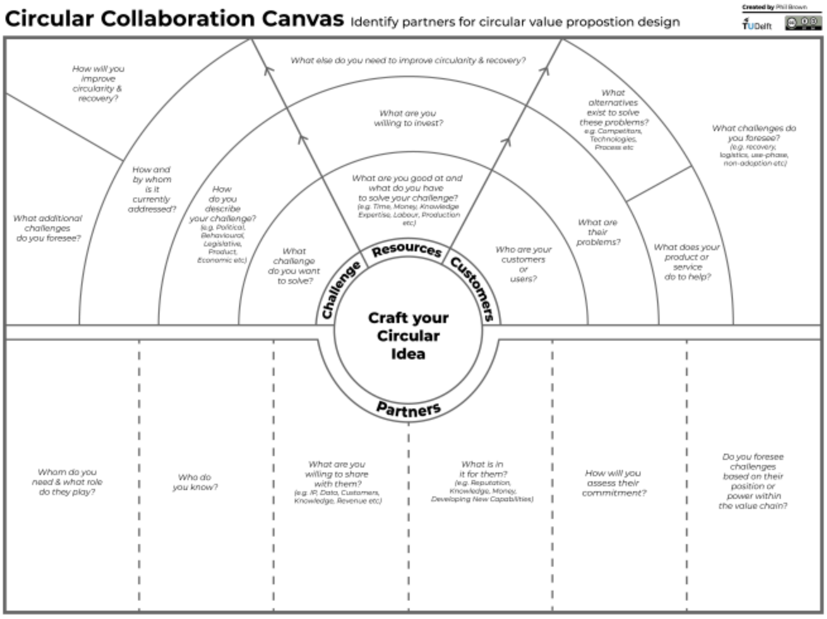


Figure C2: Circular collaboration canvas (Brown et al, 2021)

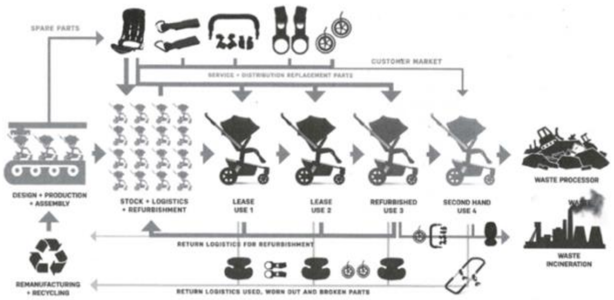


Figure C: Product journey mapping (van Boeijen et al., 2014)

Figure C4: Material journey mapping (Circular Design Guide, n.d.)

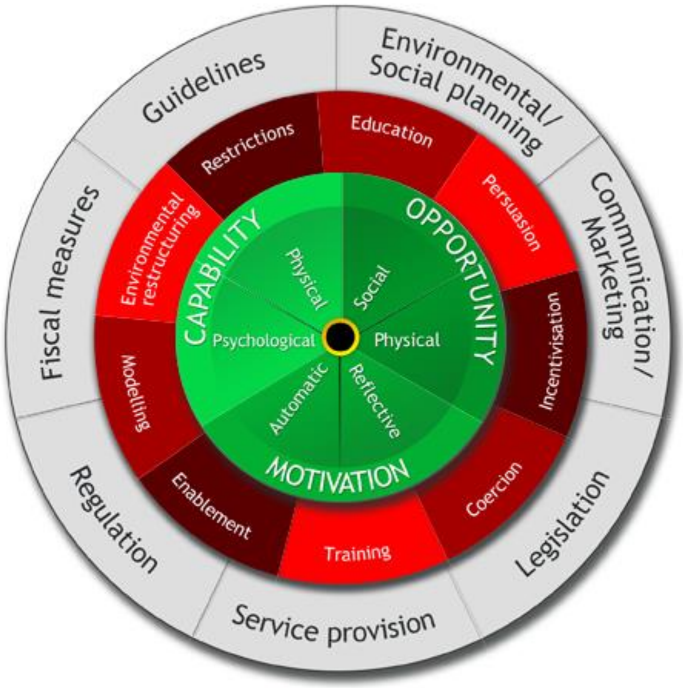


Figure C5: Behaviour change wheel (Michie et al., 2011)

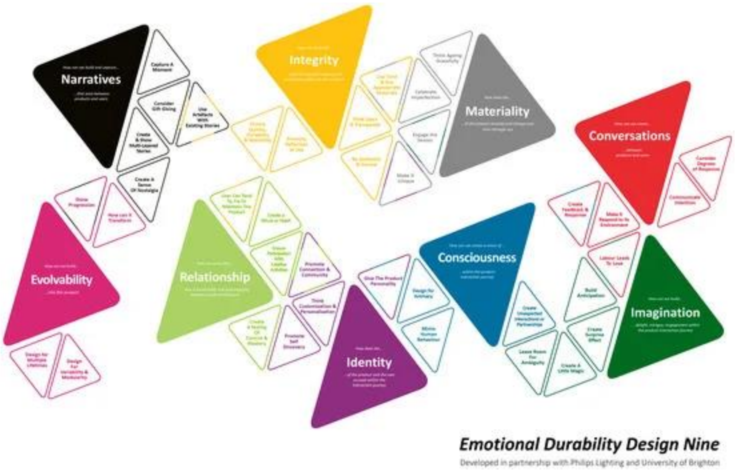


Figure C6: Emotional durability design framework (Hainnes-Gadd et al., 2018)

Figure C7: consumer intervention map (excluding intervention cards) (Sinclair et al., 2018)

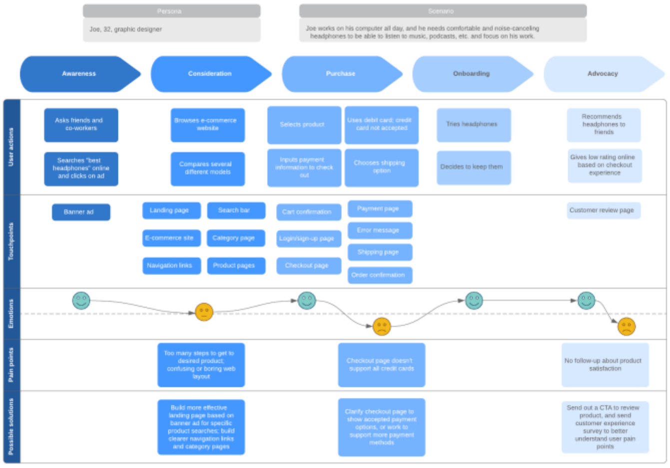


Figure C8: Example of customer journey map (Van Boeijen et al., 2014)

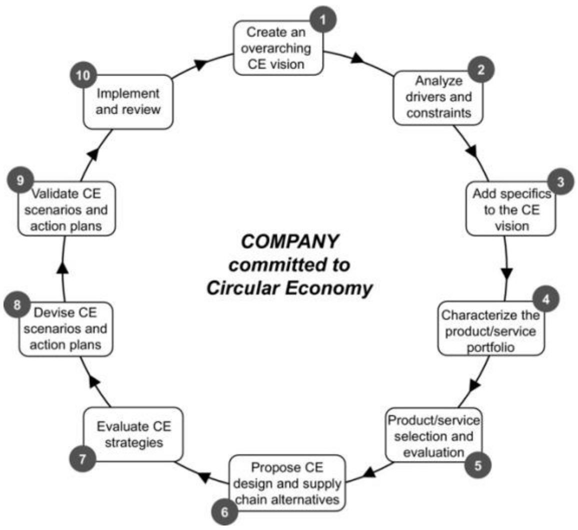


Figure C9: BECE framework (Mendoza et al., 2017)

Figure B10: RESOLVE framework (McKinsey, 2016)

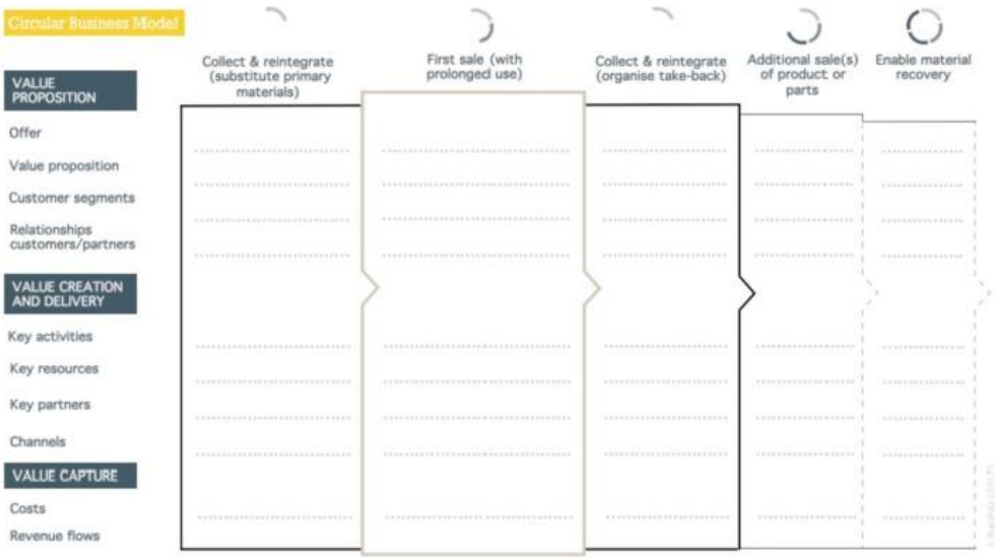


Figure C11: Circular business model mapping tool (Nussholz, 2018)

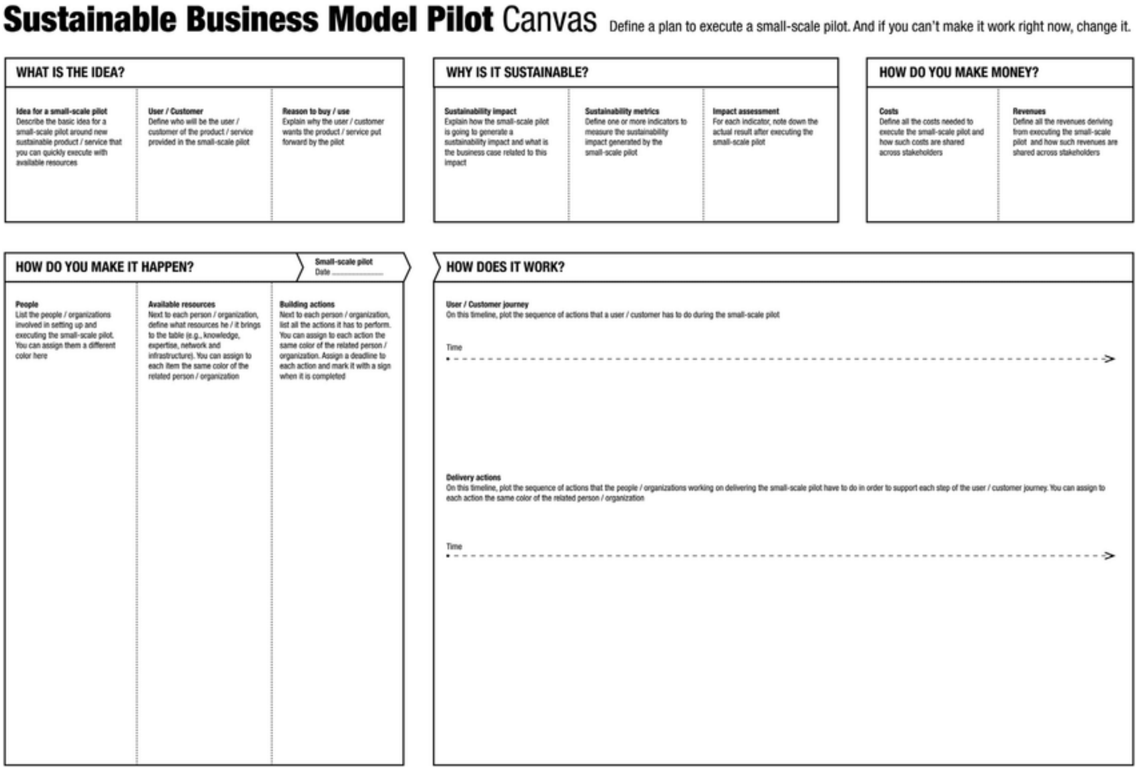


Figure C12: Sustainable business model pilot canvas (Baldassare et al., 2020)

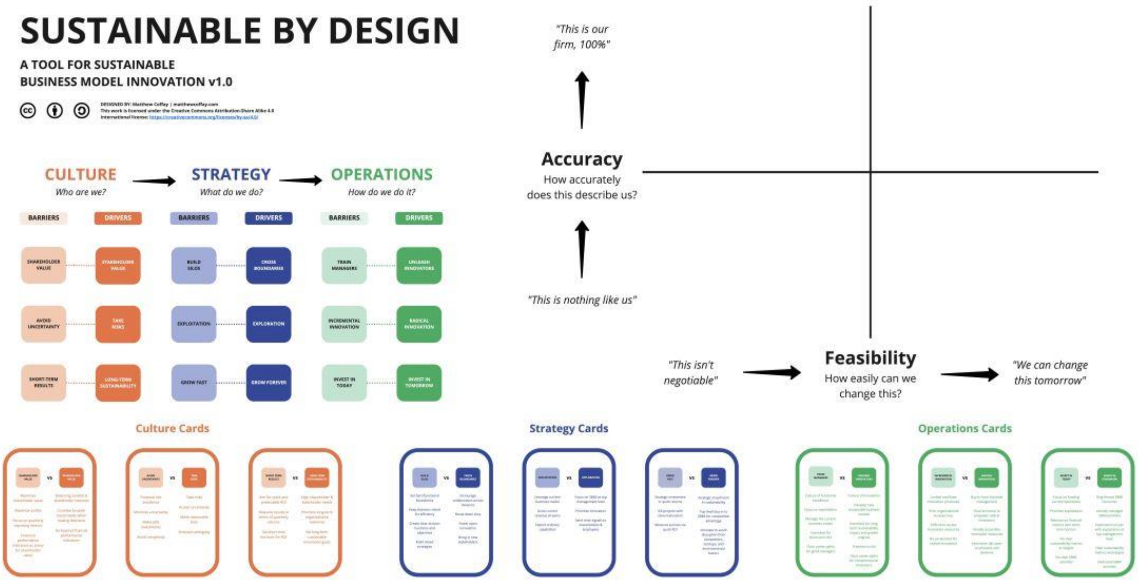


Figure C13: Sustainable by design tool (Coffay and Bocken, 2023)

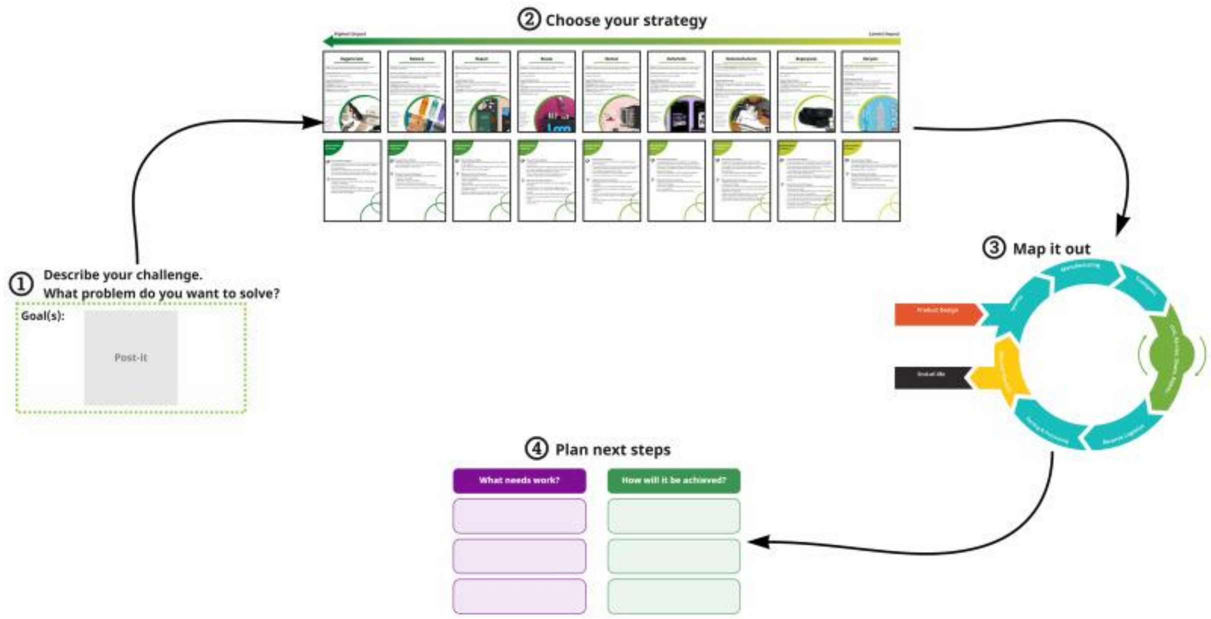


Figure C14: Circular business model rebound tool (Das et al., 2023)

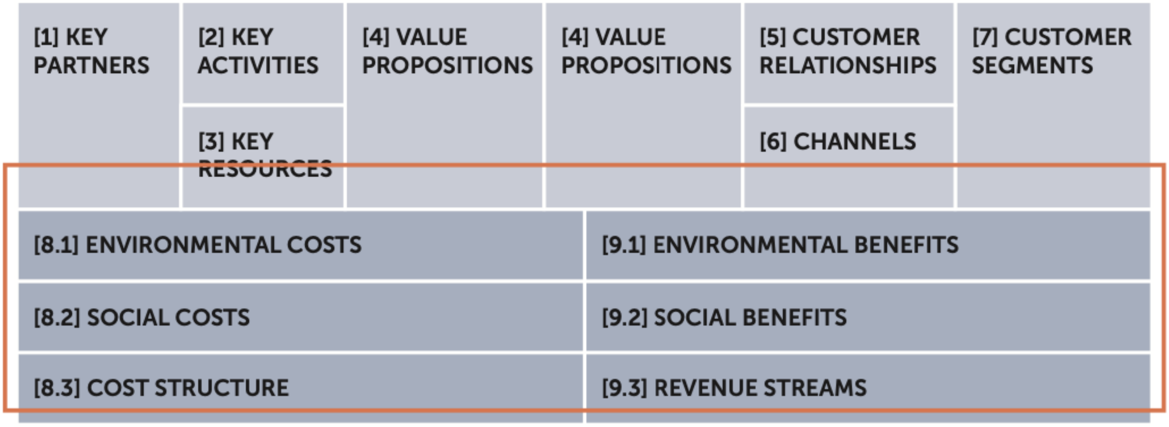


Figure C15: Canvas Plus model (van Tulder, 2020)

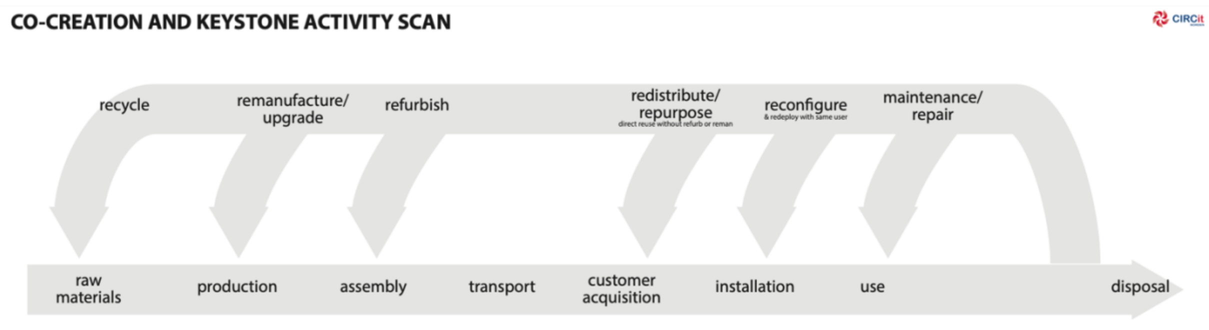


Figure C16: Co-creation and keystone activity scan (Circit Nord, 2020b)

Figure C17: keystone activity cycle (Circit Nord, 2020c)

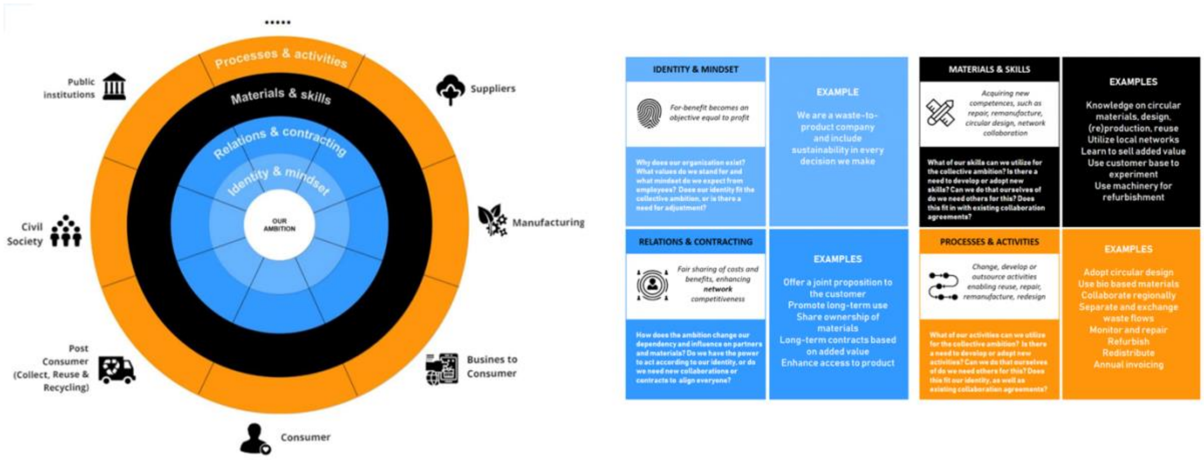


Figure C18: The boundary tool (Circular X, n.d.)

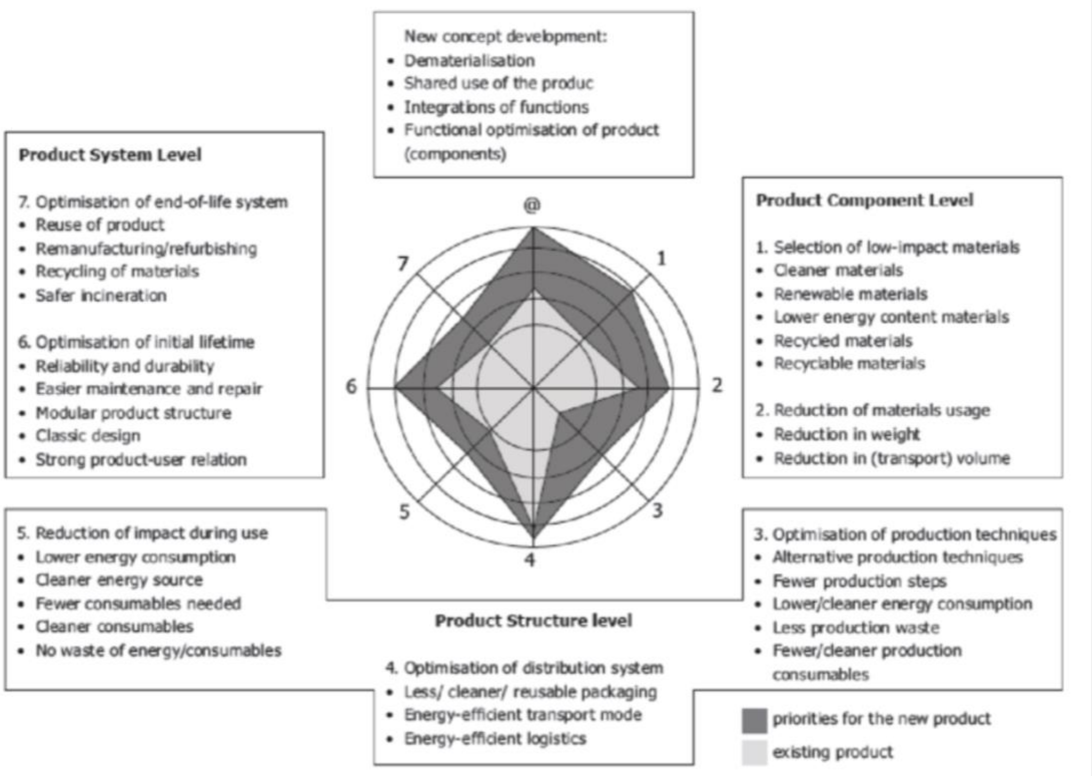


Figure C19: Eco-design strategy wheel (excluding checklist) (van Boeijen et al., 2014)

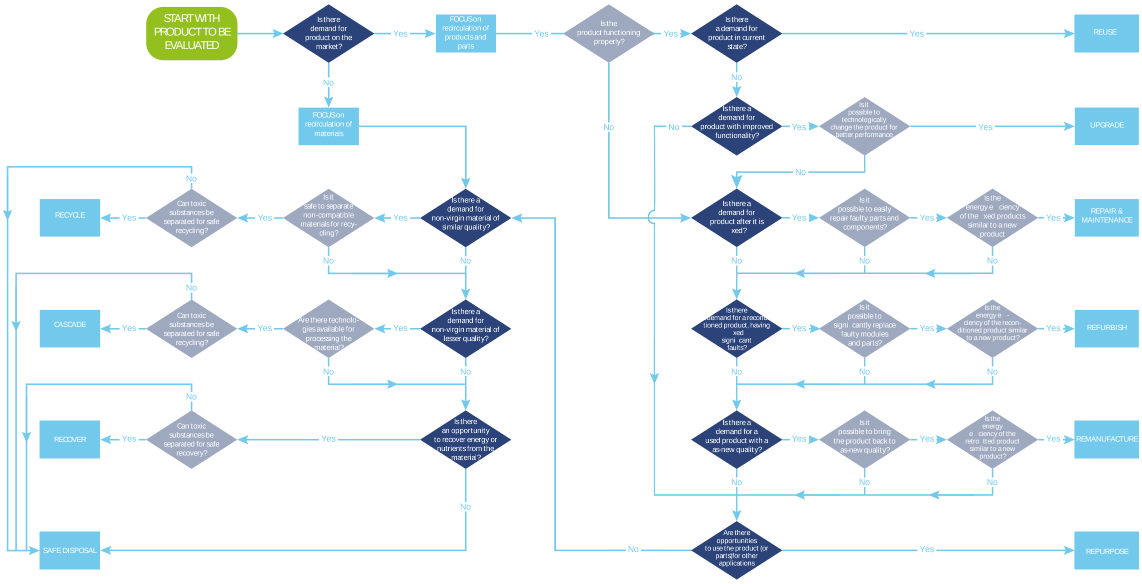


Figure C20: Circular recirculation strategy decision tree (Circit Nord, 2023)

Appendix D

Identified circular economy methods

Differentiation	collaboration	physical architecture	consumer engagement	evaluation and assessment
Circulytics EMF				
Triple-layer business model canvas	EPR	Guidelines for DfX	Guidelines for DfX	LCA
BECE framework	Circular collaboration canvas	Design for product integrity	Customer journey mapping	MFA
RESOLVE framework	Co-creation & keystone activity scan	Eco-design strategy wheel and checklist	Behavioural change wheel	LCC
Circular business model mapping tool	Keystone activity cycle	Product journey mapping	Emotional Durability Design framework (EDD)	Disassembly map
Circular economy trend cards	business ecosystem mapping	Material journey mapping	Consumer intervention mapping	EEIOA
Circular economy business model pattern cards	stakeholder value mapping	circularity assessment tool	SHIFT framework	Environmental indicators
Collaboration tool CE building sector	stakeholder exploraiton	guidelines for circular product development		Recirculation strategy decision tree
Assessment of CE business models	stakeholder opportunity cluster			VRE
BECE framework adapted version	prioritzing opportunity clusters			PLC
circular strategies scanner	best practice exploration			CI
circular economy sustainability screening	co-creation learnings finder			recycling rate
SWOT	experiment design			reuse potential
CE business model configurator poster	circular value chain roadmap			CEI
CE business model innovation roadmap	business fort sufficiency database			MCI
cE business model framework	the boundary tool			EVR
checklist of sustainability qualifying criteria	CSR			CPI
experimentation roadmap and test card s				ZWI
expert system circular business model configurator				longevity indicator
SMART circular economy strategies overview				A guidance for navigating trade-offs to support sustainability decision-making
circular experimentation workbench				CBA
The circular rebound tool				CBM pilot canvas
sustainable by design				EDD framework
circular business model pilot plan				Circular rebound tool
circularity deck				eco-design strategy wheel and checklist
key elements framework				repairability index
Canvas plus model				MET matrix
				LiDS wheel (eco-design strategy wheel)
				Eco-estimator
				ABC analysis
				Fast Five
				Full cost accounting (FCA)
				True cost accounting (TCA)

Appendix E

Examples of quotes

Quote	Case
"And that is why you can't really just take a design strategy and apply it one-on-one"	A
"We expand our environmental initiatives through collaboration with stakeholders"	A
"Our program really exists of two pillars, carbon neutrality and that of circularity of our products"	A
"I don't believe we really used those…there will probably be overlap but we did not literally apply them."	B
"We really had a lot of conversations with experts, stakeholders and potential clients"	B
"But the sustainability of the design, that is really subordinate"	B
"We had a graduation student develop a disassembly map for us"	C
"Together with a transporter we found a new method to ship our products"	C
"And I am talking to clients to see how we could get our products back and at EOL and repurpose those"	C
"I don't think we come up with new methods but maybe it is customizing them"	D
"So, aligning parties within the company to make circular proposition possible"	D
"We always try to be really careful that we are fully understanding the current system and what the opportunities are to make it more circular"	D
"Well wat we look at are the R-strategies and we now have 12 circular value spaces defined"	E
"And you really need client engagement to do that"	E
"But we did not find that a sustainable solution, it might have a good number in your LCA but it does the world more harm than good"	E
"We started with using LCA and we learned a lot about our product"	F
"We are really active with our suppliers and clients, that collaboration we really look for"	F
"If you want to make that work than you need to extract more valuable materials and that is really still a quest"	F
"There is just a lot of product variation within electronics and that makes it difficult to develop one model or framework without it becoming too generic"	A
"We need our brand values to be represented in the methods that we use and that is what drove is to develop our own methods"	C
"No, we do not use that tool but I am sure some elements will overlap"	E

Appendix F

Input-output overview of CE methods discussed in proposed model

Category	Method	Aim	Input	Output	Type	Phase	R-strategy	Source	Complexity
DIFFERENTIATION									
Vision & strategy	BECE	Motivating CE thinking in decision-making	Understanding of CE principles	Circular vision	Process tool	Define	1-10	Mendoza et al. (2017)	Expertise: L Time: M
	Key elements framework	Providing direction to companies new to CE	No prior knowledge needed	Key elements to address in a CE	Overview framework	Discover	1-10	Circle economy (2021)	Expertise: L Time: M
	RESOLVE	Providing direction to companies new to CE	No prior knowledge needed	Six action areas to address in a CE	Overview framework	Discover	1-10	McKinsey (2016)	Expertise: L Time: L
	Circularity deck	Providing direction to companies new to CE	Circular vision	Inspiration for circular products and business models	Brainstorm tool	Discover	1-10	Konietzko et al. (2020)	Expertise: L Time: L
	Sustainable by design tool	Support organizational transformation	Circular vision	Strategic circular interventions for organizational transformation	Mapping tool	Define	1-10	Coffay and Bocken (2023)	Expertise: L Time: M
Business model	Triple-layer BMC	Integrating the triple bottom line into the business model	Existing business model or product concept	Circular business model with horizontal and vertical coherence on an economic, social and environmental level	Canvas tool	Define	1-10	Joyce and Paquin (2016)	Expertise: L Time: M
	CBM mapping tool	Identification of circular interventions to expand the existing BM	Existing business model	Holistically adjusted business model that considers multiple use phases	Mapping tool	Develop	1-10	Nussholz (2018)	Expertise: L Time: M

	Canvas Plus model	Integrating environmental costs and benefits into the business model	Existing business model or product concept	CBM that includes social and environmental benefits, costs and revenue streams	Canvas tool	Define	1-10	Van Tulder (2020)	Expertise: L Time: M
	CBM pattern cards	Generate BM ideas in brainstorm	Product idea	New business model idea	Brainstorm tool	Discover	1-10	Pieroni et al. (2019)	Expertise: L Time: L
	CE trend cards	Analyzing circular trend drivers	Existing business model	Circular opportunities for new or existing business models	Brainstorm tool	Discover	1-10	Circit Nord (2020)	Expertise: L Time: L
COLLABORATION									
Extending responsibility	EPR	Supporting firms in addressing negative externalities	Understanding of firm's upstream impacts	Upstream sustainability (environmental)	Policy tool	Develop	1-10	-	Expertise: M Time: H
	CSR	Supporting firms in addressing negative externalities	Understanding of firm's upstream impacts	Upstream sustainability (social)	Policy tool	Develop	1-10	-	Expertise: M Time: H
Finding the right people	Circular collaboration canvas	Stimulate collaborative ideation of circular propositions	Reliance on a value network	Identified key partners throughout the value chain	Canvas tool	Define	1-10	Brown et al. (2021)	Expertise: L Time: M
	Co-creation and keystone activity scan	Optimizing the creation of shared value through partnerships	Reliance on a value network	Specific areas of the product lifecycle where co-creation is needed	Canvas tool	Define	1-10	Circit Nord (2020)	Expertise: L Time: L
	Keystone activity cycle	Specifying a firm's own role within the value network	Reliance on a value network	The firm's key activities within the value network	Canvas tool	Define	1-10	Circit Nord (2020)	Expertise: L Time: L
	The boundary tool	Supporting joint development and accurate partnerships in business model innovation	Partners for joint development	Joint development and solutions for BMI	Brainstorm tool	Define	1-10	Circular X (n.d.)	Expertise: L Time: L

PHYSICAL ARCHITECTURE									
Product design	Guidelines for DfX	Ensuring a particular characteristic is reflected in the design	Design concept	Design solution meeting specific characteristics (throughout the lifecycle)	Guidelines	Develop	1-10		Expertise: M Time: M
	Design methodology for managing obsolescence	Guide tailor-made solutions that manage product obsolescence	Product idea	A solution that preserves product integrity and manages obsolescence through the PD and BM	Guidelines	Develop	4-10	Den Hollander (2018)	Expertise: M Time: M
Lifecycle design	Eco-design strategy wheel and checklist	Minimizing product impact through design strategies	Design concept or product	Improved eco-design	Overview framework	Develop	1-10	Van Boeijen et al. (2014)	Expertise: L Time: M
	Product journey mapping	Keeping products in use longer	Design concept or product	Touchpoints for life-extending strategies over the product lifecycle	Mapping tool	Develop	4-10	Van Boeijen et al. (2014)	Expertise: L Time: M
	Material journey mapping	Identifying material implications throughout the lifecycle	Design concept or product	Visualization of material choices and potential implications throughout the lifecycle	Mapping tool	Develop	4-10	Circular design guide (n.d.)	Expertise: M Time: M
CONSUMER ENGAGEMENT									
Understanding behavior change	SHIFT framework	Creating an understanding of behavior change and providing drivers and barriers	Design concept with behavioral aim	Marketing tactics for behavior change	Guidelines	Discover	4-10	White et al. (2019)	Expertise: L Time: M
	Behavior change wheel	Connecting behavior targets to policy interventions	Design concept with behavioral aim	Behavior interventions to achieve a target behavior	Policy tool	Discover	4-10	Michie et al. (2011)	Expertise: L Time: M

Designing for behavior change	Consumer intervention mapping	Creating future product strategies through visualization of points in the PL where stakeholders can intervene	Design concept	Stakeholder intervention touchpoints over product lifecycle	Mapping tool	Define	4-10	Sinclair et al. (2018)	Expertise: L Time: M
	EDD framework	Life-extension of future products	Product idea	Design interventions for incorporating emotional durability in the product	Strategy framework	Develop	4-10	Haines-Gadd et al. (2018)	Expertise: L Time: M
	Guidelines for DfX	Ensuring a particular characteristic is reflected in the design	Design concept	Design solution meeting specific characteristics (throughout the lifecycle)	Guidelines	Develop	4-10		Expertise: M Time: M
	Customer journey mapping	Motivating sustainable use of products by the consumer	Design concept or product	(Service) touchpoints for life-extending strategies in customer journey	Mapping tool	Develop	4-10	Van Boeijen et al. (2018)	Expertise: L Time: M
EVALUATION AND ASSESSMENT									
Impact assessme nt	LCA	Targeted improvement of product footprints from data	Product data over lifecycle	Environmental product footprint for targeted improvement and comparison	Analysis tool	Deliver	1-10	Guinee (2001)	Expertise: H Time: H
	LCC	Targeted improvement of product footprints from data	Product costs over lifecycle	Lifecycle costs for targeted improvements and comparison	Analysis tool	Deliver	1-10	Moreau and Weidema (2015)	Expertise: H Time: H
	MFA	Mass balance for targeted improvement of product footprints from data	Product data on waste flows	Quantification of mass flows and resource productivity	Analysis tool	Deliver	1-10	Brunner and Rechberger (2016)	Expertise: H Time: H

	CBA	Appraisal of projects based on environmental welfare gains or losses from an investment/product	Product data on environmental externalities	NPV of environmental externalities	Analysis tool	Deliver	1-10	Atkinson and Mourato (2008)	Expertise: H Time: H
	EEIOA	Assessing the relationship between economic consumption and environmental impact	Input-output data and environmental impacts of sector	Assessment of embodied environmental impact in goods across economies	Analysis tool	Deliver	1-10	-	Expertise: H Time: H
	Environmental indicators	Description or measurement of the state of the environment	Product, material or process data	Measure of a particular environmental parameter	Analysis tool	Deliver	4-10	-	Expertise: H Time: H
Concept evaluation	Disassembly map	Guiding product design for dis- and reassembly	Product concept	Assessment of ease of disassembly based on 4 parameters and identification of features hindering repair	Assessment tool	Deliver	4-10	De Fazio et al. (2020)	Expertise: M Time: M
	Recirculation decision tree	Helping select recirculation strategies fitting market and product	Product concept	Recirculation strategy specific to product and market	Decision tool	Define	4-10	Circit Nord (2020)	Expertise: L Time: L
	CBM pilot canvas	Executing a small-scale pilot to bridge the design-implementation gap	Existing business model	Small-scale pilot to test the desirability, viability, feasibility and sustainability of the BM	Canvas tool	Deliver	1-10	Baldassare et al. (2020)	Expertise: L Time: M

	EDD framework	Life-extension of future products	Design concept for evaluation	Evaluation of product's emotional durability	Strategy framework	Deliver	4-10	Haines-Gadd et al. (2018)	Expertise: L Time: M
	Circular rebound tool	Identifying rebound effects to develop more sustainable BM's	Existing business model	Identifying negative environmental externalities	Brainstorm tool	Deliver	4-10	Das et al. (2023)	Expertise: L Time: M
	Eco-design strategy wheel and checklist	Evaluation of existing design or design concept and comparison in-between products	Design concept or product	Improved eco-design	Overview framework	Deliver	1-10	Van Boeijen et al. (2018)	Expertise: L Time: M
	Repairability index	Evaluation of ease of repair of product	Design concept or product	Improved repairability	Scoring tool	Deliver	4-8	French repairability index (n.d.)	Expertise: M Time: M

BECE FRAMEWORK
DIFFERENTIATION - VISION & STRATEGY

DEFINITION
BECE empowers organizations to tackle the CE holistically by embedding the concept into corporate decision making and by bringing operational and systems thinking together, thus increasing the likelihood of successful implementation.

COMPLEXITY
Low expertise - Moderate time consumption

DEVELOPMENT PHASE
Define

R-STRATEGIES
R1-10

SOURCE
Mendoza et al. (2017)

KEY ELEMENTS FRAMEWORK
DIFFERENTIATION - VISION & STRATEGY

DEFINITION
The Key Elements framework exists of eight elements of circularity that can be applied at different intervention levels (for example, national, regional, sector, business, product, process, or material). There are three core elements and five enabling elements. Core elements deal with physical flows directly, whilst enabling elements deal with creating the conditions or removing barriers.

COMPLEXITY
Introductory framework for firms new to the CE
Low expertise - Moderate time consumption

DEVELOPMENT PHASE
Define

R-STRATEGIES
R1-10

SOURCE
Circle economy
https://www.circle-economy.com/resources/the-key-elements-of-the-circular-economy-framework

RESOLVE FRAMEWORK
DIFFERENTIATION - VISION & STRATEGY

DEFINITION
the framework takes the core principles of circularity and applies them to six actions: Regenerate, Share, Optimise, Loop, Virtualise, and Exchange.

COMPLEXITY
Low expertise - Low time consumption

DEVELOPMENT PHASE
Discover

R-STRATEGIES
R1-10

SOURCE
McKinsey et al. (2016)

CIRCULARITY DECK
DIFFERENTIATION - VISION & STRATEGY

DEFINITION
a card deck-based tool that can help firms to analyze, ideate and develop the circularity potential of their innovation ecosystems. The principles are organized according to the intended circular strategy outcome that they pursue (i.e., narrow, slow, close, regenerate and inform material and energy flows), and the extent of the innovation perspective that is needed to operationalize a principle (i.e., product, business model, or ecosystem innovation).

COMPLEXITY
Low expertise - Low time consumption

DEVELOPMENT PHASE
Discover

R-STRATEGIES
R1-10

SOURCE
Konietzko et al. (2020)

SUSTAINABLE BY DESIGN
DIFFERENTIATION - VISION & STRATEGY

DEFINITION
the Sustainable By Design tool can be used by practitioners to evaluate their current organizational design, identify barriers and drivers for sustainable business model innovation, and develop strategic interventions to engage in organizational transformation.

COMPLEXITY
Low expertise - Moderate time consumption

DEVELOPMENT PHASE
Define

R-STRATEGIES
R1-10

SOURCE
Coffay and Bocken (2023)

TRIPLE-LAYER BMC
DIFFERENTIATION - BUSINESS MODEL

DEFINITION
The Triple Layered Business Model Canvas is a tool for exploring sustainability-oriented business model innovation. It extends the original business model canvas by adding two layers: an environmental layer based on a lifecycle perspective and a social layer based on a stakeholder perspective.

COMPLEXITY
Low expertise - Moderate time consumption

DEVELOPMENT PHASE
Define

R-STRATEGIES
R1-10

SOURCE
Joyce and Paquin (2016)

CBM MAPPING TOOL

DIFFERENTIATION - BUSINESS MODEL

DEFINITION
The tool offers a standardised representation of the elements and possible cycles of circular business models to prolong the useful life of products and parts, and close material loops.

COMPLEXITY
Low expertise - Moderate time consumption

DEVELOPMENT PHASE
Develop

R-STRATEGIES
R1-10

SOURCE
Nussholz (2018)

CANVAS PLUS MODEL

DIFFERENTIATION - BUSINESS MODEL

DEFINITION
CBM canvas that includes social and environmental benefits, costs and revenue streams and integrates these into the business model.

COMPLEXITY
Low expertise - Moderate time consumption

DEVELOPMENT PHASE
Define

R-STRATEGIES
R1-10

SOURCE
Van Tulder (2020)

CBM PATTERN CARDS

DIFFERENTIATION - BUSINESS MODEL

DEFINITION
The Circular Economy Business Model Pattern Cards can support you in sensing opportunities and generating ideas about potential Circular Economy business models for your company. Use this tool in interactive workshops to help your team with inspiration for ideation sessions and benchmarking about possible configurations of Circular Economy business models implemented by manufacturing companies.

COMPLEXITY
Low expertise - Low time consumption

DEVELOPMENT PHASE
Discover

R-STRATEGIES
R1-10

SOURCE
Pieroni et al. (2019)

CE TREND CARDS

DIFFERENTIATION - BUSINESS MODEL

DEFINITION
The Circular Economy Trend Cards can be used in the process of analysing trend drivers, to support the SWOT analysis. In this context, the cards can be used to prompt a discussion around which future opportunities and threats could affect the development of Circular Economy Business Models. The Circular Economy Trend Cards relate to different topics and raise specific questions about Circular Economy, which can be used to your team discussions.

COMPLEXITY
Low expertise - Low time consumption

DEVELOPMENT PHASE
Discover

R-STRATEGIES
R1-10

SOURCE
Circit Nord (2020)

EPR

COLLABORATION - EXTENDING

DEFINITION
Extended producer responsibility (EPR) is a waste and pollution management concept that encourages companies to design more sustainable and recyclable products and manufacturing processes.

COMPLEXITY
Moderate expertise - High time consumption

DEVELOPMENT PHASE
Develop

R-STRATEGIES
R1-10

SOURCE
-

CSR

COLLABORATION - EXTENDING

DEFINITION
CSR is based on the belief that businesses have a greater duty to society than just providing jobs and making profits. It asks business leaders to consider their decisions' environmental and social impacts in order to reduce harm where possible.

COMPLEXITY
Moderate expertise - High time consumption

DEVELOPMENT PHASE
Develop

R-STRATEGIES
R1-10

SOURCE
-

CIRCULAR COLLABORATION

COLLABORATION - RIGHT PEOPLE

DEFINITION

The tool integrates decision-making principles from the entrepreneurship theory of effectuation within a design thinking approach to stimulate collaborative ideation of circular propositions.

COMPLEXITY

Low expertise - Moderate time consumption

DEVELOPMENT PHASE

Define

R-STRATEGIES

R1-10

SOURCE

Brown et al. (2021)

CO-CREATION CANVAS

COLLABORATION - RIGHT PEOPLE

DEFINITION

With the Co-Creation and Keystone Activity Scan, you can identify areas where co-creation is needed or beneficial. This final step of phase 2, is the transition between designing the new value chain, and thinking about how to make the change. With the Co-Creation Scan key areas for co-creation are identified and prioritised. The result of the activity is identification of areas that could benefit from co-creating solutions together with stakeholders and alternative scenarios for keystone activities.

COMPLEXITY

Low expertise - Low time consumption

DEVELOPMENT PHASE

Define

R-STRATEGIES

R1-10

SOURCE

Circit Nord (2020)

KEYSTONE ACTIVITY CYCLE

COLLABORATION - RIGHT PEOPLE

DEFINITION

The Keystone Activity Cycle is used to zoom in on the most highly prioritised activities in the Circular Value Chain. The activity uses a similar approach as with the Circular Value Chain Activity Cycle. Here, however, it is applied at a higher resolution, focusing exclusively on the keystone activity and what is needed to perform this activity or operation. The result of the activity is insight into how the keystone activities would work.

COMPLEXITY

Low expertise - Low time consumption

DEVELOPMENT PHASE

Define

R-STRATEGIES

R1-10

SOURCE

Circit Nord (2020)

THE BOUNDARY TOOL

COLLABORATION - RIGHT PEOPLE

DEFINITION

The Boundary Tool is a process tool that helps businesses engage in multi-stakeholder collaboration for circular business model innovation by focusing on complementarities and mismatches in stakeholders' identities, relations, competences and activities. The final process tool consists of five steps to facilitate multi-stakeholder alignment for sustainable business model innovation.

COMPLEXITY

Low expertise - Low time consumption

DEVELOPMENT PHASE

Define

R-STRATEGIES

R1-10

SOURCE

Circular X (n.d.)

GUIDELINES FOR DFX

PHYSICAL ARCHITECTURE - PRODUCT

DEFINITION

esign for "X" refers to design methods that ensure that a particular characteristic, function, or quality criteria is reflected in the final design. The term "X" might refer to quality criteria such as reliability, Six Sigma manufacturing, or inspection. It might also refer to performance characteristics such as functionality, manufacturability, serviceability, maintenance, environmental impact, and usability.

COMPLEXITY

Moderate expertise - Moderate time consumption

DEVELOPMENT PHASE

Develop

R-STRATEGIES

R1-10

SOURCE

-

MANAGING OBSOLESCENCE

PHYSICAL ARCHITECTURE - PRODUCT

DEFINITION

Design methodology that can help industrial de- signers to design products with a long or extended lifetime in support of a circular economy

COMPLEXITY

Moderate expertise - Moderate time consumption

DEVELOPMENT PHASE

Develop

R-STRATEGIES

R4-10

SOURCE

Den Hollander (2018)

ECO-DESIGN STRATEGY

PHYSICAL ARCHITECTURE - LIFECYCLE

DEFINITION

Eco-design considers environmental aspects at all stages of the product development process, striving for products which make the lowest possible environmental impact throughout the product life cycle. The eco-design strategy wheel can be used to design and evaluate a product according to the eco-design principle.

COMPLEXITY

Low expertise - Moderate time consumption

DEVELOPMENT PHASE

Develop

R-STRATEGIES

R1-10

SOURCE

Van Boeijen et al. (2014)

PRODUCT JOURNEY MAP

PHYSICAL ARCHITECTURE - LIFECYCLE

DEFINITION

Circularity means rethinking a linear use cycle of your product or service with a beginning, middle, and end. If a product or service is truly circular, it will never actually have an end to its life, but continuously take a new form. Mapping this journey will ensure that your product stays in a useful state for as long as possible and adds value at every stage.

COMPLEXITY

Low expertise - Moderate time consumption

DEVELOPMENT PHASE

Develop

R-STRATEGIES

R4-10

SOURCE

Van Boeijen et al. (2014)

MATERIAL JOURNEY MAP

PHYSICAL ARCHITECTURE - LIFECYCLE

DEFINITION

The chemicals and materials used throughout the product life cycle matter because they can pose risks to humans and the environment. Developing an awareness of these risks is the first step towards designing in a different way. There are multiple approaches that can be taken to ensure safer material choices. Through this mapping exercise, you will explore which areas you can affect the most as a designer.

COMPLEXITY

Moderate expertise - Moderate time consumption

DEVELOPMENT PHASE

Develop

R-STRATEGIES

R4-10

SOURCE

Circular design guide (n.d.)

SHIFT FRAMEWORK

CONSUMER - UNDERSTANDING

DEFINITION

The framework is represented by the acronym SHIFT, and it proposes that consumers are more inclined to engage in pro-environmental behaviors when the message or context leverages the following psychological factors: Social influence, Habit formation, Individual self, Feelings and cognition, and Tangibility.

COMPLEXITY

Low expertise - Moderate time consumption

DEVELOPMENT PHASE

Discover

R-STRATEGIES

R4-10

SOURCE

White et al. (2019)

BEHAVIOR CHANGE WHEEL

CONSUMER - UNDERSTANDING

DEFINITION

A framework designed to aid intervention designers in moving from a behavioral analysis of a problem to an evidence-based intervention method. This framework allows designers to identify intervention functions and policy categories that can bring about change.

COMPLEXITY

Low expertise - Moderate time consumption

DEVELOPMENT PHASE

Disvoer

R-STRATEGIES

R4-10

SOURCE

Michie et al. (2011)

CONSUMER INTERVENTION

CONSUMER - DESIGNING

DEFINITION

he tool visualises the points within a product's lifecycle where stakeholders are able to intervene in the product's expected journey. This perspective enables the rapid construction of scenarios that explore and describe future circular product service systems.

COMPLEXITY

Low expertise - Moderate time consumption

DEVELOPMENT PHASE

Define

R-STRATEGIES

R1-10

SOURCE

Sinclair et al. (2018)

EDD FRAMEWORK

CONSUMER - DESIGNING

DEFINITION

The Emotional Durability Design Nine—consisting of nine themes: relationships, narratives, identity, imagination, conversations, consciousness, integrity, materiality, and evolvability. These nine themes are complemented by 38 strategies that help in the development of more emotionally engaging product experiences.

COMPLEXITY

Low expertise - Moderate time consumption

DEVELOPMENT PHASE

Develop

R-STRATEGIES

R4-10

SOURCE

Haines-gadd et al. (2018)

GUIDELINES FOR DFX

CONSUMER - DESIGNING

DEFINITION

esign for "X" refers to design methods that ensure that a particular characteristic, function, or quality criteria is reflected in the final design. The term "X" might refer to quality criteria such as reliability, Six Sigma manufacturing, or inspection. It might also refer to performance characteristics such as functionality, manufacturability, serviceability, maintenance, environmental impact, and usability.

COMPLEXITY

Low expertise - Moderate time consumption

DEVELOPMENT PHASE

Develop

R-STRATEGIES

R4-10

SOURCE

-

CUSTOMER JOURNEY MAP

CONSUMER - DESIGNING

DEFINITION

A customer journey map is a visual storyline of every engagement a customer has with a service, brand, or product. The customer journey mapping process puts the organization directly in the consumer's mind to better understand the customer's processes, needs, and perceptions.

COMPLEXITY

Low expertise - Moderate time consumption

DEVELOPMENT PHASE

Develop

R-STRATEGIES

R4-10

SOURCE

Van Boeijen et al. (2018)

LIFECYCLE ANALYSIS

E&A - IMPACT ASSESSMENT

DEFINITION

A way to evaluate the environmental effects associated with any given industrial activity from the initial gathering of raw materials from the earth until the point at which all residuals are returned to the earth or "cradle-to-grave."

COMPLEXITY

High expertise - High time consumption

DEVELOPMENT PHASE

Deliver

R-STRATEGIES

R1-10

SOURCE

Guinee (2001)

LIFECYCLE COSTING

E&A - IMPACT ASSESSMENT

DEFINITION

Life Cycle Cost Analysis (LCCA) is an economic evaluation technique that determines the total environmental cost of owning and operating a facility over period of time.

COMPLEXITY

High expertise - high time consumption

DEVELOPMENT PHASE

Deliver

R-STRATEGIES

R1-10

SOURCE

Moreau and Weidema (2015)

MATERIAL FLOW ANALYSIS

E&A - IMPACT ASSESSMENT

DEFINITION

Materials flow analysis is a quantitative procedure for determining the flow of materials and energy through the economy. It uses input/output methodologies, including both material and economic information. It captures the mass balances in an economy where inputs (extractions + imports) equal outputs (consumption + exports + accumulation + wastes). It too is based on the laws of thermodynamics. MFA asks whether the flow of materials is sustainable in terms of the environmental burden it creates.

COMPLEXITY

High expertise - High time consumption

DEVELOPMENT PHASE

Deliver

R-STRATEGIES

R1-10

SOURCE

Brunner and Rechberger (2016)

COST-BENEFIT ANALYSIS
E&A - IMPACT ASSESSMENT

DEFINITION
Environmental cost-benefit analysis, or CBA, refers to the economic appraisal of policies and projects that have the deliberate aim of improving the provision of environmental services or actions that might affect (sometimes adversely) the environment as an indirect consequence.

COMPLEXITY
High expertise - high time consumption

DEVELOPMENT PHASE
Deliver

R-STRATEGIES
R1-10

SOURCE
Atkinson and Mourato (2008)

EEIOA
E&A - IMPACT ASSESSMENT

DEFINITION
EEIOA is a standard methodology for assessing environmental footprints (e.g. carbon footprints) and analyzing the production and consumption structures within one or across economies.

COMPLEXITY
High expertise - high time consumption

DEVELOPMENT PHASE
Deliver

R-STRATEGIES
R1-10

SOURCE
-

ENVIRONMENTAL INDICATORS
E&A - IMPACT ASSESSMENT

DEFINITION
An environmental indicator is a numerical value that helps provide insight into the state of the environment or human health. Some examples of indicators for electronics:
Value-based resource efficiency (VRE)
Product-level circularity (PLC)
Circularity index (CI)
Resource duration indicator (RDI)
Circular economy performance indicator (CEPI)
Recycling rate (also determined by design)
Recyclability benefit rate (RBR)
Reuse potential (RP)
Circular economy index (CEI)

COMPLEXITY
High expertise - High time consumption

DEVELOPMENT PHASE
Deliver

R-STRATEGIES
R4-10

SOURCE
-

DISASSEMBLY MAP
E&A - CONCEPT EVALUATION

DEFINITION
The 'Disassembly Map' method is set up to guide product design and is aligned with the most recent research and standards on product repairability. The ease of disassembly is assessed on Four main design parameters are considered in this method to assess the ease of disassembly of: disassembly sequence/depth, type of tools, fastener reusability/reversibility, and disassembly time.

COMPLEXITY
Moderate expertise - Moderate time consumption

DEVELOPMENT PHASE
Deliver

R-STRATEGIES
R4-10

SOURCE
De Fazio et al. (2020)

CBM PILOT CANVAS
E&A - CONCEPT EVALUATION

DEFINITION
Organizations can use the circular business model pilot canvas to translate sustainable business model ideas defined "on paper" into small-scale pilots as a first implementation step.

COMPLEXITY
Low expertise - Moderate time consumption

DEVELOPMENT PHASE
Deliver

R-STRATEGIES
R1-10

SOURCE
Baldassare et al. (2020)

EDD FRAMEWORK
E&A - CONCEPT EVALUATION

DEFINITION
The Emotional Durability Design Nine—consisting of nine themes: relationships, narratives, identity, imagination, conversations, consciousness, integrity, materiality, and evolvability. These nine themes are complemented by 38 strategies that help in the development of more emotionally engaging product experiences.

COMPLEXITY
Low expertise - Moderate time consumption

DEVELOPMENT PHASE
Deliver

R-STRATEGIES
R4-10

SOURCE
Haines-Gadd et al. (2018)

CIRCULAR REBOUND TOOL

E&A - CONCEPT EVALUATION

DEFINITION

The Circular Rebound Tool' nudges users to scrutinize their assumptions about the environmental impact reduction potential of their new circular business model ideas, and nurtures further experimentation towards high-impact circular business models. The tool is designed for use by practitioners with basic knowledge of circular economy without expert guidance.

COMPLEXITY

Low expertise - Moderate time consumption

DEVELOPMENT PHASE

Deliver

R-STRATEGIES

R4-10

SOURCE

Das et al. (2023)

ECO-DESIGN STRATEGY

E&A - CONCEPT EVALUATION

DEFINITION

Eco-design considers environmental aspects at all stages of the product development process, striving for products which make the lowest possible environmental impact throughout the product life cycle. The eco-design strategy wheel can be used to design and evaluate a product according to the eco-design principle.

COMPLEXITY

Low expertise - Moderate time consumption

DEVELOPMENT PHASE

Deliver

R-STRATEGIES

R1-10

SOURCE

Van Boeijen et al. (2018)

REPAIRABILITY INDEX

E&A - CONCEPT EVALUATION

DEFINITION

The index assesses 5 criteria:

1. Documentation
2. Disassembly
3. Availability of spare parts
4. Price of spare parts
5. Product-specific aspects

The first 4 criteria are the same for all products groups, the 5th criterion looks into product-specific properties. For smartphones, laptops and TVs this includes software aspects.

COMPLEXITY

Moderate expertise - Moderate time consumption

DEVELOPMENT PHASE

Deliver

R-STRATEGIES

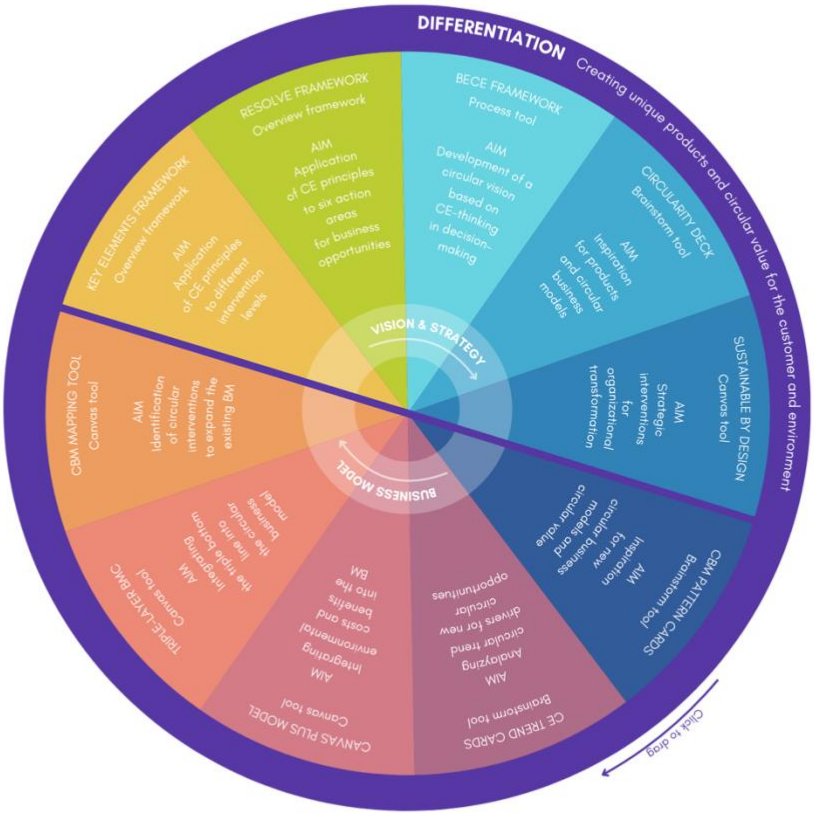
R4-8

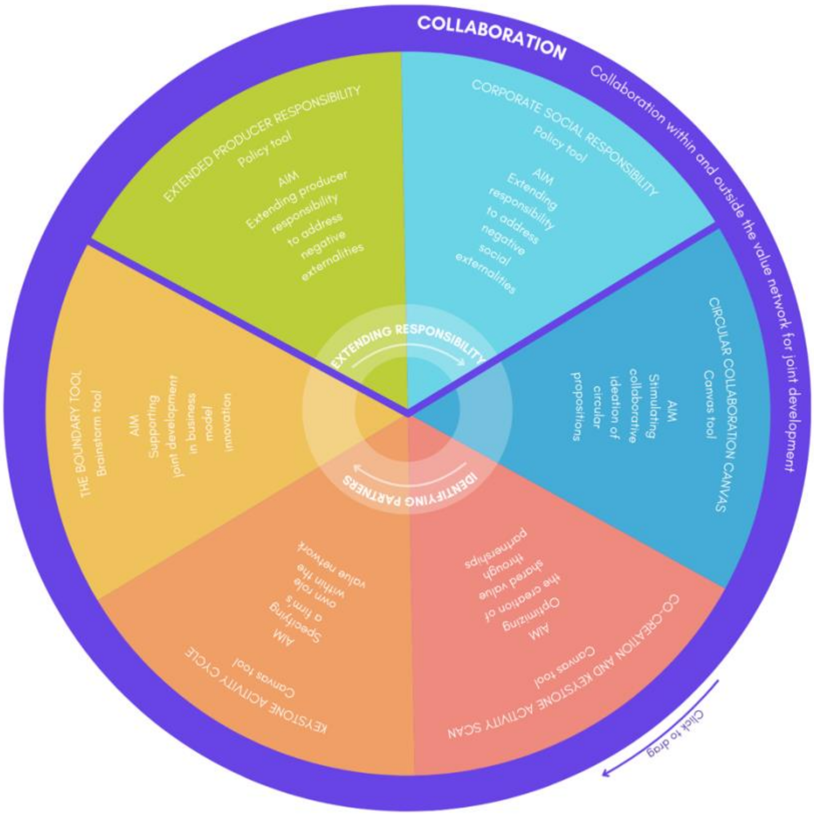
SOURCE

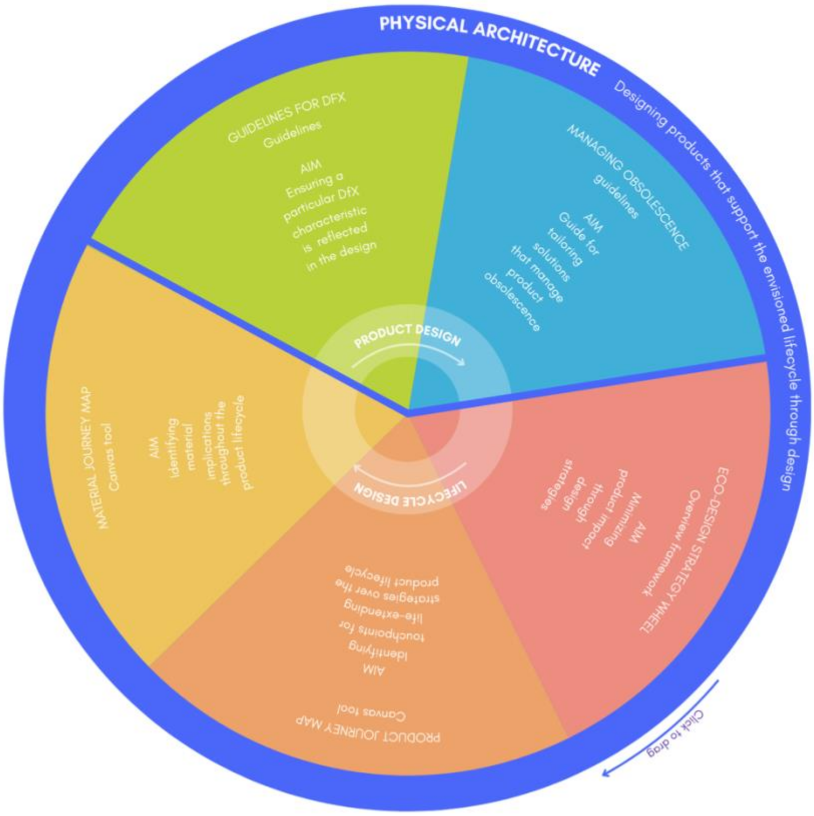
French repairability index (n.d.)

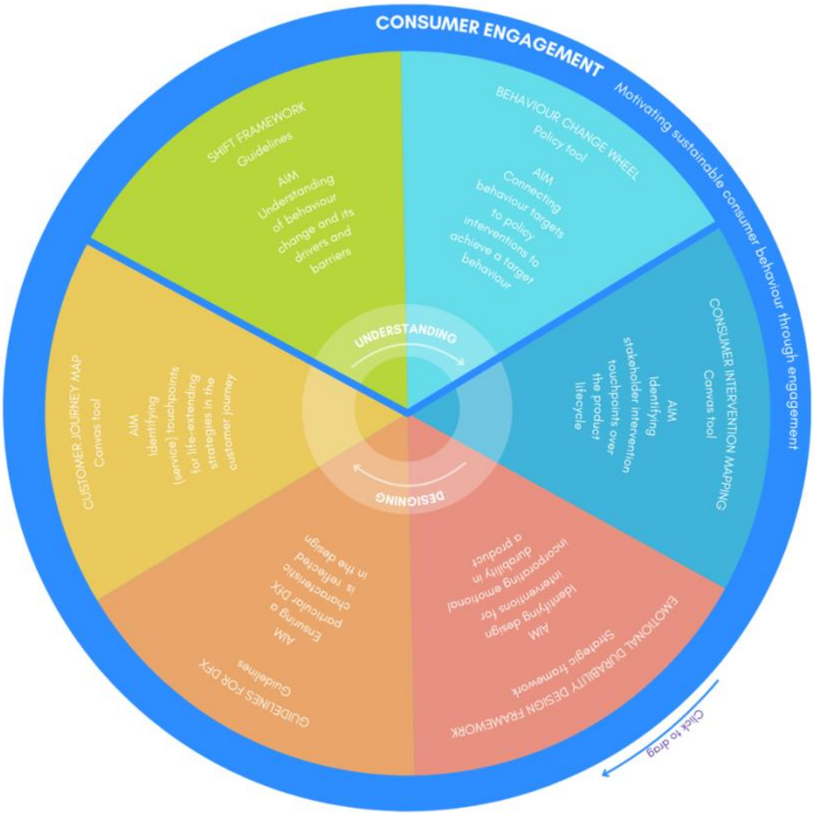
Appendix G

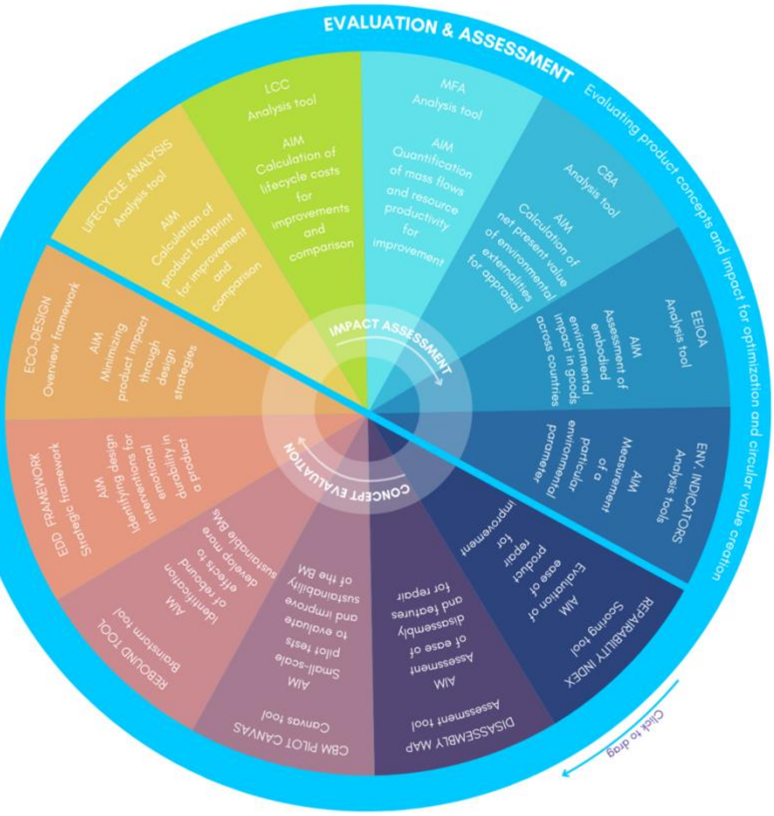
Visual overview of proposed model






PHYSICAL ARCHITECTURE
Designing products that support the envisioned lifecycle through design
GUIDELINES FOR DFX
Guidelines
AIM
Ensuring a particular DfX characteristic is reflected in the design
MANAGING OBSOLESCENCE
guidelines
AIM
Guide for tailoring solutions that manage product obsolescence
ECO-DESIGN STRATEGY WHEEL
Overview framework
AIM
Minimizing product impact through design strategies
PRODUCT JOURNEY MAP
Canvas tool
AIM
Identifying touchpoints for life-extending strategies over the product lifecycle
MATERIAL JOURNEY MAP
Canvas tool
AIM
Identifying material implications throughout the product lifecycle
PRODUCT DESIGN
LIFECYCLE DESIGN
Click to drag


CONSUMER ENGAGEMENT
Motivating sustainable consumer behaviour through engagement
SHIFT FRAMEWORK
Guidelines
AIM
Understanding of behaviour change and its drivers and barriers
BEHAVIOUR CHANGE WHEEL
Policy tool
AIM
Connecting behaviour targets to policy interventions to achieve a target behaviour
CONSUMER INTERVENTION MAPPING
Canvas tool
AIM
Identifying stakeholder intervention touchpoints over the product lifecycle
EMOTIONAL DURABILITY DESIGN FRAMEWORK
Strategic framework
AIM
Identifying design interventions for incorporating emotional durability in a product
GUIDELINES FOR DFX
Guidelines
AIM
Ensuring a particular DfX characteristic is reflected in the design
CUSTOMER JOURNEY MAP
Canvas tool
AIM
Identifying (service) touchpoints for life-extending strategies in the customer journey
UNDERSTANDING
DESIGNING
Click to drag



KEY ELEMENTS FRAMEWORK

DIFFERENTIATION - VISION & STRATEGY

DEFINITION

The Key Elements framework exists of eight elements of circularity that can be applied at different intervention levels (for example, national, regional, sector, business, product, process, or material). There are three core elements and five enabling elements. Core elements deal with physical flows directly, whilst enabling elements deal with creating the conditions or removing barriers.

COMPLEXITY

Introductory framework for firms new to the CE
Low expertise - Moderate time consumption

DEVELOPMENT PHASE

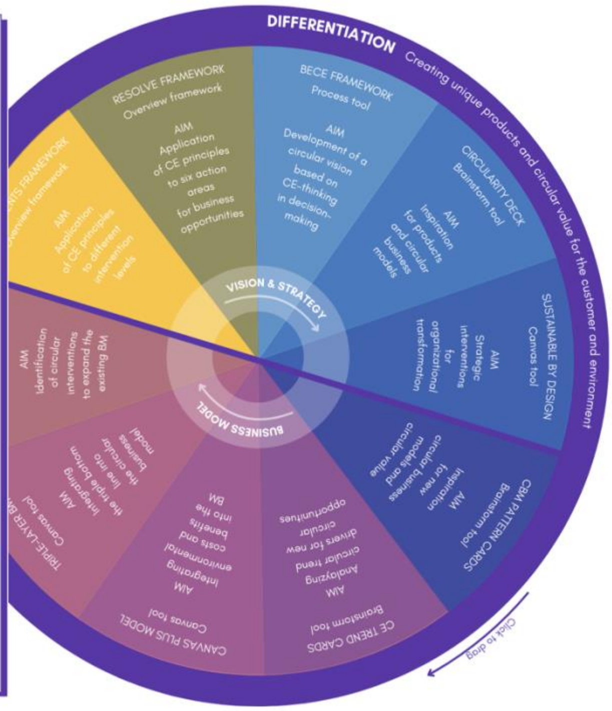
Define

R-STRATEGIES

R1-10

SOURCE

Circle economy
https://www.circle-economy.com/resources/the-key-elements-of-the-circular-economy-framework




DIFFERENTIATION Creating unique products and circular value for the customer and environment
COLLABORATION Collaboration within and outside the value network for joint development
PHYSICAL ARCHITECTURE Designing products that support the envisioned lifecycle through design
CONSUMER ENGAGEMENT Motivating sustainable consumer behaviour through engagement
EVALUATION AND ASSESSMENT Evaluating product concepts and impact for optimalisation of circular value
SMART PRODUCT AND MATERIAL USE
Refuse Rethink Reduce
EXTEND LIFETIME OF PRODUCTS AND PRODUCT PARTS
Reuse Repair Repurpose Refurbish Remanufacture
USEFUL APPLICATION OF MATERIALS
Recycle


DIFFERENTIATION Creating unique products and circular value for the customer and environment
COLLABORATION Collaboration within and outside the value network for joint development
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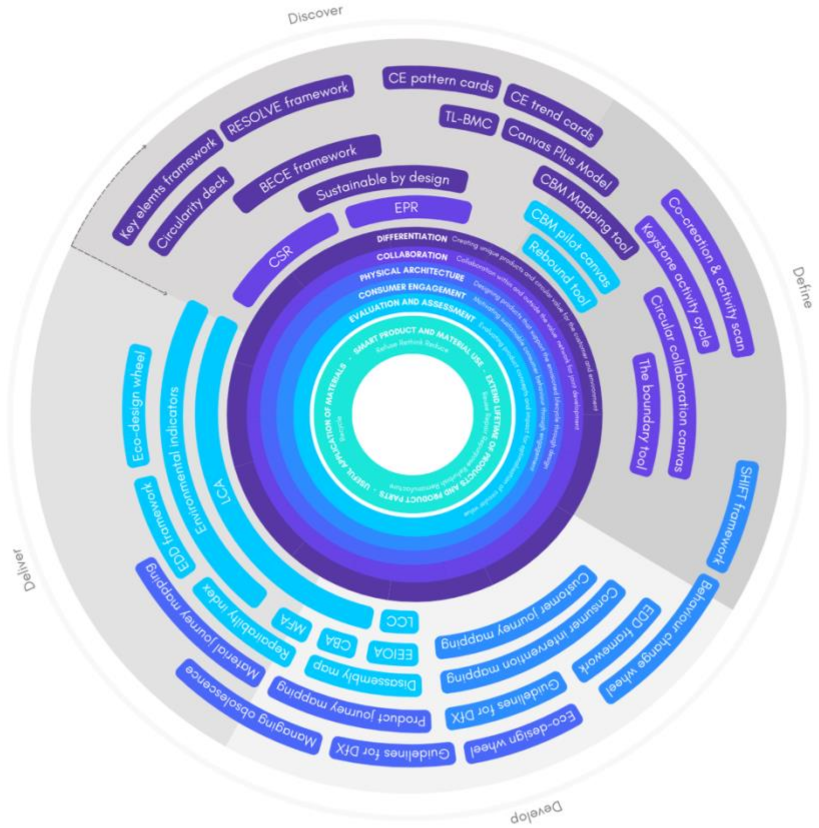
USEFUL APPLICATION OF MATERIALS
Recycle
KEY ELEMENTS FRAMEWORK
EDD FRAMEWORK
CE TREND CARDS
LIFECYCLE ANALYSIS
PRODUCT JOURNEY MAP
COLLABORATION CANVAS
CBM MAPPING TOOL


Discover
Define
Develop
Deliver
CE pattern cards
CE trend cards
TL-BMC
Canvas Plus Model
RESOLVE framework
Key elements framework
Circularity deck
BECE framework
Sustainable by design
EPR
CSR
CBM Mapping tool
CBM pilot canvas
Rebound tool
Co-creation & activity scan
Keystone activity cycle
Circular collaboration canvas
The boundary tool
SHIFT framework
Behaviour change wheel
EDD framework
Consumer intervention mapping
Customer journey mapping
Guidelines for DfX
Eco-design wheel
Guidelines for DfX
Product journey mapping
Disassembly map
EEIOA
LCC
CBA
MFA
Reparability index
Material journey mapping
Managing obsolescence
EDD framework
Eco-design wheel
Environmental indicators
LCA
DIFFERENTIATION
COLLABORATION
PHYSICAL ARCHITECTURE
CONSUMER ENGAGEMENT
EVALUATION AND ASSESSMENT
SMART PRODUCT AND MATERIAL USE
EXTEND LIFETIME OF PRODUCTS AND PRODUCT PARTS
USEFUL APPLICATION OF MATERIALS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CE trend cards
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RESOLVE framework
Key elements framework
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Behaviour change wheel
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Guidelines for DfX
Eco-design wheel
Guidelines for DfX
Product journey mapping
Disassembly map
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LCC
CBA
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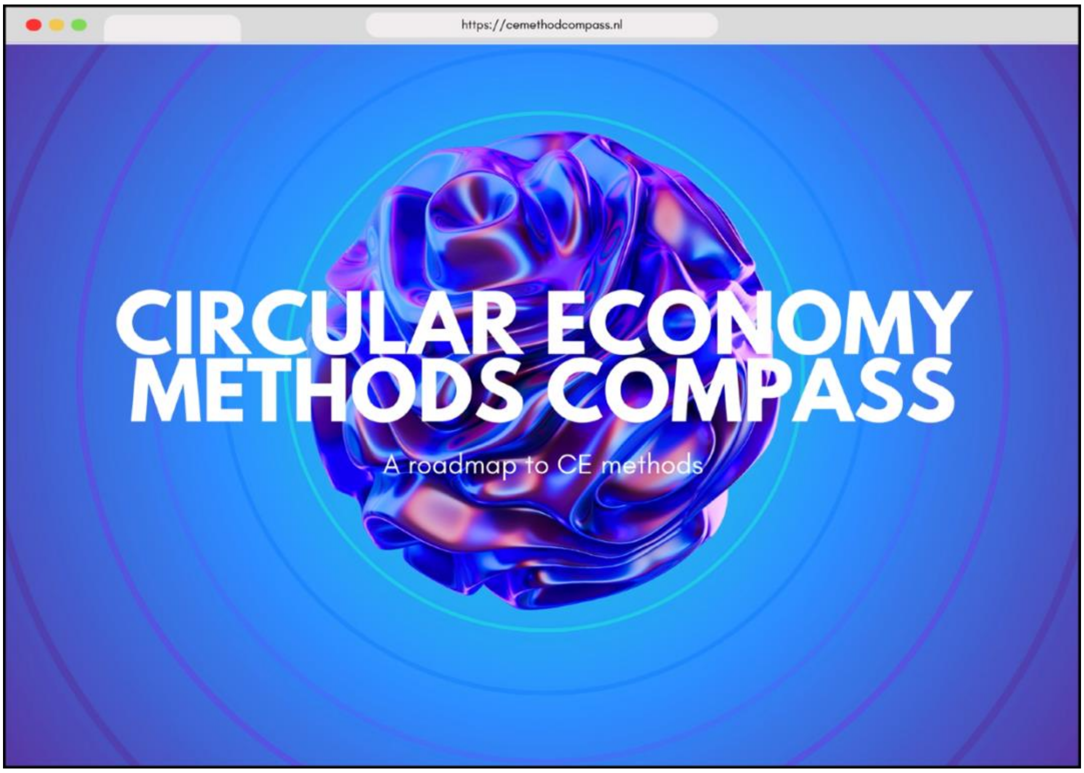
EDD framework
Eco-design wheel
Environmental indicators
LCA
DIFFERENTIATION
COLLABORATION
PHYSICAL ARCHITECTURE
CONSUMER ENGAGEMENT
EVALUATION AND ASSESSMENT
SMART PRODUCT AND MATERIAL USE
EXTEND LIFETIME OF PRODUCTS AND PRODUCT PARTS
USEFUL APPLICATION OF MATERIALS

Appendix H

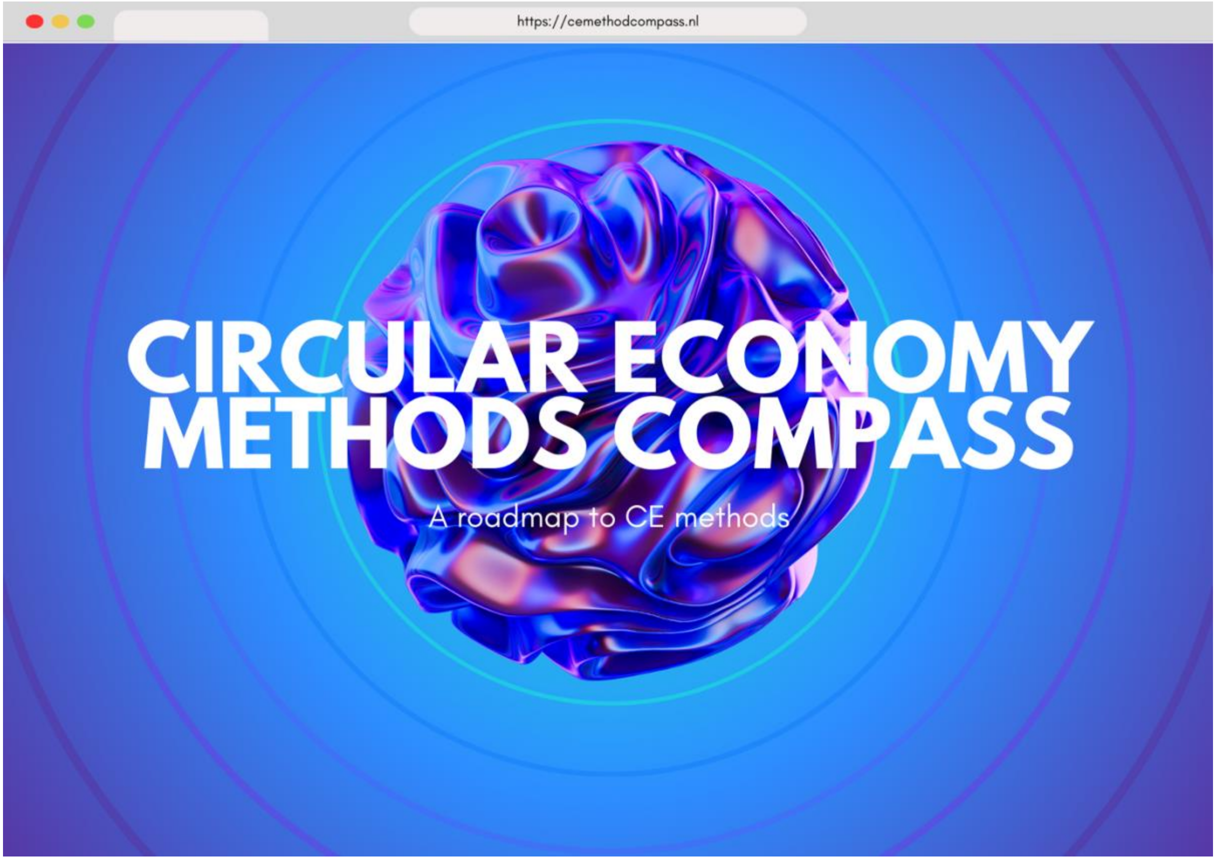
Visuals and link of mock-up of website

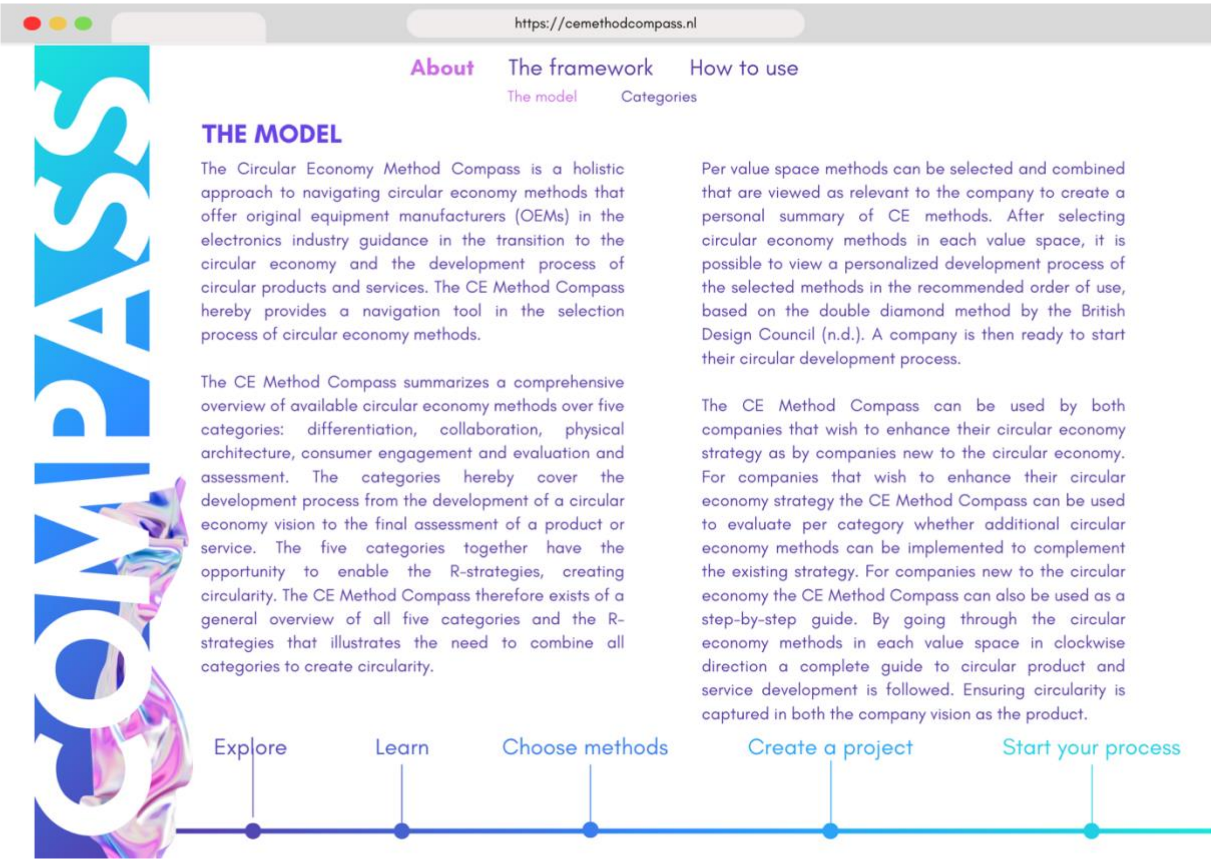
Link to mock-up
https://www.figma.com/proto/Zsu2V5VRQJB9fWZyFcGT0B/Thesis-website?node-id=7-22&t=6QSLTRl6YgYrtVdF-1&scaling=contain&page-id=0%3A1&starting-point-node-id=7%3A22

Video tour of website



Visuals of website





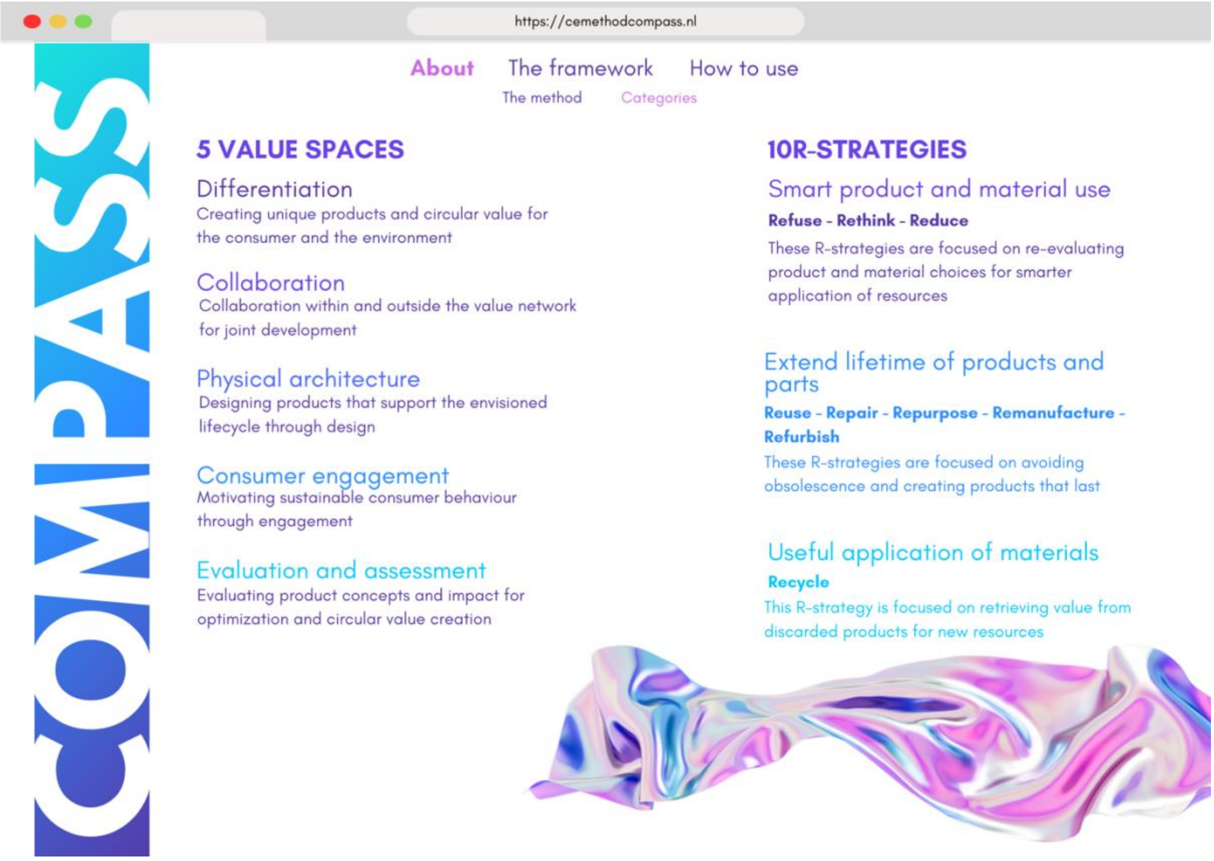
THE MODEL

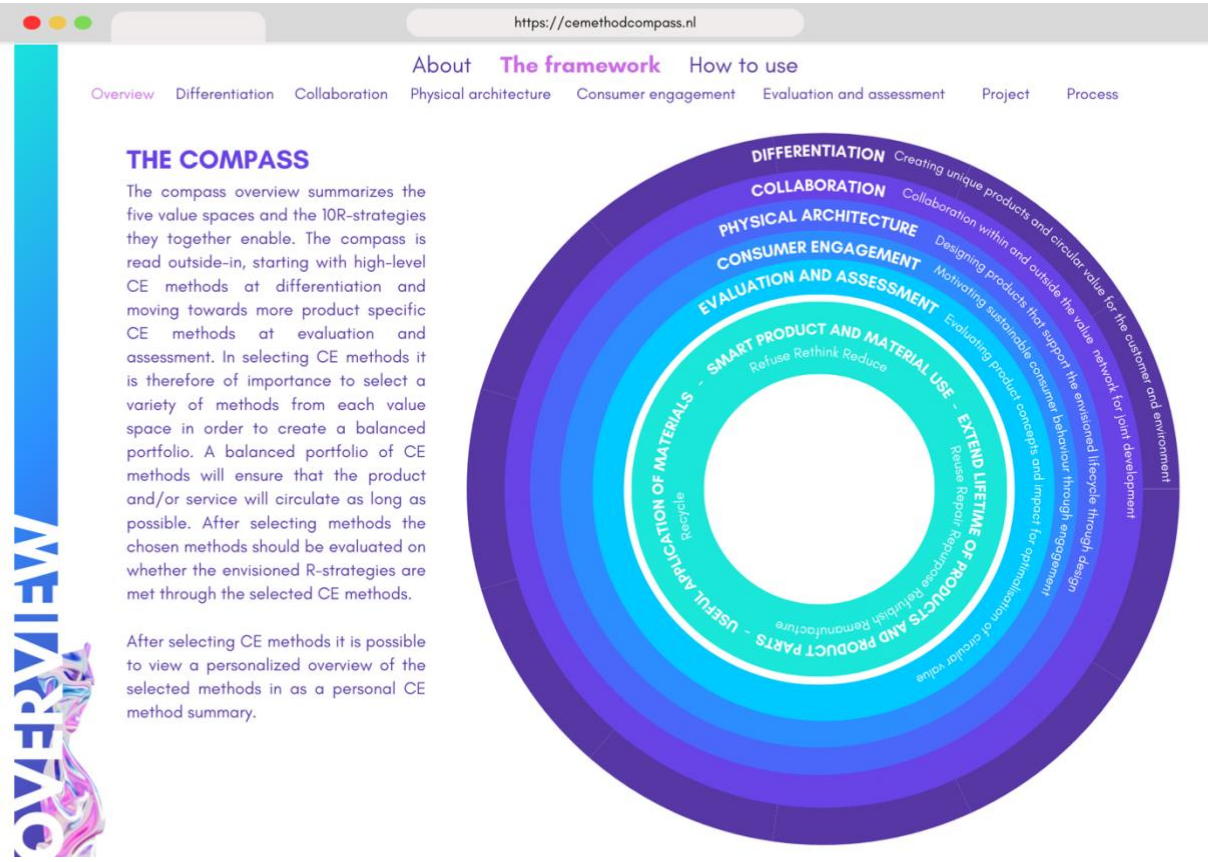
The Circular Economy Method Compass is a holistic approach to navigating circular economy methods that offer original equipment manufacturers (OEMs) in the electronics industry guidance in the transition to the circular economy and the development process of circular products and services. The CE Method Compass hereby provides a navigation tool in the selection process of circular economy methods.

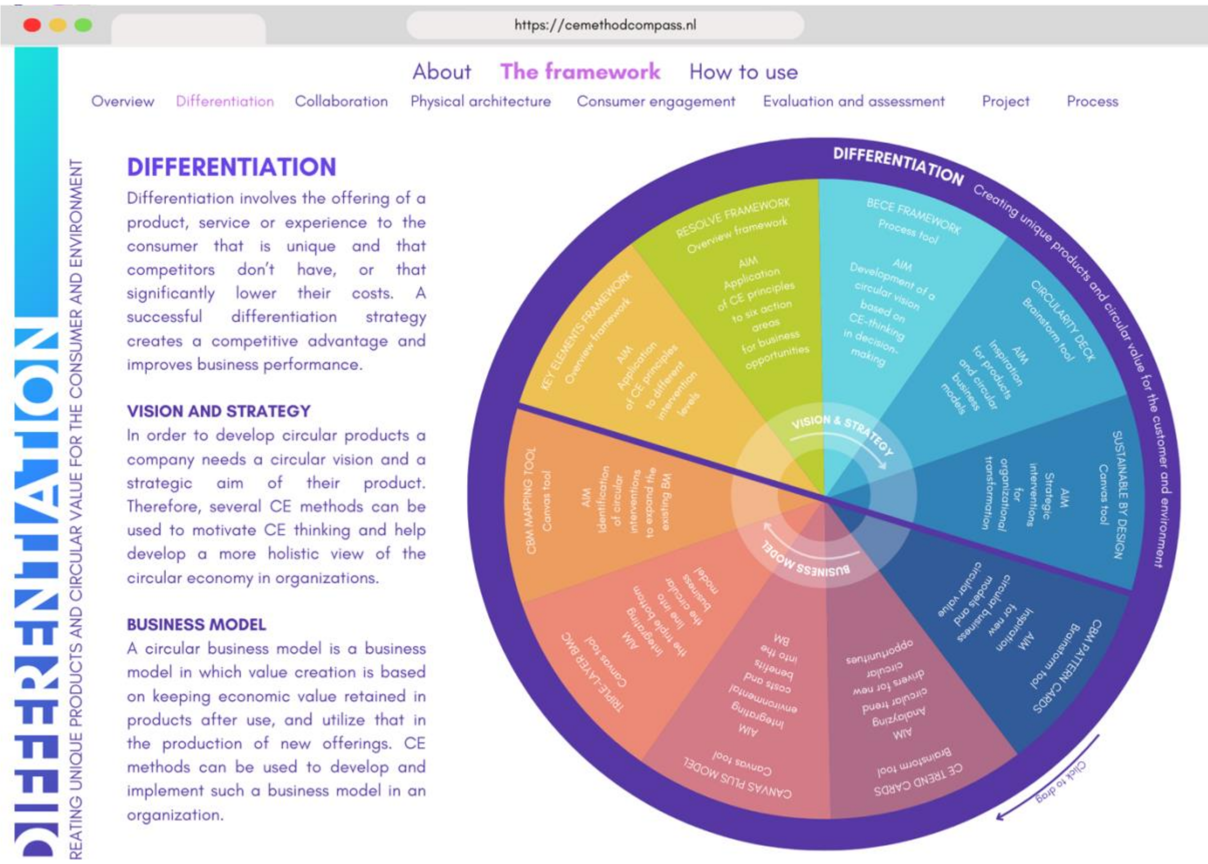
The CE Method Compass summarizes a comprehensive overview of available circular economy methods over five categories: differentiation, collaboration, physical architecture, consumer engagement and evaluation and assessment. The categories hereby cover the development process from the development of a circular economy vision to the final assessment of a product or service. The five categories together have the opportunity to enable the R-strategies, creating circularity. The CE Method Compass therefore exists of a general overview of all five categories and the R-strategies that illustrates the need to combine all categories to create circularity.

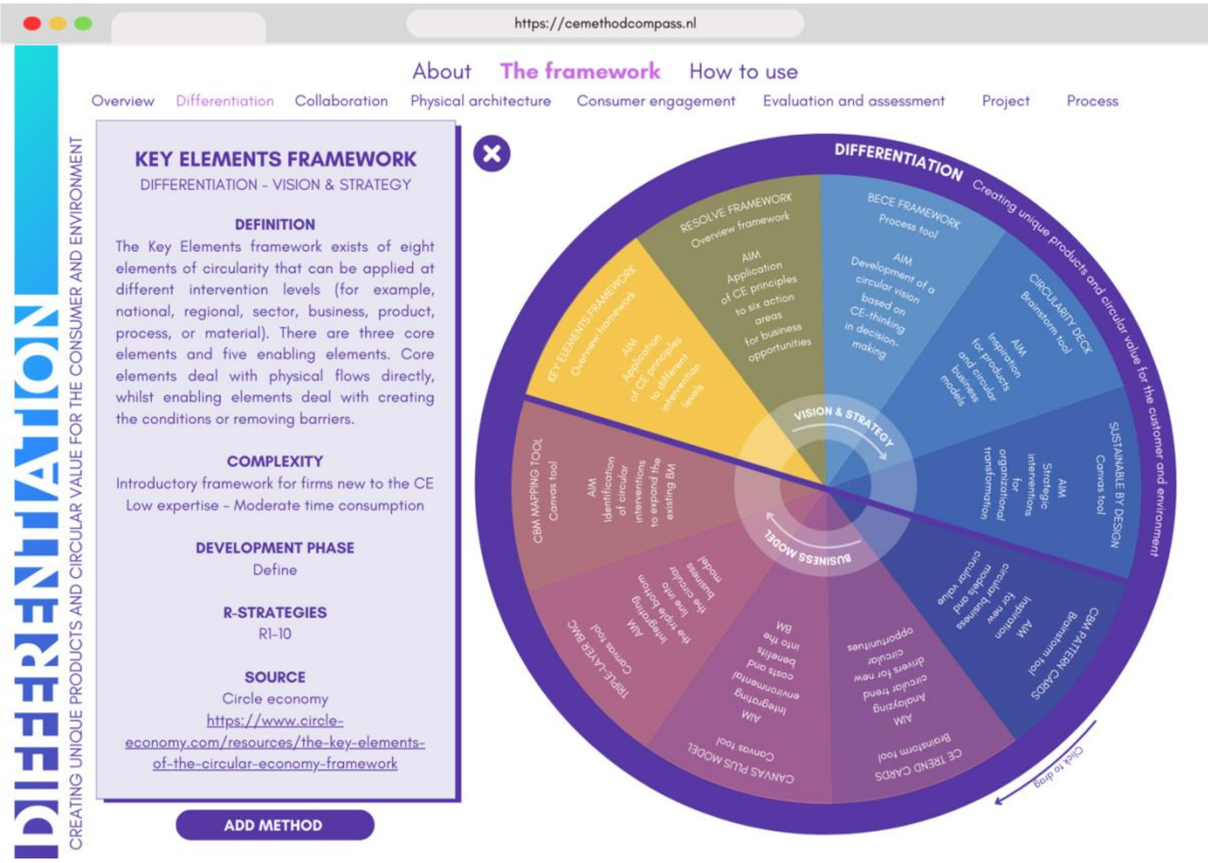
Per value space methods can be selected and combined that are viewed as relevant to the company to create a personal summary of CE methods. After selecting circular economy methods in each value space, it is possible to view a personalized development process of the selected methods in the recommended order of use, based on the double diamond method by the British Design Council (n.d.). A company is then ready to start their circular development process.

The CE Method Compass can be used by both companies that wish to enhance their circular economy strategy as by companies new to the circular economy. For companies that wish to enhance their circular economy strategy the CE Method Compass can be used to evaluate per category whether additional circular economy methods can be implemented to complement the existing strategy. For companies new to the circular economy the CE Method Compass can also be used as a step-by-step guide. By going through the circular economy methods in each value space in clockwise direction a complete guide to circular product and service development is followed. Ensuring circularity is captured in both the company vision as the product.


https://cemethodcompass.nl
About
The framework
How to use
The method
Categories
COMPASS
5 VALUE SPACES
Differentiation
Creating unique products and circular value for the consumer and the environment
Collaboration
Collaboration within and outside the value network for joint development
Physical architecture
Designing products that support the envisioned lifecycle through design
Consumer engagement
Motivating sustainable consumer behaviour through engagement
Evaluation and assessment
Evaluating product concepts and impact for optimization and circular value creation
10R-STRATEGIES
Smart product and material use
Refuse - Rethink - Reduce
These R-strategies are focused on re-evaluating product and material choices for smarter application of resources
Extend lifetime of products and parts
Reuse - Repair - Repurpose - Remanufacture - Refurbish
These R-strategies are focused on avoiding obsolescence and creating products that last
Useful application of materials
Recycle
This R-strategy is focused on retrieving value from discarded products for new resources


https://cemethodcompass.nl
About
The framework
How to use
Overview
Differentiation
Collaboration
Physical architecture
Consumer engagement
Evaluation and assessment
Project
Process
OVERVIEW
THE COMPASS
The compass overview summarizes the five value spaces and the 10R-strategies they together enable. The compass is read outside-in, starting with high-level CE methods at differentiation and moving towards more product specific CE methods at evaluation and assessment. In selecting CE methods it is therefore of importance to select a variety of methods from each value space in order to create a balanced portfolio. A balanced portfolio of CE methods will ensure that the product and/or service will circulate as long as possible. After selecting methods the chosen methods should be evaluated on whether the envisioned R-strategies are met through the selected CE methods.
After selecting CE methods it is possible to view a personalized overview of the selected methods in as a personal CE method summary.
DIFFERENTIATION Creating unique products and circular value for the customer and environment
COLLABORATION Collaboration within and outside the value network for joint development
PHYSICAL ARCHITECTURE Designing products that support the envisioned lifecycle through design
CONSUMER ENGAGEMENT Motivating sustainable consumer behaviour through engagement
EVALUATION AND ASSESSMENT Evaluating product concepts and impact for optimalisation of circular value
SMART PRODUCT AND MATERIAL USE
Refuse Rethink Reduce
EXTEND LIFETIME OF PRODUCTS AND PRODUCT PARTS
Reuse Repair Repurpose Refurbish Remanufacture
USEFUL APPLICATION OF MATERIALS
Recycle


https://cemethodcompass.nl
About
The framework
How to use
Overview
Differentiation
Collaboration
Physical architecture
Consumer engagement
Evaluation and assessment
Project
Process
DIFFERENTIATION
CREATING UNIQUE PRODUCTS AND CIRCULAR VALUE FOR THE CONSUMER AND ENVIRONMENT
DIFFERENTIATION
Differentiation involves the offering of a product, service or experience to the consumer that is unique and that competitors don't have, or that significantly lower their costs. A successful differentiation strategy creates a competitive advantage and improves business performance.
VISION AND STRATEGY
In order to develop circular products a company needs a circular vision and a strategic aim of their product. Therefore, several CE methods can be used to motivate CE thinking and help develop a more holistic view of the circular economy in organizations.
BUSINESS MODEL
A circular business model is a business model in which value creation is based on keeping economic value retained in products after use, and utilize that in the production of new offerings. CE methods can be used to develop and implement such a business model in an organization.
DIFFERENTIATION Creating unique products and circular value for the customer and environment
RESOLVE FRAMEWORK
Overview framework
AIM Application of CE principles to six action areas for business opportunities
BECE FRAMEWORK
Process tool
AIM Development of a circular vision based on CE-thinking in decision-making
KEY ELEMENTS FRAMEWORK
Overview framework
AIM Application of CE principles to different intervention levels
CIRCULARITY DECK
Brainstorm tool
AIM Inspiration for products and circular business models
SUSTAINABLE BY DESIGN
Canvas tool
AIM Strategic interventions for organizational transformation
CBM MAPPING TOOL
Canvas tool
AIM Identification of circular interventions to expand the existing BM
VISION & STRATEGY
BUSINESS MODEL
TRIPLE-LAYER BMC
Canvas tool
AIM Integrating the triple bottom line into the circular business model
CANVAS PLUS MODEL
Canvas tool
AIM Integrating environmental costs and benefits into the BM
CE TREND CARDS
Brainstorm tool
AIM Analyzing circular trend drivers for new circular opportunities
CBM PATTERN CARDS
Brainstorm tool
AIM Inspiration for new circular business models and circular value
Click to drag


https://cemethodcompass.nl
About
The framework
How to use
Overview
Differentiation
Collaboration
Physical architecture
Consumer engagement
Evaluation and assessment
Project
Process
DIFFERENTIATION
CREATING UNIQUE PRODUCTS AND CIRCULAR VALUE FOR THE CONSUMER AND ENVIRONMENT
KEY ELEMENTS FRAMEWORK
DIFFERENTIATION - VISION & STRATEGY
DEFINITION
The Key Elements framework exists of eight elements of circularity that can be applied at different intervention levels (for example, national, regional, sector, business, product, process, or material). There are three core elements and five enabling elements. Core elements deal with physical flows directly, whilst enabling elements deal with creating the conditions or removing barriers.
COMPLEXITY
Introductory framework for firms new to the CE
Low expertise - Moderate time consumption
DEVELOPMENT PHASE
Define
R-STRATEGIES
R1-10
SOURCE
Circle economy
https://www.circle-economy.com/resources/the-key-elements-of-the-circular-economy-framework
ADD METHOD
DIFFERENTIATION Creating unique products and circular value for the customer and environment
VISION & STRATEGY
BUSINESS MODEL
Click to drag

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COLLABORATION

COLLABORATION WITHIN AND OUTSIDE THE VALUE NETWORK FOR JOINT DEVELOPMENT

COLLABORATION

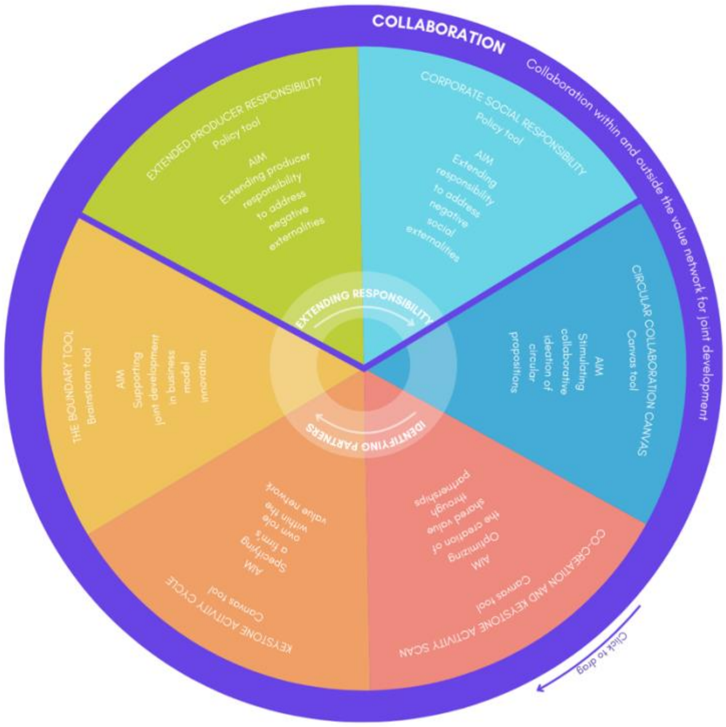
Collaboration is defined by the value network in which value is co-created. Activities revolve around the value-creating system instead of the company or industry itself. Where different economic actors (suppliers, partners, stakeholders, clients and more) co-produce value through collaborative partnerships. Client engagement is also considered in this value space.

EXTENDING RESPONSIBILITY

Considering the increasing complexity of supply and value chains and the involvement of different parties throughout, collaboration has become an important strategy to achieve shared goals. CE methods can be used to extend the responsibility of an organization to the ecosystem.

IDENTIFYING PARTNERS AND STAKEHOLDERS

CE methods can support organization in identifying potential partners that can fulfil the needed roles required throughout the value chain for a particular product in joint development.



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PHYSICAL ARCHITECTURE

DESIGNING PRODUCTS THAT SUPPORT THE ENVISIONED LIFECYCLE THROUGH DESIGN

PHYSICAL ARCHITECTURE

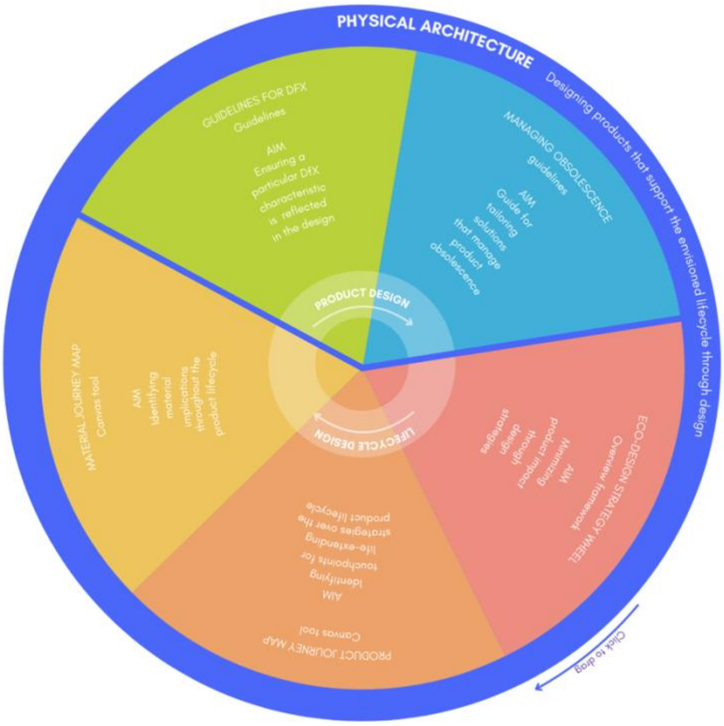
The physical architecture of a product is defined by its technical design. Factors that affect the physical architecture of a product are the design requirements and strategies that are used as well as the lifecycle of the product that results in certain design choices and requirements.

PRODUCT DESIGN

Each CE strategy requires a different design strategy and each design strategy calls for a different design approach. Together these will influence the lifecycle of the product. CE methods can be used to guide and support this design process.

LIFECYCLE DESIGN

Besides the product itself, its lifecycle also needs to be envisioned to ensure proper handling of the product throughout its lifetime. CE methods can be used to envision such a lifecycle and identify touchpoints where intervention might be needed.



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CONSUMER ENGAGEMENT

MOTIVATING SUSTAINABLE CONSUMER BEHAVIOUR THROUGH ENGAGEMENT

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CONSUMER ENGAGEMENT

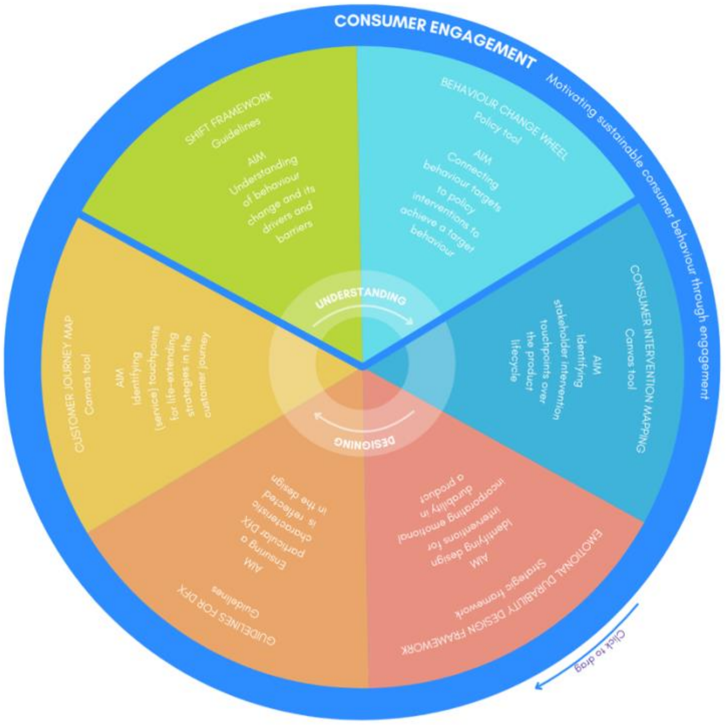
Consumer engagement involves the shift from traditional consumption in a linear economy to sustainable consumer behaviour in a circular economy. Sustainable consumer behaviour is key to circular economy in order to keep products in use for longer and close the loop at end-of-life.

UNDERSTANDING BEHAVIOUR CHANGE

Besides strategies focused at creating circular products, the use of the product is also an important element to consider for circularity to be achieved. CE methods can be used to understand how behaviour change comes about in order to design products that motivate behaviour change.

DESIGNING FOR BEHAVIOUR CHANGE

When behaviour change is understood properly, CE methods can be used to identify design and/or service interventions that have the ability to alter consumer behaviour for sustainability.



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EVALUATION & ASSESSMENT

EVALUATING PRODUCT CONCEPTS AND IMPACT FOR OPTIMALISATION OF CIRCULAR VALUE

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EVALUATION & ASSESSMENT

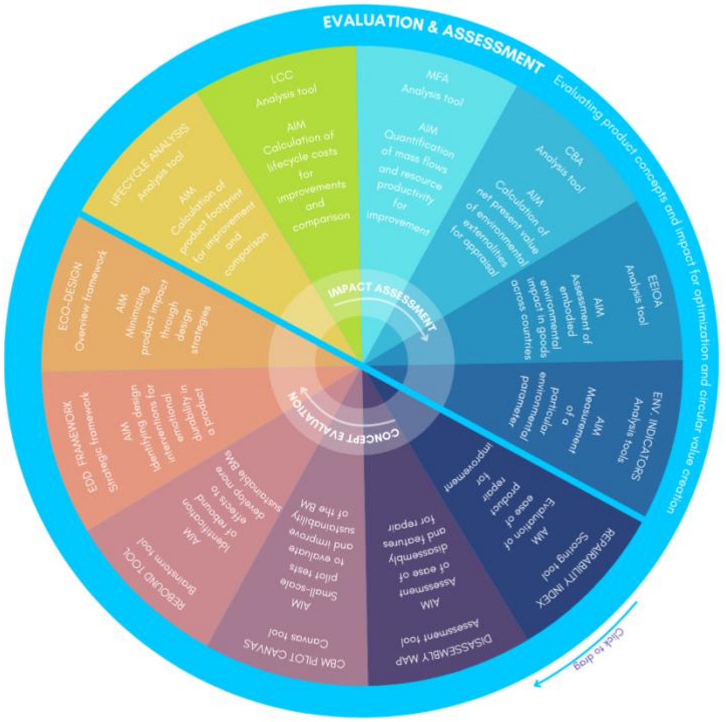
Evaluation and assessment involves the quantitative or qualitative assessment of products and their environmental impact throughout the lifecycle.

IMPACT ASSESSMENT

For the evaluation of products, several environmental indicators and tools are developed to indicate and/or quantify environmental impacts. These methods can be used throughout the lifecycle of a product and help assess the environmental hotspots of a product.

CONCEPT EVALUATION

Besides methods to assess the impact of products, there is also a range of methods to evaluate upon product concepts during the development phase to evaluate whether a design achieves its intended result.



SUMMARY OVERVIEW

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PROJECT OVERVIEW

The summary figure below shows an overview of the selected CE methods per circular value space for an illustrative example. During this phase of the selection process, it should be evaluated whether the selected CE methods covers all five value spaces as well as the intended R-strategies. A balanced selection has the most opportunity to create circular value for the organization, client, consumer and the environment.

PROCESS

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PROCESS

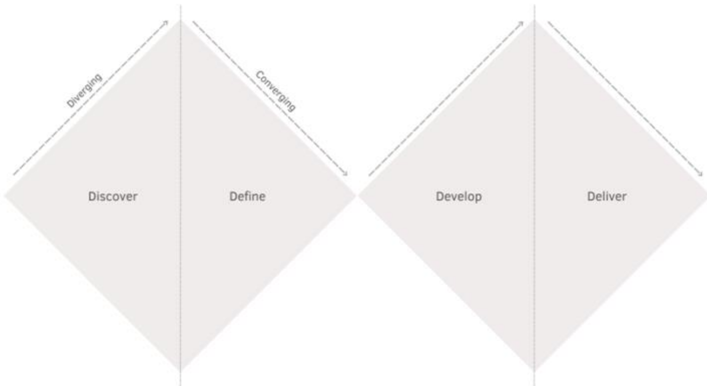
The process overview is based on the phases of the double diamond method by the British Design Council. The double diamond model is a well-known design process tool divided in four phases: discover, define, develop and deliver. The two diamonds represent a process of diverging and converging.

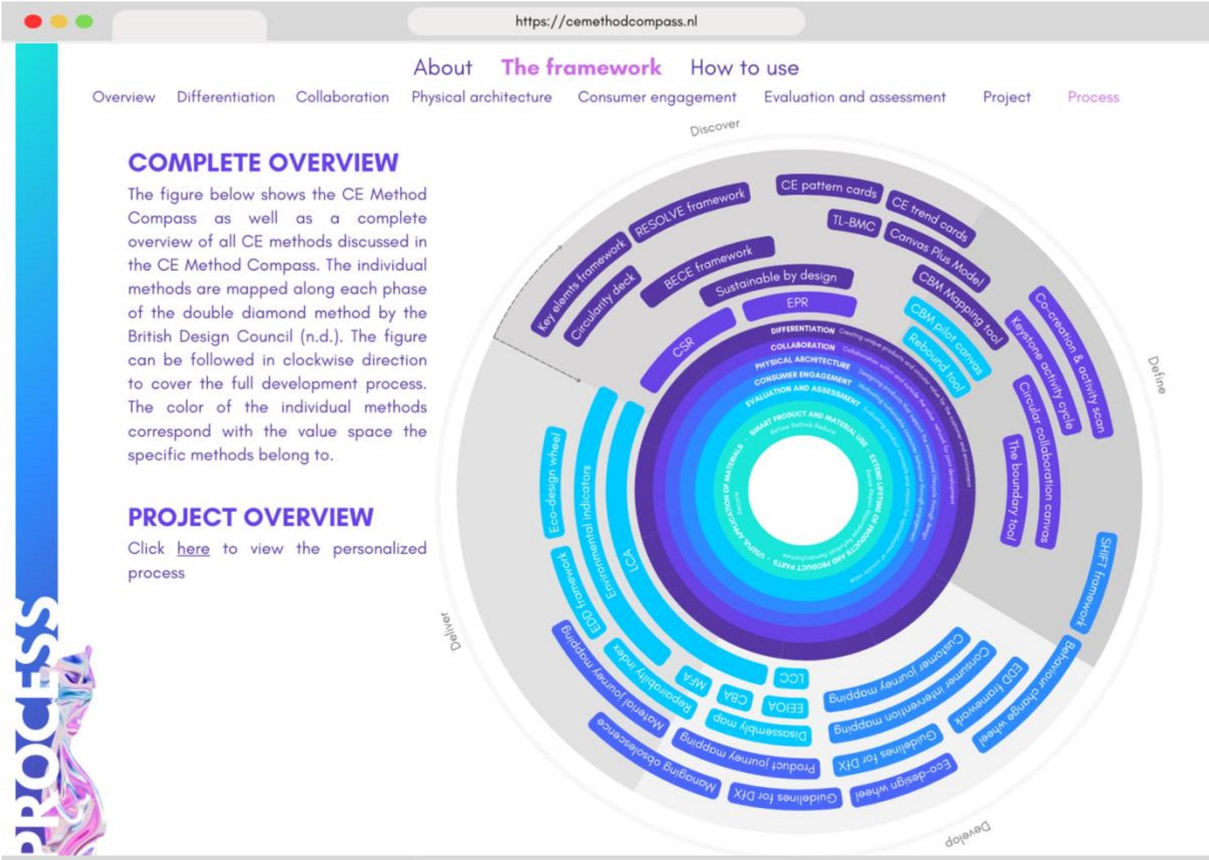
DISCOVER
Understanding the problem

DEFINE
Defining the challenge

DEVELOP
Answering a defined problem

DELIVER
Small-scale testing of different solutions

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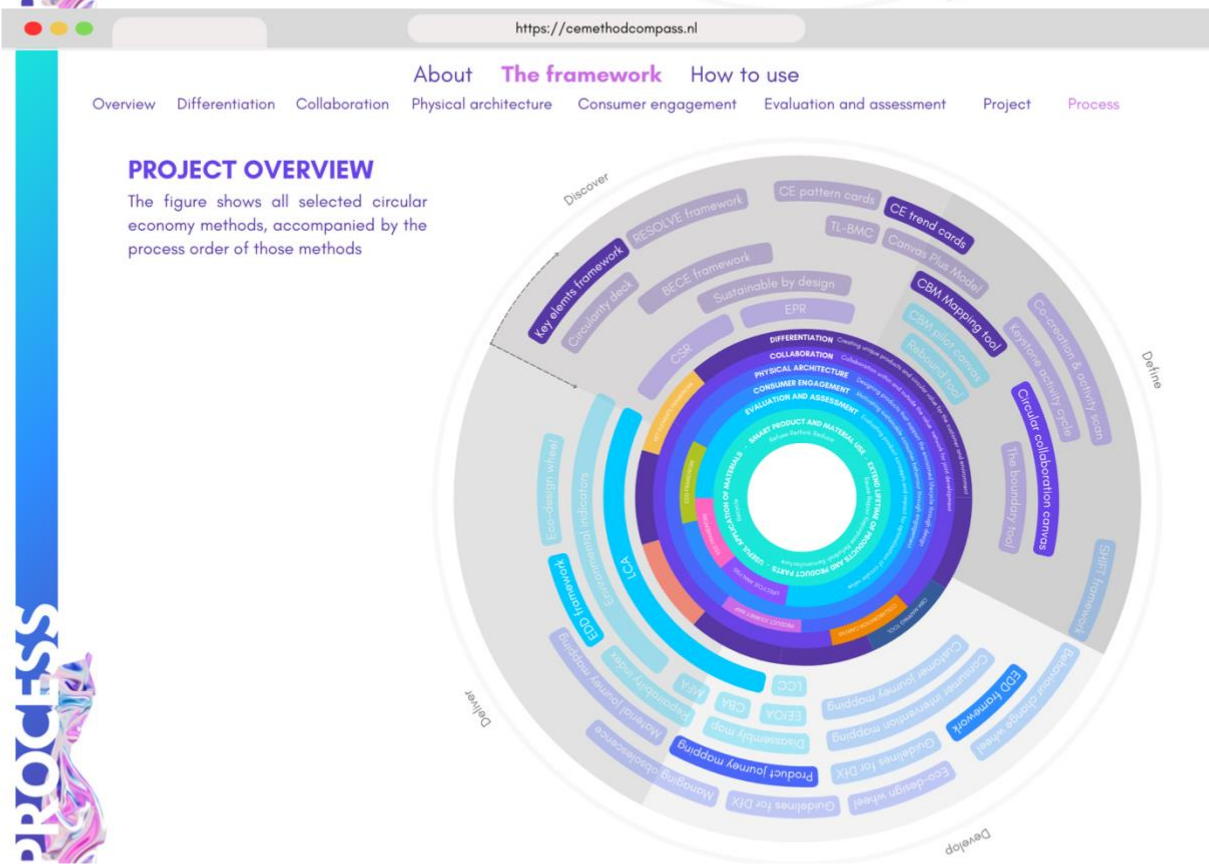
COMPLETE OVERVIEW
The figure below shows the CE Method Compass as well as a complete overview of all CE methods discussed in the CE Method Compass. The individual methods are mapped along each phase of the double diamond method by the British Design Council (n.d.). The figure can be followed in clockwise direction to cover the full development process. The color of the individual methods correspond with the value space the specific methods belong to.
PROJECT OVERVIEW
Click here to view the personalized process
PROCESS
Discover
Define
Develop
Deliver
CE pattern cards
CE trend cards
RESOLVE framework
TL-BMC
Canvas Plus Model
Key elements framework
Circularity deck
BECE framework
Sustainable by design
CBM Mapping tool
EPR
CBM pilot canvas
Rebound tool
CSR
Co-creation & activity scan
Keystone activity cycle
Circular collaboration canvas
The boundary tool
SHIFT framework
Behaviour change wheel
EDD framework
Eco-design wheel
Environmental indicators
LCA
LCC
EEIOA
CBA
MFA
Reparability index
Disassembly map
Material journey mapping
Managing obsolescence
Product journey mapping
Guidelines for DfX
Customer journey mapping
Consumer intervention mapping
DIFFERENTIATION
COLLABORATION
PHYSICAL ARCHITECTURE
CONSUMER ENGAGEMENT
EVALUATION AND ASSESSMENT
SMART PRODUCT AND MATERIAL USE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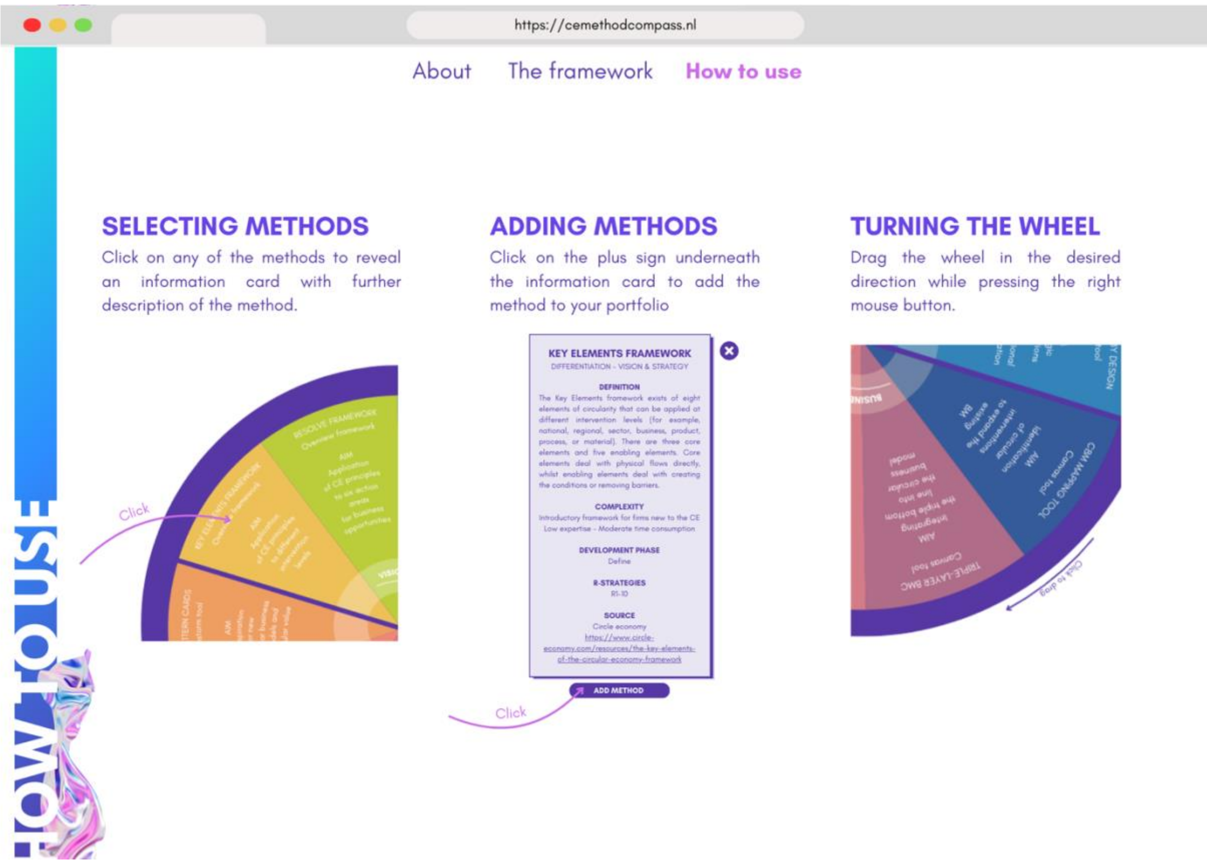
PROJECT OVERVIEW
The figure shows all selected circular economy methods, accompanied by the process order of those methods
PROCESS
Discover
Define
Develop
Deliver
Key elements framework
CE trend cards
CBM Mapping tool
Circular collaboration canvas
LCA
EDD framework
Product journey mapping
DIFFERENTIATION
COLLABORATION
PHYSICAL ARCHITECTURE
CONSUMER ENGAGEMENT
EVALUATION AND ASSESSMENT
SMART PRODUCT AND MATERIAL USE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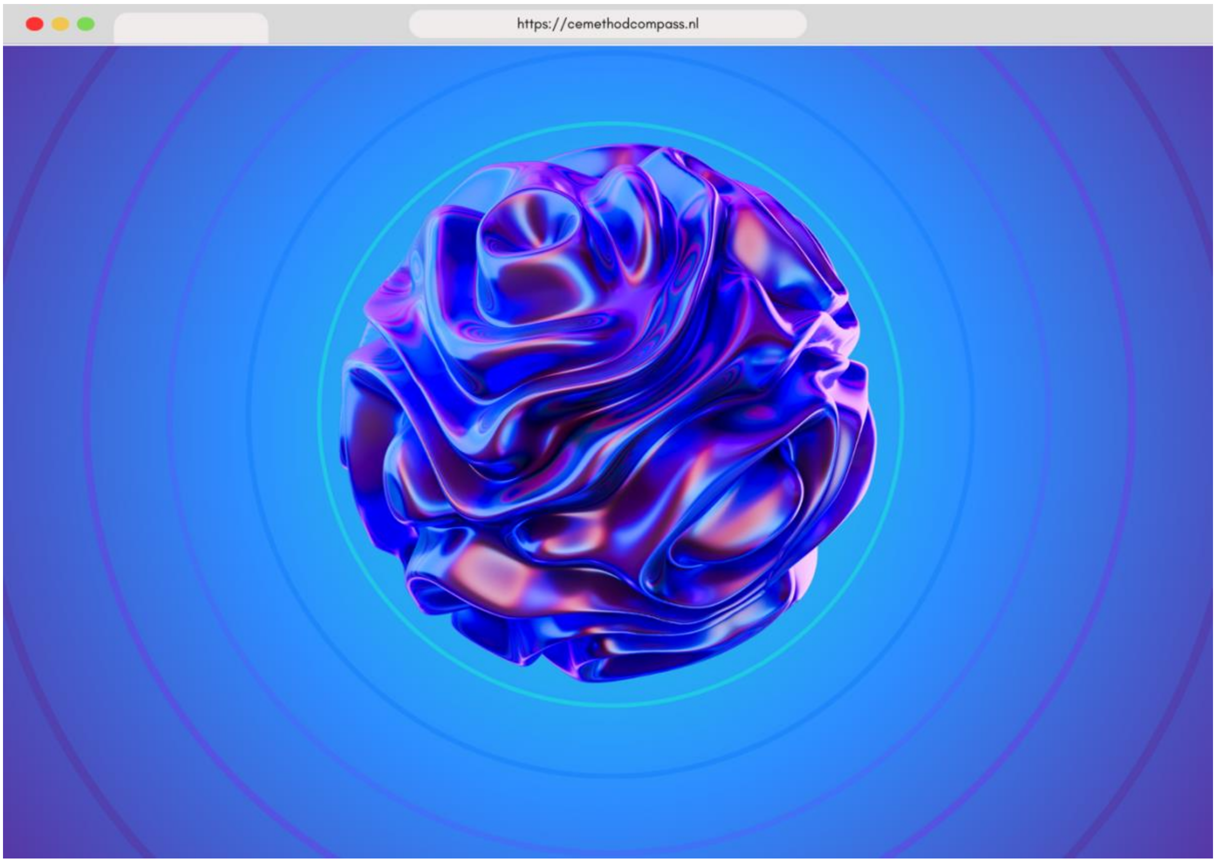
SELECTING METHODS
Click on any of the methods to reveal an information card with further description of the method.
ADDING METHODS
Click on the plus sign underneath the information card to add the method to your portfolio
TURNING THE WHEEL
Drag the wheel in the desired direction while pressing the right mouse button.
Click
KEY ELEMENTS FRAMEWORK
ADD METHOD
Click
HOW TO USE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