report

Developing a dedicated tool to support the development of domestic boilers for a circular economy

Master thesis Industrial Design Engineering

Niek van den Hout

03/2017

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Preface

This report is the result of a master thesis that has been conducted to obtain the Master of Science (MSc) degree in Industrial Design Engineering at the University of Twente in the Netherlands. The research project has been performed at Remeha B.V., a large boiler manufacturer based in Apeldoorn.

This thesis has pursued and implemented a sustainable approach to product development in the corporate environment of Remeha. I believe that we need to change our ways of interpreting and achieving progress in order to sustain our wellbeing on earth. It has been a challenging and rewarding experience to act on this ideology and to find ways for its practical implementation in an industrial organisation. As product developers, I believe we play a crucial role in the transition to a sustainable future. This provides us the opportunity and responsibility to consider the holistic consequences of our decisions. Therefore, this thesis proposes a new approach to product development and a practical tool that supports its realisation by design.

Acknowledgements

I wish to acknowledge those who have been involved in the execution of this thesis. Their support and guidance have been of great value and have made this research into an inspiring and enjoyable experience. Bart van Diepen, who has been my mentor at Remeha, has always supported me with great dedication and enthusiasm. Your critical view on my work has encouraged and enabled me to translate abstract theory into a concrete solution. Ir. Marten Toxopeus, your professional guidance has been of meaningful and much appreciated value to my research. I have enjoyed our challenging discussions in which you always engaged with the utmost interest and positive energy. I wish to thank Jacco Blumink, Klaas Ophoff, and Eddy Slurink for providing me the trust and opportunity to perform my thesis at Remeha. And a special thanks goes out to Idse de Wit, whose expertise and endorsement have been an essential contribution to this research. I have enjoyed our collaboration and I have learned a lot from our many discussions.

Furthermore, I would like to express my gratitude for the unwavering support of my family and friends. You have shared in both my joy and frustrations and always motivated me to give my best. I would like to thank my parents Rina and Fred, my brother Ruben, and my sisters Emma and Amber for their unconditional love and encouragement. And especially my girlfriend Joska, on who I can always rely for care and support. Our shared conviction to contribute to a more sustainable world has been a great source of motivation and your thoughtful insights have been an inspiration to my work.

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Summary

Since the twentieth century, the demand for continuous growth has been met by a high-throughput economy that extracts, uses, and eventually disposes resources. The large-scale consequences of this wasteful system in combination with a growing population have manifested in global issues such as resource depletion and environmental degradation. These consequences give rise to pressing concerns about sustainability that are increasingly expressed through market demands and legislation. This motivates organisations to adopt new and more sustainable ways of development. Remeha, a large boiler manufacturer, shares this motivation and has commissioned this research to develop a tool for considering sustainability in their product development process.

Sustainability is understood as a continuous state of productive balance between society, environment, and economy. In this respect, sustainable development is interpreted as a principle for organising temporal processes to reach and maintain that balanced state. Adopting sustainable development is a deliberate, strategic choice in the pursuit for sustainability. One that answers to society's need for technological progress and therefore one that aligns with Remeha's corporate practice as a product manufacturer.

There is a multitude of different concepts to interpret and practice sustainable development in a corporate environment. An analysis of these concepts has revealed the circular economy as an appropriate and promising approach to sustainable development that will be adopted for this research. The circular economy proposes a model for organising industrial processes in fundamentally different and more resource effective ways. It centres around the idea of an economy that uses resources in closed loops rather than linear flows. This way, the circular economy decouples economic growth from resource extraction. However, this concept remains too abstract to be put into practice by Remeha. Therefore, a framework is proposed that describes five key principles of the circular economy by which processes can be arranged for a circular transition. These principles can be applied to three distinct areas of Remeha's organisation: product design, supply chain, and business model. Given Remeha's need to pursue sustainability through product development, the primary focus of this research is on implementing the principles of circularity in the area of product design. To further support this implementation with business potential, a new business model is considered as a secondary focus. This leads to the development of a product-service system that allows financial and strategic benefit from developing boilers in a more resource-effective way.

In translating the principles of circularity into the product development domain, different design strategies can be distinguished to develop boilers for increased resource effectivity. One design strategy that aims to realise closed-loop resource flows by design has been selected for further implementation. This design strategy aims to develop boilers in a way that allows the value they embed to be recovered, restored, and used again once the boiler becomes obsolete. The end-of-life stages of the product lifecycle are introduced as a priority in design and regards the boiler not just as a functional object, but as a carrier of future resources. The design strategy provides a clear line of thought for development, but it does not answer how it could be realised by design. This presents a challenge to Remeha's product engineers, because they are unfamiliar with developing products for a circular economy. To this end, a digital design tool is developed that guides product engineers in realising the proposed strategy through their design decisions. The principle of the tool is to provide product engineers with practical information about the relation between product characteristics and the processes that collect and restore their value. This information is embodied by design guidelines that inform and inspire design decisions through prescriptive recommendations. In the tool, the guidelines are accessible through an interactive user interface. The tool is applicable in the early stages of development and particularly focuses at increasing opportunities to recover embedded resources from end-of-life boilers by design. A usability test has verified that the tool provides engineers with applicable insights on design for the circular economy that translate into new design solutions for domestic boilers.

Samenvatting

Sinds de twintigste eeuw wordt de vraag naar continue groei voorzien door een economisch systeem dat in hoge doorstroom grondstoffen delft, gebruikt, en uiteindelijk afdankt. Dit verspillende systeem in combinatie een groeiende populatie heeft grootschalige gevolgen die zich manifesteren in globale problematiek. Problemen als grondstof uitputting en schade aan het milieu geven aanleiding tot dringende zorgen over duurzaamheid. Deze zorgen worden in toenemende maten uitgedrukt in de markt en in wetgeving en motiveren bedrijven om nieuwe en meer duurzame manieren van ontwikkeling aan nemen. Remeha, een grote producent van cv-ketels, deelt deze motivatie en heeft opdracht gegeven tot het uitvoeren van dit onderzoek om een hulpmiddel te ontwikkelen om rekening te houden met duurzaamheid in het productontwikkelingsproces.

Duurzaamheid wordt geïnterpreteerd als een continue staat van balans waarin maatschappij, milieu, en economie in harmonie functioneren en ontwikkelen. Vanuit dit perspectief wordt duurzame ontwikkeling gezien als een principe voor het organiseren van tijdelijke processen voor het realiseren en behouden van die continue gebalanceerde conditie. Het in praktijk brengen van duurzame ontwikkeling is een bewuste en strategische keus in het nastreven van duurzaamheid. Een die invulling geeft aan de maatschappelijke behoefte voor technologische vooruitgang en daarmee een die aansluit bij Remeha's beroepspraktijk als een producent van cv-ketels.

Er bestaat een verscheidenheid aan concepten om duurzame ontwikkeling te interpreteren en in praktijk te brengen in een bedrijfsomgeving. Een analyse van deze concepten identificeert de circulaire economie als een geschikte en veelbelovende benadering voor duurzame ontwikkeling die wordt aangenomen voor dit onderzoek. De circulaire economie draagt een model aan voor het organiseren van industriële processen op een fundamenteel andere manier die effectiever met grondstoffen omgaat. Hierin staat het idee centraal van een economie waarin grondstoffen worden gebruikt in een gesloten kringloop in plaats van een lineaire doorstroom. Op deze manier is economische groei niet langer direct afhankelijk van het delven van ruwe grondstoffen. Desondanks blijft dit idee te abstract om in praktijk te brengen bij Remeha. Daarom is er een framework ontwikkeld dat de circulaire economie beschrijft aan de hand van vijf principes waarmee processen kunnen worden georganiseerd voor een circulaire transitie. Deze principes kunnen worden toegepast in drie afzonderlijke gebieden van Remeha's organisatie: productontwikkeling, bevoorradingsketen, en verdienmodel. Gezien de behoefte van Remeha richt dit onderzoek zich hoofdzakelijk op het implementeren van de circulaire principes in het gebied van product-ontwikkeling. Om deze implementatie verder te ondersteunen met een bedrijfskundig potentieel wordt het verdienmodel behandeld vanuit een secondaire focus. Dit leidt tot de ontwikkeling van een product-servicesysteem dat financieel en strategisch voordeel biedt van cv-ketels die op een effectievere manier met grondstoffen omgaan.

In de vertaalslag van de circulaire principes naar het domein van productontwikkeling kunnen verschillende ontwerp strategieën worden onderscheiden voor het ontwikkelen van cv-ketels voor verhoogde grondstof effectiviteit. Een ontwerp strategie is geselecteerd voor verdere implementatie, gericht op het realiseren van gesloten grondstofkringlopen door ontwerp. Volgens deze ontwerp strategie worden cv-ketels zo ontwikkeld dat de waarde die ze bevatten, kan worden hersteld en opnieuw gebruikt nadat het product is afgedankt. Zo wordt de afdankingsfase van de levenscyclus een prioriteit voor productontwikkeling. Hiermee is de cv-ketel niet langer uitsluitend een gebruiksproduct, maar een drager van grondstoffen voor de toekomst. De ontwerpstrategie formuleert een duidelijke visie voor ontwikkeling, maar het omschrijft niet hoe die visie moet worden gerealiseerd door ontwerp. Dit vormt een uitdaging voor Remeha's product engineers, omdat ze nog geen ervaring hebben met het ontwikkelen van producten voor een circulaire economie. Daarom is er een digitale ontwerptool ontwikkeld die product engineers ondersteunt in het realiseren van de ontwerpstrategie door hun ontwerpbeslissingen. Het ondersteuningsprincipe van de tool is om product engineers te voorzien van praktisch toepasbare informatie over de relatie tussen productkarakteristieken en de processen die waarde van het product weer herstellen. Deze informatie is gevat in ontwerprichtlijnen die ontwerpbeslissingen informeren en inspireren. In de ontwerptool worden de ontwerprichtlijnen toegankelijk gemaakt via een gestructureerde en interactieve gebruiksinterface. De ontwerptool is toepasbaar in de vroege stadia van ontwikkeling en is specifiek gericht op het stimuleren van mogelijkheden om de grondstoffen in een afgedankt product weer te herstellen en opnieuw te gebruiken. Een gebruikstest heeft aangetoond dat de ontwerptool toepasbare inzichten biedt aan product engineers waarmee ze in staat zijn om nieuwe ontwerpoplossingen te ontwikkelen voor consumenten cv-ketels.

Glossary of terms

BDR Thermea	A world leading manufacturer and distributor of climate and hot water sanitary solutions. It was founded as a holding company of several European brands, including Baxi (UK), Brötje (BE), Chappée (BE), and Remeha (NL).
Boiler	A device that generates heat from the controlled combustion of gas to provide heating and hot water to domestic or industrial buildings.
Business model	A business model describes how an organisation creates, delivers and captures value and can support more resource effective approaches to design with a strategic and financial incentive.
Circular economy	An approach to sustainable development that proposes an economic model for organising industrial processes to increase resource effectivity. One of its central thoughts is to use resources in closed-loop flows where value is used, restored, and used again.
Design strategy	A design strategy embodies the more high-level principles of the circular economy and offers specific directions to develop boilers for increased resource effectivity in a circular economy.
Embedded value	Resource value (function, material, and energy) that is embedded in the product and its components.
End-of-life stage	The stage in the product lifecycle that succeeds the use phase and in which the product has become obsolete. In a circular economy, the end-of-life stage is dedicated to bringing value back into the economy in a useful state.
Guideline	A way to guide actions towards a desirable result by offering prescriptive and practical recommendations for design decisions.
Implementation area	An area in an organisation where the principles of the circular economy can be applied. This research distinguishes three implementation areas in a manufacturing organisation such as Remeha: product design, supply chain, and business model.
Product development	The process of defining a product: its functionality, its physical structure, and the processes for realisation. It what type of resources are required and how they should be transformed through production processes to meet customer demands and thereby influences resource effectivity in a circular economy.
Product-service system	A type of business model that focuses its value proposition at selling and using the functionality instead of the possession of a product. It delivers the value proposition through a combination of a tangible product with an intangible service.

R&D Competence Centre Apeldoorn	A Research & Development department that is responsible for developing a specific part of the BDR Thermea product portfolio according to a specific expertise. R&D Competence Centre Apeldoorn is specialised in the development of gas-fired and high-efficiency wall-hanging and floor-standing boilers. A competence centre is directly managed by BDR Thermea and not associated to any particular brand.
Recycle	A reverse cycle process that aims to recover pure materials from products so these materials can be used again as secondary resources.
Refurbish	A reverse cycle process that aims to restore component to initial OEM performance specifications or improved quality.
Resource effectivity	Using resources in a way that simulates a positive impact to surrounding systems. Resource effectivity aims for positive effects whereas resource efficiency is concerned with reducing negative impact.
Resource productivity	See resource effectivity
Remeha	An organisation based in Apeldoorn that manufactures high-efficiency boilers for the domestic and utility market. The organisation includes commercial and operational departments to market, manufacture, and distribute boilers. Unless noted otherwise, the notion of Remeha includes R&D Competence Centre Apeldoorn.
Resource	A source for industrial processes to create benefit. With respect to product manufacturing, a resource is regarded as either energy, material, or functionality.
Reuse	A reverse cycle process that aims to apply a product in its current condition for a different user.
Reverse cycle	A process that treats end-of-life products to recover and restore their embedded value so it can be used again as a secondary resource.
Secondary resource	A non-virgin source of value that is used as input for industrial processes. Secondary resources are by no means inferior to primary resources in quality or value.
Supply chain	A complex network of organisations, activities and resources that are aligned to bring products and services to the customer.
Sustainable development	A principle of organisation to fulfil the needs of current and future generations through economic and societal development.
Sustainability	A state of balance in which society, environment, and economy can develop productively, now and in the future.

chapter

01

Introducion

Since the industrial revolution the product development industry has grown to global proportions. It answers society's needs with an innumerable and ever-evolving variety of products. The past century can be characterised by a continuous advancement of wealth and technological possibilities. If we continue this line of development into the future, the possibilities for growth seem endless. But are they?

In order to manufacture all these products and supply them across the globe, the economy heavily relies on the earth's natural resources for energy and material. However, the ways in which these resources are processed and the scale on which they are extracted, cause negative effects that threaten our well-being on a global scale. A relevant example is the effect of global warming that is directly linked to excessive CO_2 emissions. Our ways of development are flawed and cannot continue to meet the needs of future generations. Resonated by increasing public and political awareness, there is a pressing need for action. At the centre of the issue, we require new ways of development that restore and keep the balance between progressing economies and societies and the natural environment. This is commonly referred to as sustainable development. Remeha has taken an interest in sustainable development, driven by the opportunity of strategic advantage and the pressure of changing market needs and legislative requirements. The R&D department at Remeha has commissioned this research to develop a tool for implementing sustainability in their product development process.

There are various ways to interpret or practice the field of sustainable development in a corporate environment. As will appear from section 2.4, the circular economy seems to be the most appropriate approach to be adopted for this research. The circular economy has gained prominence in recent years as a new model for organising industrial processes in fundamentally different and more resource effective ways. It centres around the idea of an economy that uses resources in closed loops, rather than linear flows. In this system, the output of one process becomes the input of another, which effectively eliminates the concept of waste. The circular economy allows to decouple economic growth from resource extraction and thereby creates a balanced system that can continue to develop within the constraints of the ecosystem.

This introductory chapter elaborates the starting points for this research. To indicate the corporate context and scope for this project, section 1.1 introduces Remeha and its parent company BDR Thermea as the corporate environment for this research. Section 1.2 offers a description of the drivers that motivate the exploration of the circular economy for Remeha. Subsequently, the problem statement in section 1.3 describes a key issue in the field of circular economy that will be addressed in this research. This chapter will conclude with section 1.4 by describing the research questions and the structure of this report.

1.1 Company profile and scope

A general description of Remeha and its parent company BDR Thermea is presented in this section to provide an initial impression of the corporate context of this research. Chapter 4 describes the corporate context of Remeha more elaborately and explains how this thesis focuses at a specific part of the organisation.

Remeha: the start of a warming business

Remeha develops energy-efficient heating systems for the industrial and domestic market. The company started as a technical trading office in 1935, specialising in the sales of coal-fired boilers when coals were the most common fuel. At that time, the boilers were developed and manufactured by external partners under supervision of Remeha. In 1948 Remeha advanced their business by starting to develop their own boilers, and has been doing so ever since. To date, Remeha specialises in gas-fired boilers and stands at the forefront of high-efficiency heating systems. Boilers are engineered and assembled on site in Apeldoorn. Part production is outsourced to suppliers.

Over the past 80 years, Remeha has grown to become one of Europe's largest manufacturers of heating systems. In the Netherlands, Remeha leads the market in floor-standing boilers as well as certain segments of wall-hanging boilers. At the head office in Apeldoorn, over 400 employees contribute to the development and production of about 229,000 boilers in 2015. An extensive network of service channels distributes products to national and international markets.

BDR Thermea: joining forces

At the start of the 21st century, Remeha prospered and gained substantial profits. To advance their growth the company pursued expansion to international markets. This led to the take-over of De Dietrich in 2004 and Baxi Group in 2009. This collective of knowledge, sales channels, and capacity provided new opportunities for development. To manage policies and interests in the newly established partnership, the BDR Thermea Group was founded as an overarching organisation. Through this organisational structure, Remeha became one of several business units that belong to the BDR Thermea group, including De Dietrich (FR), Baxi (UK), Brötje (BE), Chappée (BE) and Baymak (TR). Together, these business units comprise an elaborated group product portfolio, ranging over heat pumps, solar thermal solutions, smart thermostats, and (commercial) boilers.

To effectively control the development of the product portfolio, development at the business units was re-arranged to establish 11 R&D competence centres according to domains of application and technology. Each competence centre is responsible for developing a specific part of the group product portfolio, being directly managed by BDR Thermea and not associated to any specific brand. This way, the R&D department at Remeha became R&D Competence Centre Apeldoorn, dedicated to the development of gas-fired and high-efficiency wall-hanging and floor-standing boilers. R&D Competence Centre Apeldoorn is the client and primary stakeholder for this research. Chapter 4 will explain more elaborately what the distinction between the R&D department and Remeha will mean for the scope of this research. It is recognised that R&D Competence Centre Apeldoorn is organisationally separated from Remeha as it is directly managed by BDR Thermea. However, the R&D department is located at the Remeha head office and closely collaborates with local Remeha departments (such as quality, procurement, product management, and production) during the product development process. Therefore, the R&D Competence Centre Apeldoorn is henceforth considered part of Remeha in speaking terms. Affiliation of the R&D competence centre to BDR Thermea is only explicitly mentioned in this report when the organisational distinction is specifically relevant.

1.2 Research motive

Remeha's need to implement sustainability in their product development, is motivated by particular drivers. Identifying these drivers is essential to understanding the company's need and answer it with a meaningful solution. Moreover, clarifying the key motivations to research the circular economy has proved valuable to convince and commit various stakeholders to this project. This is especially relevant since the need to research sustainability in product development initially originated from the R&D department and was not yet fully recognised or understood by other parts of the organisation. The three key drivers for initiating this research are:

- **Increased awareness of the public and customer demands**
  Markets are increasingly aimed at sustainable products as the public awareness of environmental and social responsibility is growing (Bevilacqua, Ciarapica, & Giacchetta, 2007). Companies like Philips, Bugaboo, Desso, and Gispen are actively pursuing the development of products for the circular economy. Remeha recognises the societal shift towards sustainable awareness and has received specific requests from clients – Paradigma (IT) and De Dietrich (FR) - regarding their product's sustainable character. Furthermore, it is a priority to BDR Thermea's stakeholders to maximise product sustainability (BDR CSR report 2016).
- **Strategic business advantage**
  Maxwell and Van der Vorst (2003) indicate that the development of sustainable products can enhance a company's competitive advantage. A product's sustainable characteristics are increasingly valued by the market and allow distinction from competitors. Remeha wishes to exploit the strategic advantages that sustainability offers by taking a notable, but not necessarily leading, position on sustainable development in the heating systems sector.

- **Government regulations and legislation**
  On European and national level governments are concerned with sustainability-related issues. Such concerns are demonstrated by policies and regulations that stimulate more sustainable development. Some policies even focus specifically at the circular economy. Examples of legislative restrictions can be found in European directives like the Waste Electrical and Electronics Equipment (WEEE), Restriction of Hazardous Substances (RoHS), EcoDesign, and Energy Labelling. Such regulations increase pressure on manufacturing industries to develop sustainable products (Maxwell & Van der Vorst, 2003). Appendix A provides a more elaborate overview of sustainability-related directives and regulations, including the ones mentioned in this paragraph. It is expected that regulations like these will continue to expand and become more stringent in the future. Embracing the circular economy will allow Remeha to anticipate and even benefit from future legislative changes.

1.3 Problem statement

Implementing sustainability in the product development process requires a solid interpretation of sustainability and how it can be influenced through development. In this respect, the circular economy has appeared as the most suitable approach to sustainable development for Remeha. Section 2.4 will elaborate more closely on this focus, but for now the circular economy is considered as a central notion to this thesis.

In recent years, the circular economy has gained much attention from academics, industry, and politics. Since 2009, the Ellen MacArthur Foundation (EMF) has been one of the key contributors to developing this field and to demonstrating its potential as a new economic system. In spite of such efforts, the circular economy is still a developing field. Currently, the majority of studies, including publications by the EMF, approach the circular economy from a macro perspective. This scale regards national, regional or even global economies and how they could be influenced through policy-making. On a micro scale, these economies consist of a network of corporations, including product manufacturing companies like Remeha. How should these corporations develop their products in a circular economy? This appears to be a complex topic and elaborate literature research has not identified established methods that answer this question structurally and in an actionable way. Circle Economy, a Dutch cooperative that helps businesses to adopt and implement circular principles, recognises this issue and the need for it to be addressed in the transition towards a circular economy[1]. More briefly put, the problem statement can be formulated as:

1 Based on an interview with the Circle Design Programme manager of Circle Economy at 11 October 2016.

No established methodology has been found that provides a structural and actionable way to determine how an organisation like Remeha should organise its product development activities in pursuit of a circular economy.

Researching the circular economy at a micro scale, focusing at its implementation in product development, will contribute to the development of the field. Moreover, it will allow Remeha to start developing their boilers for a circular system and it will provide a basis for other manufacturing companies to do the same with their products.

1.4 Research approach

This research intends to overcome the stated problem by researching the circular economy and how it applies to Remeha's product development environment. These insights provide the basis for developing a practical design tool that supports Remeha's product engineers to pursue sustainability through their design decisions. This approach can be formulated into research questions that will be answered through this research. The primary research question, capturing the essential scope of this research, is to be formulated as:

Primary research question

How can the circular economy be implemented in Remeha's product development process to pursue sustainability?

The primary research question can be further specified by three secondary research questions. They each indicate a specific sub-area that needs to be addressed in order to answer the primary research question.

Secondary research questions

- What is the circular economy?
- How should the principles of the circular economy be applied to Remeha's product development?
- How can the development of boilers for a circular economy be supported by a dedicated tool for product engineers?

These secondary questions represent the three parts into which this thesis is structured. Table 1.1 elaborates on this structure by introducing the different topics that that will be discussed by this report. Each topic is related to the secondary research question to which it contributes and the report chapter by which it is addressed.

Table 1.1: Research structure.

Part 1	**What is the circular economy?**
Ch. 2	Specify a clear interpretation of sustainability and sustainable development and structure various concepts for practicing sustainable development.
Ch. 3	Describe resource flows in a circular economy and characterise the concept in terms of five principles that can be applied through three areas in an organisation.
Part 2	**How should the principles of the circular economy be applied to Remeha's product development?**
Ch. 4	Describe Remeha's corporate context in the areas of product design, supply chain, and business model and specify the research focus in the organisation.
Ch. 5	Develop a new business model to support the adoption of more resource-effective strategies in design with a business incentive.
Ch. 6	Translate the principles of circularity into the area of product development in terms of design strategies. Analysing several strategies and choosing one for further application at Remeha.
Part 3	**How can the development of boilers for a circular economy be supported by a dedicated tool for product engineers?**
Ch. 7	Formulate a coherent set of guidelines to support product engineers in realising the circular design strategy.
Ch. 8	Develop a digital design tool that provides interactive access to the guidelines to promote their application.
Ch. 9	Evaluate the design tool with the product engineers to assess its usability and applicability for the development of domestic boilers.

Looking ahead to the contents of this report, figure 1.1a and 1.1b provide a schematic representation of the most important research results. This overview is meant to inform the expectations of the reader and to provide a holistic perspective from which to interpret the research results wile progressing through this report. Moreover, the overview specifies the relations between the different topics of this thesis and demonstrates how their combined results lead to the development of a dedicated design tool.

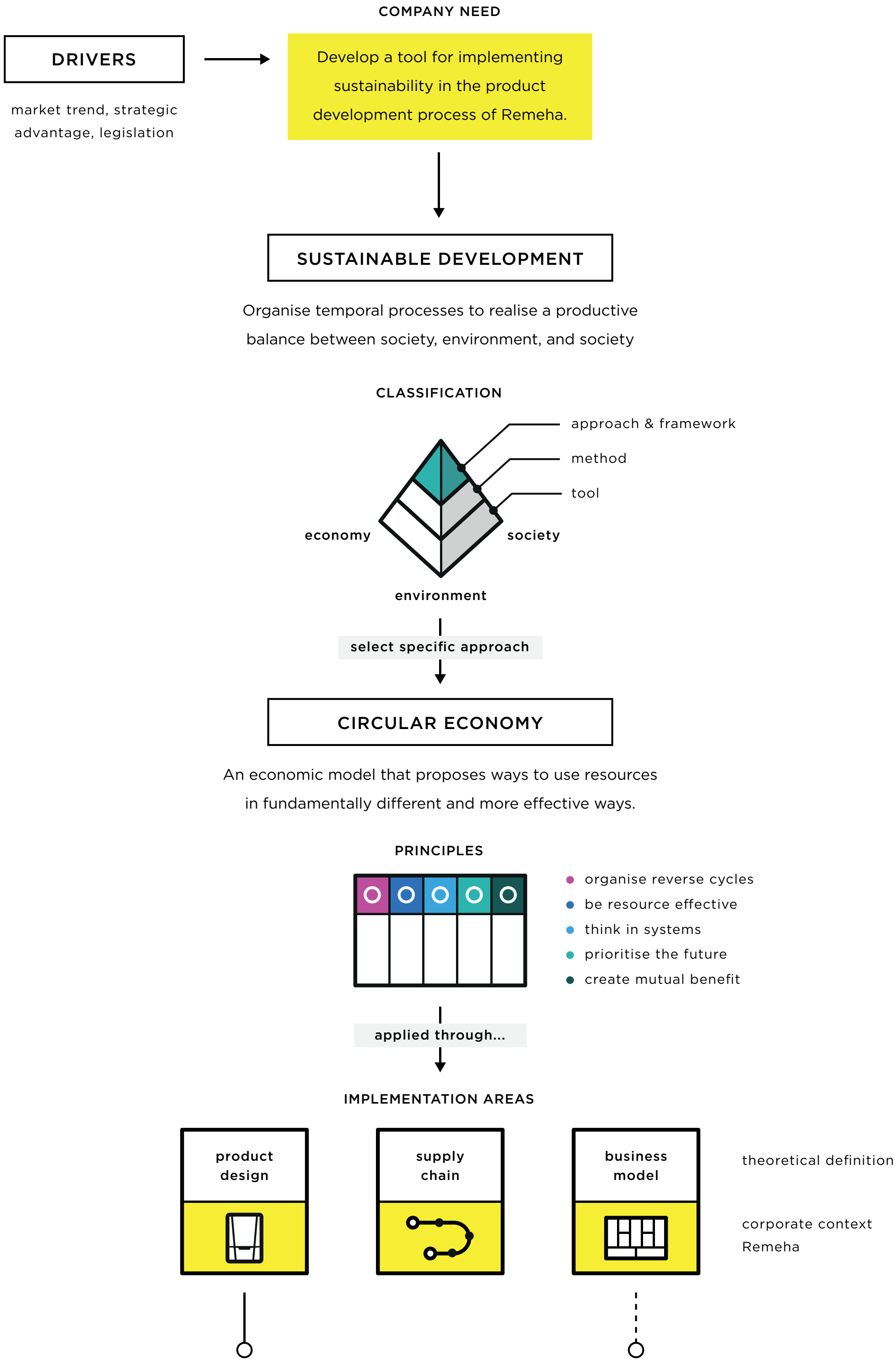


Figure 1.1a Preview research structure and results (part 1).

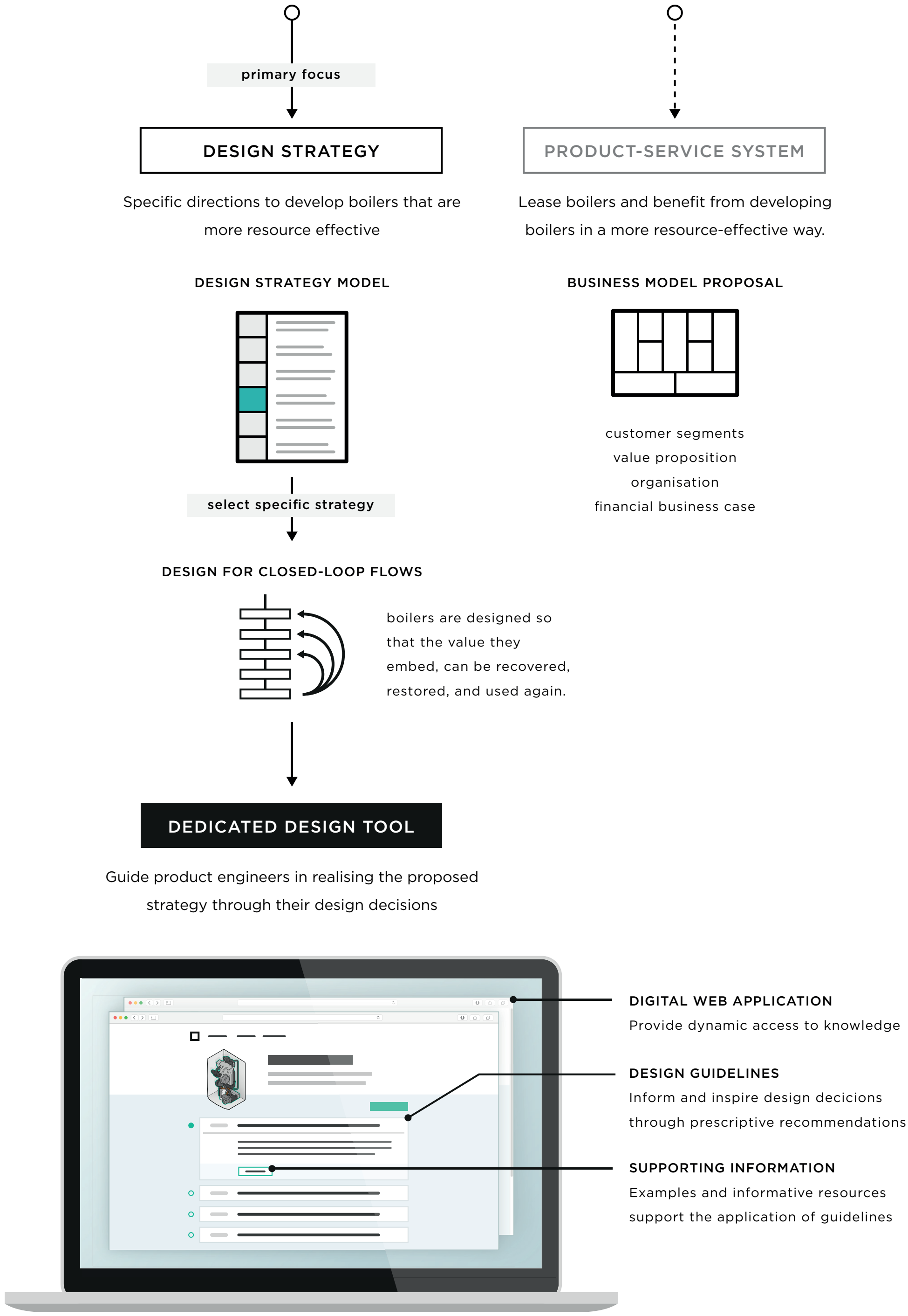


Figure 1.1b Preview research structure and results (part 2).

part 1

Describing the circular economy

chapter 02

Sustainability and how it can be realised through development

Specify a clear interpretation of sustainability and sustainable development and structure various concepts for practicing sustainable development.

chapter 03

The circular economy: a theoretical framework

Describe resource flows in a circular economy and characterise the concept in terms of five principles that can be applied through three areas in an organisation.

chapter

02

Sustainability and how it can be realised through development

Continuous technological advancements and the persistent aim for economic growth have contributed to the rise of global problems like social inequality, environmental degradation, and resource scarcity. A growing awareness that these issues affect the prospects of future growth, motivates a change in the methods for achieving progress. In this context, sustainable development arises as a new model for economic growth.

However, organising industrial processes according to the principles of sustainable development, requires an understanding of how sustainable development is to be influenced. Consequently, a multitude of different concepts has been developed to offer specific approaches and methods for practicing sustainable development. These concepts help organisations like Remeha to focus their activities at realising sustainability through development. The circular economy is one of these concepts. As will be argued by section 2.4, it provides an approach that is especially relevant to this research. Therefore, the circular economy will be adopted as the framework for interpreting sustainable development and applying it to Remeha's product development process. Before analysing the circular economy in chapter 3, this chapter aims to elaborate the idea of sustainability and sustainable development, why it is relevant, and how the circular economy should be seen as a specific approach for addressing it.

2.1 Sustainability explained

Sustainability is a familiar but complex notion, which is often used without clear conception of its true meaning or implications. The term literally translates to 'the ability to sustain'. In general, it indicates the endurance of a system, but the system boundaries are open to interpretation. This ambiguity has led to many different understandings and definitions of sustainability. However, in order to implement considerations of sustainability in Remeha's product development, it is essential to adopt a clear understanding of sustainability and to use it consistently.

Sustainability is a complex notion to define, but it is commonly interpreted in relation to three dimensions. The World Commission on Environment and Development (WCED) (1987) has provided the first impulse for this multi-dimensional approach, by stating that social equity, environmental maintenance, and economic growth can be achieved simultaneously. The three dimensions – society, environment, and economy – were later introduced as the triple bottom line by John Elkington (1994). Other approaches to the sustainability dimensions have been proposed in response to the triple bottom line. Examples are the Two Tiered Sustainability Equilibria (TTSE) that adds time as a fourth dimension to the triple bottom line (Lozano, 2008) and the five-dimensional framework by Seghezzo (2009) that distinguishes the three dimensions of space (Place), the fourth dimension of time (Permanence), and the fifth human dimension (Person).

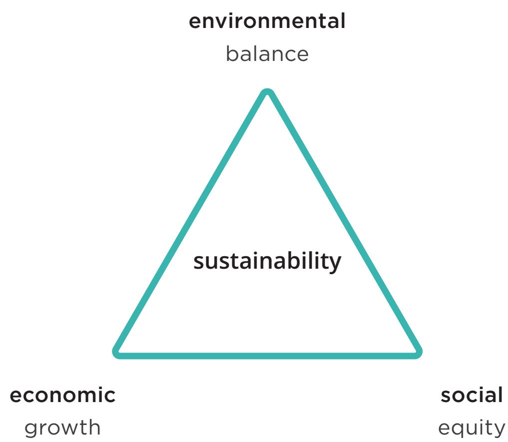


Figure 2.1: Sustainability triangle.

Over the years, the triple bottom line has become the most accepted interpretation of sustainability (Gmelin & Seuring, 2014). Figure 2.1 depicts a model for representing its three sustainability dimensions. It provides the fundamental insight that our world is an interconnected whole of social, environmental, and economic domains. At the extremes of the spectrum, value is identified in a single realm. Socialism regards equality to be the ultimate purpose, environmentalism values ecological health most profoundly, and capitalism measures value merely in economic growth. While all these persuasions are meant to improve the human condition, their narrow approach neglects part of the system and impedes long-term success (McDonough & Braungart, 2002). A sole focus on environmental benefit disregards the importance of a healthy economy to provide effective innovations and the necessity of a healthy and educated society to drive change. In order to realise sustainability, all three dimensions need to be considered with equal importance (Buchert, Neugebauer, Schenker, Lindow, & Stark, 2015; Gmelin & Seuring, 2014; Lozano, 2012). Following the triple bottom line interpretation, sustainability is understood as:

> A state of balance in which society, environment, and economy can develop productively, now and in the future.

This definition is not believed nor meant to be comprehensive or generally applicable. It is, however, a meaningful interpretation within the scope of this research. It characterises sustainability as a desirable state in which society, environment, and economy are balanced and equally important. In this sense, sustainability would be a goal to pursue and should become and remain the new status quo for how society, environment, and economy interact.

2.2 Coupling notions of sustainability and development

The continuous advancement of society and economy have led to rising concerns about sustainability. This section will put these concerns into a brief historical perspective and elaborate how sustainable development has emerged in response. In this context, sustainable development will be explained as a notion that couples the idea of development to sustainability.

The emergence of sustainable development

Between 1800 and 1970 – following the Industrial Revolution – society experienced a period of unparalleled growth. The world's population tripled to over 3,500 million and the global production of the manufacturing industry increased about 1730 times (Rostow, 1978). Society witnessed the great advancement of technology and experienced the new benefits it provided. The possibilities for human progress seemed endless, which stimulated a public expectation of ever-increasing economic growth. This belief has justified the exploitation and neglect of the ecological system in the pursuit for maximum economic production (Du Pisani, 2006).

However, the glorified advancement of industrial progress turned out to bring undesired consequences. Around the 1960s, issues of rapid population growth, pollution, and resource depletion emerged and led to growing concerns about sustainability (Du Pisani, 2006). Academics openly expressed concerns in literature that 'if we continue our present practices we will face a steady deterioration of the conditions under which we live' (Nathan Glick in Dubos et al., 1970) and that we 'may destroy the ability of the earth to support life' (LaMont C. Cole in Dubos et al., 1970). Such concerns were further substantiated with scientific studies, which fuelled the public debate. Arguably one of the most influential publications in this respect was the report by the Club of Rome titled 'the limits to growth' (Meadows, Meadows, Randers, & Behrens, 1972). It supported a moral appeal for a better world with a scientific model (Verstegen & Hanekamp, 2005). The report concluded that earth's finite supply of natural resources was not able to support the contemporary growth trends of population and industry.

In spite of growing awareness of global issues in the 1960s, the mood remained quite optimistic. It was believed that any global issues would be solved by expanded economic growth. But in the 1970s the optimism faded and the idea of continuous progress was losing much of the fascination it had had for earlier generations. Economic growth did not prove to be the hoped-for solution and environmental concern became more acute and radical. Some advocated the stagnation of material growth to stabilise living standards and conserve environmental conditions. But, this idealist view did not attract much support in practice. While people are willing to tackle the issues of sustainability, they are not prepared to give up continued material progress (Verstegen & Hanekamp, 2005).

However, in order to continue economic progress while countering the issues of sustainability, a new way of development was required. This realisation inspired the rise of sustainable development.

Sustainable development as the new model for growth

The awareness that current ways of growth were limited, stimulated a new mode of thinking about development. In response, the notion of sustainable development has emerged as an alternative to unlimited economic growth (Du Pisani, 2006). It offers a compromise between perceptions of development (exploitation of resources) and conservation (protection of resources). It does not advocate a stagnation of growth as it is currently known, but it argues for a reconsideration of the ways to attain it.

Just like the perception of sustainability, sustainable development is interpreted and applied in various ways. The absence of a comprehensive definition after two decades of research most likely relates to its dynamic nature (Mazi, 2015); its meaning strongly depends on the context and scope in which it is regarded. However, there is one definition that is frequently quoted and has become an accepted interpretation of sustainable development. This definition originates from the so-called Brundtland Report and states that 'sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs' (World Commission on Environment and Development (WCED), 1987). For this thesis, sustainable development is regarded more specifically in relation to the notion of sustainability explained in section 2.1. Where sustainability should be interpreted as an ultimate state or even goal of equilibrium, sustainable development is a principle for organising temporal processes to reach and maintain that balanced state. In this respect, sustainable development is explained as:

> A principle of organisation to fulfil the needs of current and future generations through economic and societal development

While this definition remains quite abstract and ambiguous, it serves to express the distinction between sustainability and sustainable development. By providing a brief historical context, it becomes clear that **adopting sustainable development is a deliberate, strategic choice in the pursuit for sustainability. One that answers to society's need for technological progress and therefore one that aligns with Remeha's corporate practice as a product manufacturer**. As this research will show, the idea of realising sustainable living conditions through technological development can align with and even strengthen corporate objectives. Section 2.4 will further explore the notion of sustainable development by looking at various concepts by which its principles are applied in an organisation. But first, the relevance to adopt sustainable ways of development is explained in the next section.

2.3 The relevance of sustainable development today

The previous section has explained sustainable development as a way to achieve growth while realising or maintaining a sustainable condition. Its emergence has been illustrated in a historical context, but why is it relevant to actively pursue sustainable development today? Actually, the principle of sustainable development is relevant to all evolving systems, regardless of scale or time. As long as systems are mutually dependent, their growth must be balanced in order to persist and be productive. However, as this section will show, the persistent growth of our population and economy combined with current living standards cannot be sustained by the earth's ecosystem. The destructive consequences of excessive growth can already be observed and are projected to increase as current expansion rates continue. By describing three global concerns of sustainability, namely over-population, resource depletion, and environmental pollution, this section aims to clarify the destructive path of conventional ways of development. Thereby, substantiating the need to shift from a non-sustainable to a sustainable way of development that restores a productive balance. In this light, sustainable development could be interpreted as a problem-solving strategy that is widely regarded as the solution to global problemacy (Hanss & Böhm, 2012).

Over-population

Since the start of the 15th century, the human population has been growing continuously with particularly high growth rates in the past 50 years (figure 2.2). The population has almost tripled from 2.5 billion in 1950 to 7.3 billion in 2015 and is prospected to reach 10 billion around 2050 (United Nations, 2015). Noteworthy is that the majority of population growth occurs in under-developed countries, while the population in developed countries has remained largely constant around 1.0-1.2 billion.

A growing population in itself is not necessarily an issue. However, it can be problematic in the context of our living environment. The earth's ecosystem provides services to support its population, like clean drinking water, agricultural land, and material resources. But these services are limited in how much they can provide. In other words, the earth can only support a population up to a certain size, which is also referred to as the earth's carrying capacity. A condition of over-population occurs when the global population exceeds the carrying capacity of the earth. Such a situation is by definition unsustainable, because it implies that the ecosystem cannot provide for the needs of a population. When this takes place, ecological conditions can degrade in a negative spiral, which makes countermeasures to restore balance increasingly challenging. While the exact carrying capacity of the earth can hardly be specified, a meta-analysis of 69 past studies indicates that the projected world population for 2050 at least 'exceeds several meta-estimates of a world population limit' (Van Den Bergh & Rietveld, 2004).

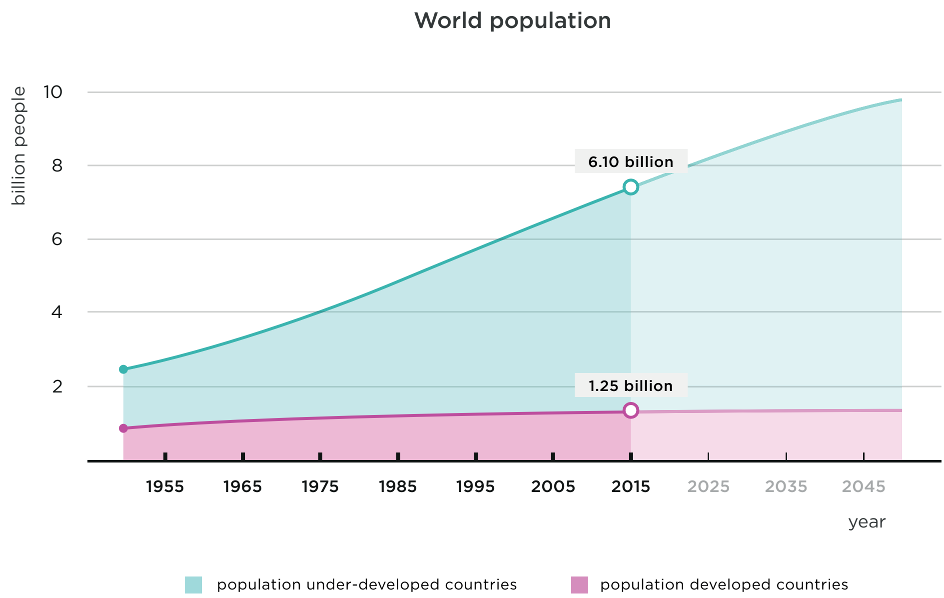


Figure 2.2: World population, based on data from United Nations (2015).
More developed regions comprise Europe, Northern America, Australia/New Zealand and Japan. Less developed regions comprise all regions of Africa, Asia (except Japan), Latin America and the Caribbean plus Melanesia, Micronesia and Polynesia.

Resource depletion

The economy uses natural resources to create value and growth. Agricultural land is harvested for food to feed the population, fuels are mined for energy to run industrial processes, and metals are sourced as a construction material for consumer products. Figure 2.3 shows the amounts of extracted resources that enter the economic system, demonstrating a continuous progression of extracted quantities. In the 30 years following 1980, global resource extraction has more than doubled to 73.7 billion tonnes in 2010. Not just the total amount of extracted resources has increased, but also the extraction per capita has steadily increased with almost 30% over the same time period.

Economy's resource extraction stands in proportion to the market's demand for goods. An increase in demand is likely result in more resources to be extracted from the earth. Persistent population growth (figure 2.2) and the development of emerging markets like China and India will influence future demand for goods and resources. By 2030, the global middle-class is expected to rise with 3 billion people, who will bring an unequalled surge of demand that is larger and occurs in a shorter time period than ever before (Dobbs, Oppenheim, Thompson, Brinkman, & Zornes, 2011).

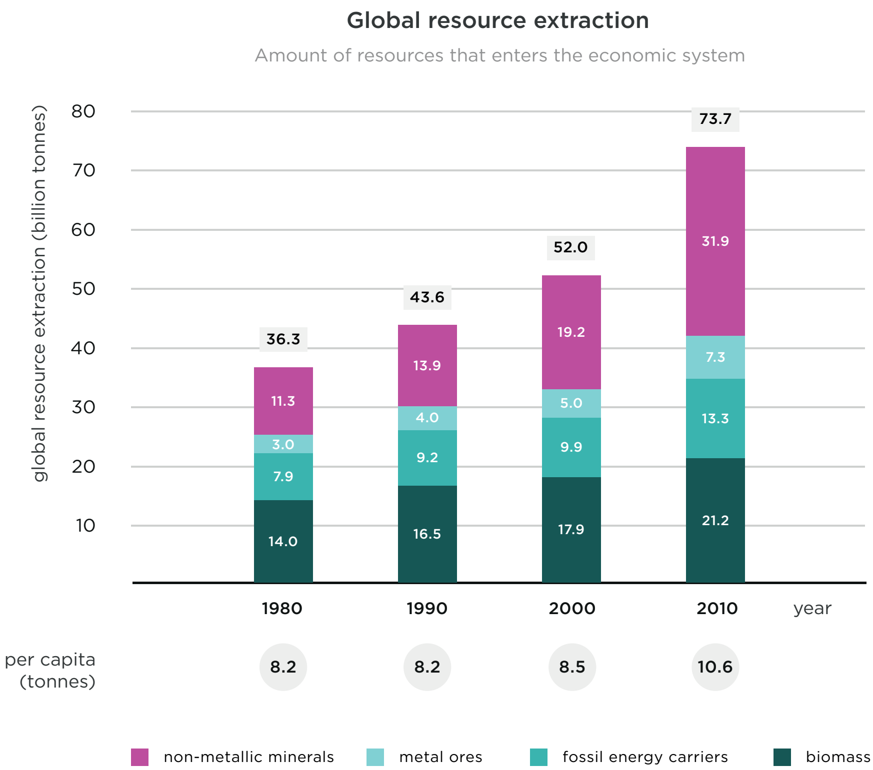


Figure 2.3 Global resource extraction, based on data from Sustainable Europe Resource Institute (2014).

At the same time, the supply of resources becomes more challenging, because resource reserves are rapidly depleting and new sources are often difficult to reach and less productive (Dobbs et al., 2013). Continued and increasing extraction of non-renewable resources will inevitably lead to a point when global deposits are no longer an economically feasible source of large-scale extraction. However, predicting when exactly this will become problematic is a complex task, especially because it is unknown how much sources remain undiscovered. If a projection were to be made based on currently recoverable reserves and extraction levels, iron, copper, and bauxite would be available for merely 72, 53, and 124 years respectively (UNEP International Resource Panel, 2016).

As a result of increasing demand and accelerating depletion of supply, resource prices are driven up (Dobbs et al., 2013). Figure 2.4 shows the average resource price development, relative to years 1999-2001. The commodity price index (green line) is based on the arithmetic average of four commodity sub-indexes: food, non-food agricultural raw material, metal, and energy. During the whole 20th century, resource became progressively cheaper, which supported further economic growth.

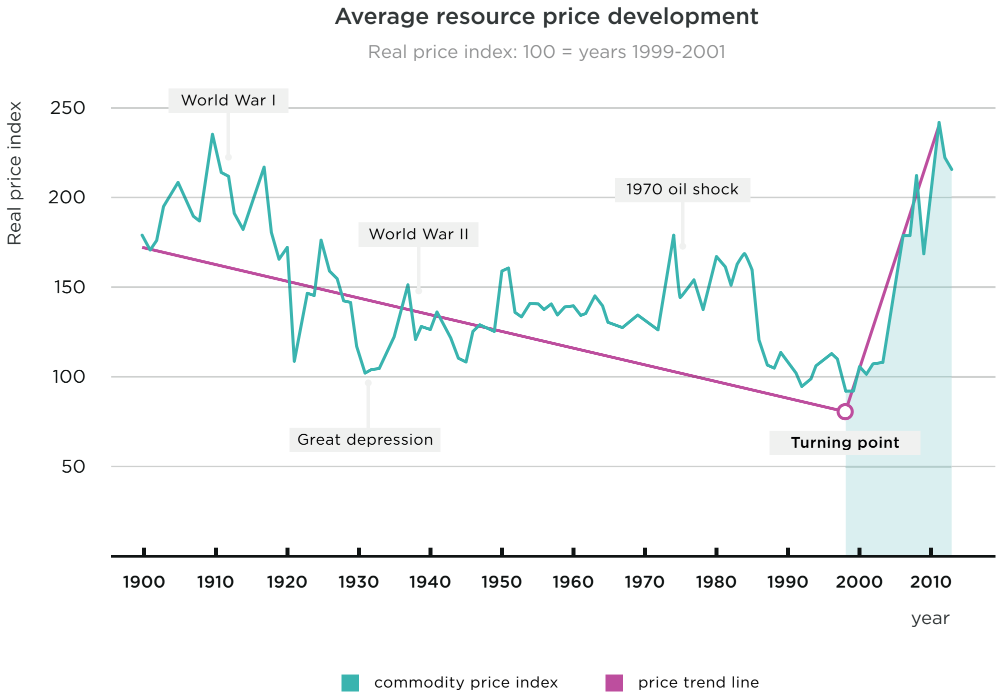


Figure 2.4 Average resource price development (Dobbs et al., 2013).

However, around the turn of the century the declining price trend turned as well. Since 2000, average commodity prices have increased at a high rate. The steady decline of commodity prices over the course of a century has been undone in just 10 years. Additional to stock prices increasing, they also become increasingly volatile. At the start of the 21st century, volatility levels for metals, food, and non-food agricultural items, were higher than they had ever been in the preceding century and are expected to remain high and volatile until at least 2030 (Dobbs et al., 2011).

Environmental pollution

As described earlier in this section, the economy takes in substantial amounts of resources at the front-end of the system. These resources are transformed by industrial processes into valuable consumer goods, which are eventually disposed. This take-make-dispose approach results in enormous amounts of waste, like production waste or goods that have become obsolete to the user. Figure 2.5 shows the amounts of waste that are generated by economic activities and households in the EU-27. In 2014, waste levels rose to 2.59 billion tonnes, the highest amount recorded since 2004. These high waste levels have long been accepted and further stimulated by low resource prices.

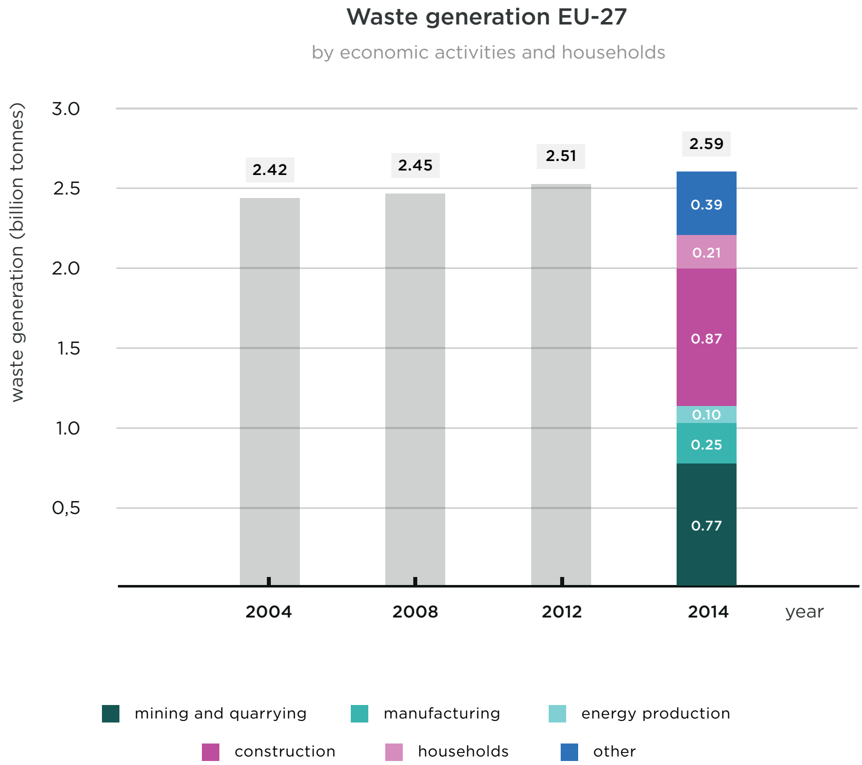


Figure 2.5 Waste generation in EU-27, based on data from Eurostat (2016a).

The economy's generated waste represents a high potential of resources, like functional product components, material and energy. However, the historical ease of extracting resources and low costs for disposal did not provide any economic incentive to reuse any resources (Ellen MacArthur Foundation, 2012). Of the 2.15 billion tonnes waste[2] that was processed in the EU in 2014, almost 44% ended up in landfill (Eurostat, 2016b). Disposing high quantities of industrial waste back into the environment, can have a significant impact to surrounding systems. Soil and water become polluted and potentially damage fresh water supply, agricultural land, and biodiversity.

Besides generating solid waste, industrial processes emit substances into the atmosphere, polluting the air. For instance, particulates from vehicular or industrial emissions cause smog episodes in densely populated urban areas, imposing health risks to the population. Another example, is the issue of global warming as a consequence of excessive CO_2 emissions. Research shows a causal relation between rising CO2 concentrations in the atmosphere and the rise of global temperatures (Jones et al., 2007).

2 The amount of waste that was treated in the EU is not directly comparable to the generated waste volumes, because waste is exported to or imported from other regions in the world.

Global surface temperature and atmospheric CO_2 concentration

Surface temperature anamolies relative to a base period of 1880-1900

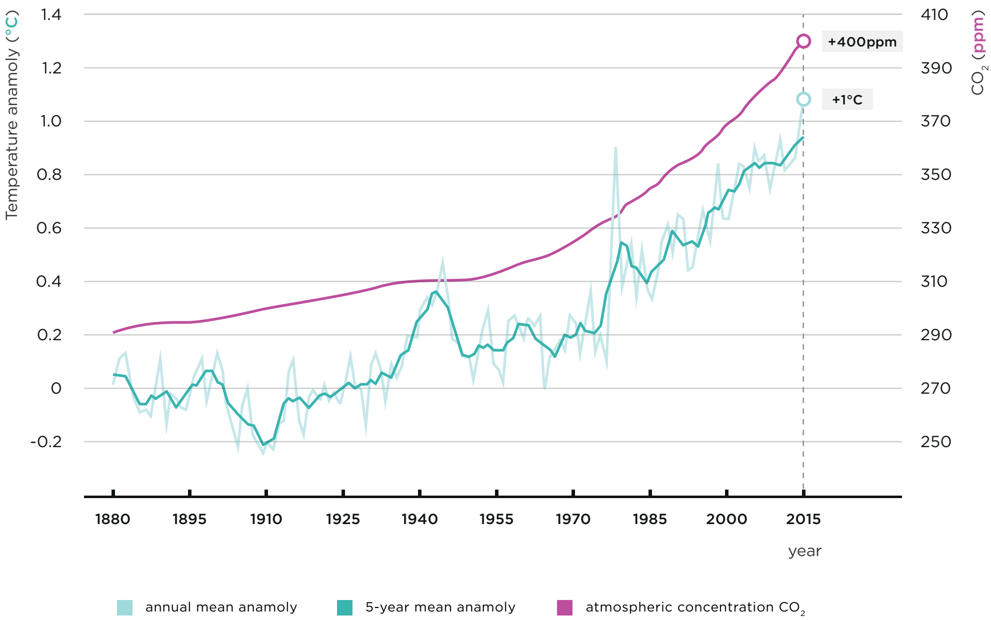


Figure 2.6 Global temperature development with respect to atmospheric CO_2 concentrations, based on data from Goddard Institute for Space Studies (2015) and European Environment Agency (2016).

As an indication, figure 2.6 shows the global temperature changes[3] in the context of atmospheric CO_2 concentrations. In 2015, global temperatures have increased with an average of 1°C compared to 1880-1900 levels and the concentration CO_2 in the atmosphere has increased to over 400 ppm. The rise of global temperatures, as a direct consequence of human activity, could disrupt the ecosystem drastically. The effects of such disruption, like droughts, sea-level rise, and loss of biodiversity, can already be observed today and could potentially take on more extreme conditions in the future. In the case of this example, it is estimated that there is already enough CO_2 in the atmosphere to cause global temperatures to climb further to an average of 2°C increase.

Conclusion

This section has introduced three issues of sustainability: over-population, the depletion of natural resources, and the degradation of the ecosystem. All these issues occur on a global scale and show growth trends of increasing severity. So how should this description be interpreted in light of this research? First of all, describing these

3 Temperature changes depict how much the global surface temperature has increased or decreased, compared to a base period of 1880-1900.

issues helps to understand the state of today's social, environmental and economic systems. As it turns out, these states are currently out of balance and are in most cases projected to worsen in the near future. It is, amongst others, these issues that motivate developments in legislation and market demands for more sustainable solutions. These, in turn, drive Remeha to explore the topic of sustainability, as identified in section 1.2. So, knowing about the described issues helps to understand the existence of the need for sustainable development. Furthermore, it helps to value this need as one that is prominently relevant today and will become increasingly relevant in the future.

2.4 Addressing sustainable development at Remeha

Ever since sustainable development became a topic of interest for research and business, initiatives have been developed to put the principles of sustainable development into practice. These concepts, also referred to in this document as concepts, help organisations to interpret and apply the abstract notion of sustainable development. Similarly, adopting such concepts will help Remeha to implement considerations of sustainability in their product development process. Building this research upon such an existing concept, provides a foundation for further analysis and allows the utilisation of knowledge that is already available. In order to identify the concept that is most suitable to this research, a collection of existing concepts is analysed, classified, and evaluated in this section.

Mapping the sustainable development field

A selection of concepts for sustainable development has been researched to develop an understanding of applications and terminology in the field of sustainable development. The range of concepts and terminology has appeared to be extensive. While it has been attempted to consider a wide scope of concepts, it is acknowledged that there are concepts still unaccounted for by this research. Based on an elaborate literature study, involving review studies by Glavič and Lukman (2007) and Lozano (2012), a selection of 25 commonly used concepts has been identified. It is assumed that this selection represents a sufficient scope to understand the range of available concepts. An overview of these concepts and their goals is provided by appendix B.

Looking further into the concepts from appendix B, it appears that concepts differ on a variety of aspects. At the bases of their distinction, concepts adopt a different understanding of sustainable development and apply a different focus for achieving it. They can aim for social or environmental aspects and target industrial or management processes. Some propose a narrow focus while others suggest a more integrated and system-level perspective. But there is also fundamental similarity between seemingly distinct concepts. By example, the terms Eco-design, Design for Environment, and Environmentally Conscious Design are used interchangeably while indicating essentially the same concept (Bhander, Hauschild, & McAloone, 2003). Such distinctions and similarities between concepts are often difficult to grasp but meaningful to understand.

Classifying concepts for sustainable development

There is much confusion on the meaning of different concepts for sustainable development (Glavič & Lukman, 2007) and companies are challenged in adopting concepts that fit their objectives. A classification model is introduced to promote a better understanding of the different sustainable development concepts and their mutual relations. A classified structure provides a deeper understanding of available concepts and in what way their application contributes to sustainable objectives.

Classification is a method for organising concepts to better understand them. It includes an ordered set of related classes to group concepts according to similarities. Concepts within a class share similar characteristics, while concepts from different classes are essentially distinct. When seeking to apply sustainable development, the choice between concepts like circular economy (CE) and ecological footprint (EF) is unequal. Circular economy can be understood as a high-level philosophy for organising the processes in an economic system. On the other hand, the ecological footprint is a measure for performance without guiding performance optimisation. Both are useful concepts, but they function at a different level. This type of distinction is indicated as 'operational distinction' and it is taken as a basis for classification. By focusing on the concept's level of operation, it can be clarified how a concept supports an organisation's actions towards sustainable development.

Based on the operational distinction, three classes have been identified: approaches & frameworks, methods, and finally tools. Each class represents a different functional level of operation. Approaches & frameworks are the highest level of classification, providing a fundamental model for the behaviour and interaction of the system. Methods are more specific to provide guidance for adjusting processes to approaches. At the lowest operational level are the tools that directly support action to align with approaches and influence the system towards sustainable development. Below, the three classes are further specified.

1. **Approaches & frameworks:** An approach defines behaviour of system components; how they can be activated to achieve sustainable development. Within the approach class, a sub-level is distinguished for high-level approaches. These are frameworks that encompass a number of approaches. In themselves frameworks provide no new approach, but they offer new insights through synergy.
2. **Methods:** Underlying the approaches are the methods. They are types of activities or ideologies that are utilised to substantiate the more abstract approaches. Several methods can contribute to one or multiple approaches.

3. **Tools:** Support the application of methods and approaches towards sustainability. Tools help to take action in realising sustainable development and they enable a reflection on the effectiveness of this action in relation to the approaches.

Figure 2.7 visualises the classification system as a hierarchy of triangular planes. Each plane represents a class. The top two planes are the highest level of hierarchy where the approaches & frameworks operate. The lowest level of classification is represented by the bottom plane where concepts are closely related to executive activities. Where a concept node is positioned on the plane represents its relation to the dimensions of sustainability, as introduced in section 2.1. How concepts relate to the three dimensions determines what parts of the total system they address. Each of the three corner points of the plane relates to a specific dimension. The closer a concept is positioned to a corner, the stronger it relates to the corresponding dimension. A concept that is centred on the plane, relates to all three dimensions. It should be noted that the specific positions are not defined in exact sense, but rather determined relatively. This is done based on the author's understanding and based on Glavič and Lukman (2007) who have adopted a similar model.

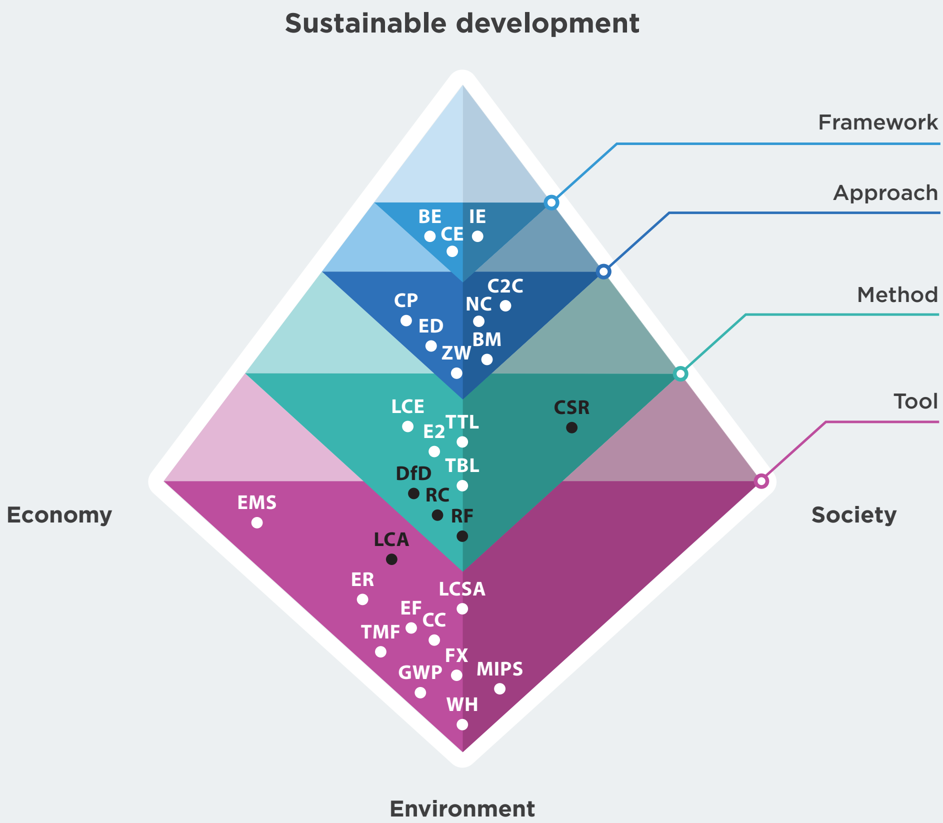
Applying the classification model to identify the most suitable concept for Remeha

In general, the classified structure of sustainable development concepts can be used in two ways:

- To determine how concepts that are currently adopted by an organisation, contribute to sustainable development;
- To identify a concept to direct an organisation's strategies, processes, and activities towards sustainable development, as a first concept or in addition to applied concepts.

For this research, the classification model will be applied in both ways. Remeha is already undertaking some concepts that are concerned with sustainable development. First, these concepts are briefly analysed to identify where there is room for further development. Subsequently, the concepts within this class are evaluated to select the appropriate framework for this research. This will be the circular economy.

The concepts for sustainable development that are currently adopted by Remeha, operate at mid- or low-level orders of classification (marked black in figure 2.7). Corporate social responsibility (CSR) and refurbishment could be explained as methods for arranging particular company processes. They contribute to sustainable development, but they do not offer a coherent and holistic strategy to manage a complex system. Life cycle analysis (LCA) helps to manage activities with quantified scores and targets. However, as low-level tool it does not offer any strategic guidance on how to influence an impact score through industrial processes, like product design.



- Blue Economy (BE), Circular Economy (CE), Industrial Ecology (IE)
- Biomimicry (BM), Cradle to Cradle (C2C), Cleaner Production (CP), Ecodesign (ED), Natural Capitalism (NC), Zero-waste (ZW)
- Corporate Social Responsibility (CSR), Design for Disassembly (DfD), Eco-efficiency (E2), Life Cycle Engineering and Design (LCE), Recycling (RC), Refurbishment (RF), Triple Bottom Line (TBL), Triple Top Line (TTL)
- Carrying Capacity (CC), Ecological Footprint (EF), Ecological Management Systems (EMS), Ecological Rucksack (ER), Factor X (FX), Global Warming Potential (GWP), Life Cycle Analysis (LCA), Life Cycle Sustainability Analysis (LCSA), Material Intensity Per Service unit (MIPS), Total Material Flow (TMF), Waste hierarchy (WH)

Figure 2.7 Classification model to structure concepts for sustainable development.

Other initiatives relating to sustainable development include lean manufacturing, a pilot for CO_2-neutral homes, and a research project by Willem Haanstra on reverse cycles.

These initiatives are commonly practiced from the domain of a specific department within Remeha. They contribute to similar goals in terms of sustainability, but not always seem aligned to a shared purpose or developed from one holistic strategy. Currently, the R&D department does not apply any concept or strategy to structurally consider sustainability in their product development process. In addition to current initiatives, Remeha needs a holistic interpretation of sustainable development and a clear strategy for organising processes, like product development. Remeha's contribution to sustainable development will benefit from adopting a high-level approach to provide a holistic strategy that connects existing initiatives and offers a framework for further development.

Consequently, the approaches & frameworks as classified by figure 2.7 are evaluated to identify a concept that is best suited to be adopted by Remeha and to be implemented through this research. Concepts are evaluated on their regard for the sustainability dimensions, their applicability to product development, and their relevance for political and societal movements. Appendix C elaborates this evaluation in more detail. It reveals the circular economy as the framework that is most fitful to be adopted for sustainable development at Remeha. As such, the circular economy offers a number of advantages that distinguish it from other approaches and provide significant value to this research. These advantages are mentioned below.

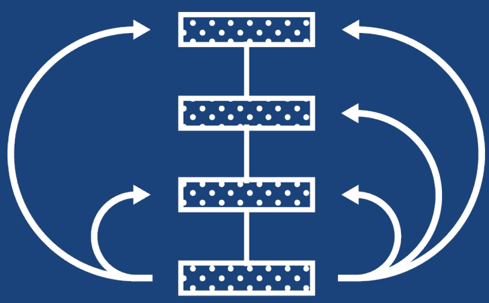
The circular economy:

- targets industrial processes like product development in combination with a business-oriented approach to realisation. It acknowledges the boundaries of current economic systems and proposes effective changes that achieve sustainable benefit through economic growth. This feature stimulates to make sustainable development an intrinsic aspect of an organisation's strategy and processes, rather than dealing with it as a separated subject.
- provides a framework to integrate existing approaches and methods to a coherent collective. It adds value through synergy and thus effectively utilises available knowledge on sustainable development.
- is a familiar and commonly valued approach in the contemporary sustainability field, including society, industry, and politics. Alignment with this framework provides the opportunity to lift on its reputation and relate to already known principles and terminology.
- is relatively new and immature, which leaves room for development. Especially in supporting the implementation of its principles in a corporate environment. Here, this study can contribute to developing the research field while creating a tailored solution for Remeha.

Circular economy gives a strategy to deal with sustainable development while acknowledging business goals and practices. This makes it an interesting approach to apply in a corporate environment, like Remeha. It furthermore provides a solid framework to consistently implement sustainability objectives with underlying methods and tools.

Conclusion

This chapter has specified how interpretations of sustainability and sustainable development have led to the circular economy as a more specific framework of interpretation. Consequently, within the scope of this research, the pursuit for sustainability is effectively replaced by the pursuit for a circular economy. As a result, the circular economy will henceforth be the leading notion in this report.



chapter

03

The circular economy: a theoretical framework

The circular economy is a framework for interpreting and realising sustainable development, specifically aimed at industrial and economic activity. As such, the circular economy is adopted by this research as a model for organising Remeha's product development. In order to do so, the concept of the circular economy and its underlying principles first need to be understood.

The development of today's society is driven from a linear economic system that has prevailed since the Industrial Revolution. Resources are taken from the environment, transformed into products, and disposed back to the environment after use. This model builds value on the high throughput of resources and produces significant amounts of waste (figure 2.5). As a result, the linear economy causes the continuous degradation of our natural environment and systematically fails to balance society's growing demand and earth's finite supply of resources.

As an alternative to the exhaustive linear model, circular economy proposes a fundamentally different system that is restorative by design. The circular economy intends to organise economic processes such that resource productivity is maximised throughout successive use cycles. In this cyclical model, industrial operations are designed to restore the sources of energy and material that are used, so they can be used again. Instead of relying on the large-scale accessibility of natural resources, the circular economy uses resources from end-of-life products as the primary source of economic growth. Then, the products of today become the resources of tomorrow. This way, circular economy provides a new paradigm that allows to persist economic development while respecting environmental constraints.

In recent years, the circular economy has gained increasing attention in business and politics around the world (Ellen MacArthur Foundation, SUN, & McKinsey & Co., 2015). Highly competitive corporations such as Philips, IKEA, and Nike adopt and advocate circular economy. Its opportunities and applications are explored by non-profit organisations like the Ellen MacArthur Foundation and research institutions like the University of Twente. Also, governments on European and national level aim their policies at the circular economy, both implicitly and explicitly. The European Commission, by example, has adopted the Circular Economy Package in 2015, including a concrete action plan for waste management and closed-loop product lifecycles (European Commission, 2015).

As one of the leading authorities on circular economy, the Ellen MacArthur Foundation describes the concept in terms of principles, characteristics, building blocks, and sources of value creation. While these typifications offer valuable insights, their mutual relations or relevance to company processes are not specified, which hinders their application. Literature study has revealed no other characterisation of the circular economy that allows its structural implementation in an organisation like Remeha. A structural framework is required by which the concept of circularity can be applied in an organisation. To this end, this chapter proposes a framework of the circular economy according to five principles that relate to three areas of application within an organisation. This framework offers a characterisation of the circular economy concept and will be used to apply the principles of circularity to Remeha's product development process.

Validity

The framework presented in this section is constructed primarily from the perspective of a manufacturing company. This perspective has been influential in determining the structure, formulation, and selection by which the principles are presented. While the principles are considered to generically apply to economic activity, the proposed framework is not necessarily the optimum interpretation for every organisation. For instance, different emphases probably apply to other perspectives like finance, education, or policy-making.

3.1 Resource flows in the circular economy

The circular economy is essentially about resource productivity. By proposing new strategies for resource handling that are technically and economically feasible, it addresses issues of sustainability through development. This approach rests on the recognition that resources are at the centre of the sustainability conflict. The economy transforms natural resources like materials and energy into products that satisfy society's needs. The way in which our current (linear) economy handles the transformation of resources, causes issues that threaten its own capacity to sustain over time. Extracting non-renewable resources from a finite natural supply causes depletion and limits the sources of value creation and growth. Emitting harmful substances and waste as a result of resource transformation disrupts the ecosystem and endangers society's safety.

Circular economy offers a new approach to resource management in the economy. Through rearranging industrial processes and business models, resources can be optimally utilised and restored within a closed-loop system. This model aims to realise an endless and self-sustaining flow of resources to create economic growth without generating waste. Thereby, creating a condition where economy and society can thrive on the resources nature provides while maintaining a constructive balance within the system. This is the goal, but how exactly should it be realised? Because of the circular economy's resource-oriented approach, it is relevant to first consider the different resources flows in a circular economy.

The circular economy system diagram

Since resource use is at the heart of the concept of circularity, the circular economy's model for resource handling is first discussed. In the circular economy, resource flows are divided in biological and technical cycles, which shows substantial parallels with the concept of Cradle to Cradle. The biological cycle is concerned with the flow of renewable materials (consumables) that are consumed through cascaded cycles. Resources in the biological cycle are returned to the biosphere and regenerated through natural processes.

The technical cycle involves non-renewable materials (durables) whose flows are controlled by managing finite stocks. In order to keep using technical materials in a closed loop, they need to be restored through industrial processes. To this end, the circular economy identifies four key processes: repair, reuse, refurbishment, and recycling. Repair focuses at the product in its use phase, aiming to prevent obsolescence by restoring the products quality. This includes maintenance at regular intervals and service in case of malfunction. When a product does become obsolete, it can be returned to the value chain through the other three processes. First, reuse aims to find a new application for products and components. This process is mainly distributional and does not involve any reprocessing. When reuse is not possible, used components can be refurbished to restore their state to a level that is equal to or better than its new condition. As a final option, the recycling process restores energy and materials such that they can be used as secondary resources for making new components. The order in which these processes have just been described represents a hierarchy of preference for their application. Repair should be preferred over recycling, because it saves embedded energy by focusing at the functional level rather than the material level. The Ellen MacArthur Foundation (2012) refers to this hierarchy as 'power of the inner circle': the smaller the loop, the better.

Figure 3.1 shows a system diagram of these biological and technical cycles. The diagram is based on the butterfly diagram of the (Ellen MacArthur Foundation, 2012), but incorporates some changes in the hierarchy of the biosphere and harvesting in the system. The diagram offers a useful model for organising economic systems and processes towards circularity, but it is not perfect. It would, for instance, benefit from the inclusion of energy flows, but implementing such changes would exceed the scope of this research.

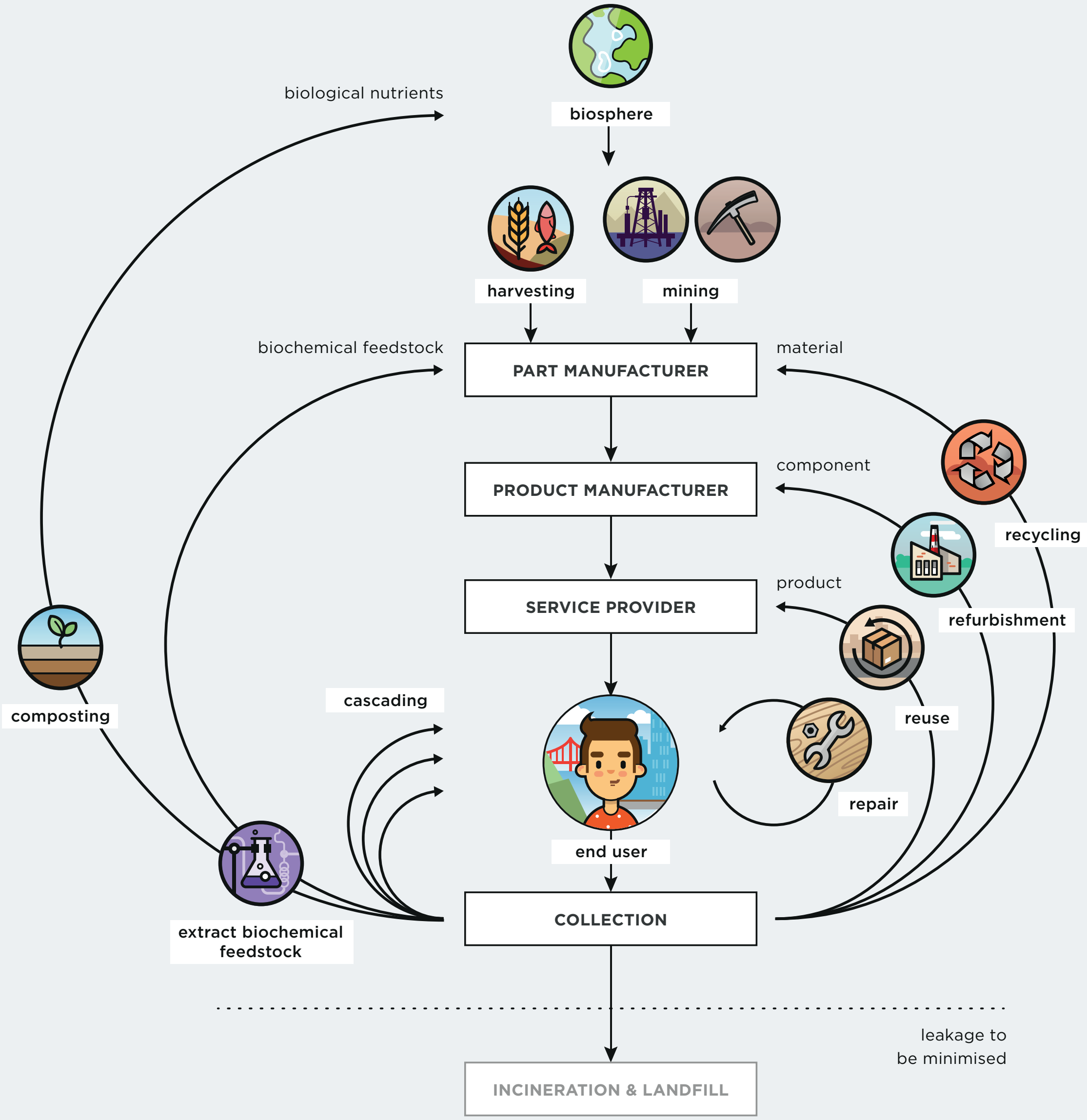


Figure 3.1 System diagram of the circular economy

Figure 3.2 Principles of the circular economy.

3.2 The principles of circularity

The circular economy is built upon several schools of thought that have been around since the late 20th century. In essence, the circular economy offers no fundamentally new approach to sustainable development. Instead, it adds value through synergy: combining multiple approaches to one coherent strategy. Concepts most influential to the foundation of circular economy include the Cradle to Cradle® philosophy by McDonough and Braungart (2002), the performance economy of Stahel (2006), the design principles of biomimicry as introduced by Benyus (1997), the industrial ecology of Lifset and Graedel (2002), the blue economy systems approach by Pauli (2010), and the natural capitalism view by Lovins, Lovins, and Hawken (1999). These schools of thought have been researched to identify their fundamental thoughts. Combined with contemporary interpretations of the circular economy, this analysis has led to the identification of five key principles that are fundamental to a circular economy. These are:

- organise reverse cycles;
- be resource effective;
- think in systems;
- prioritise the future;
- create mutual benefit.

While each of these principles is distinctly characteristic to the circular economy, there are strong interrelations between principles. A true circular economy embodies all five principles in coherence and acknowledges their relatedness. From a reverse perspective, these principles can be adopted by a company, such as Remeha, to organise its processes for a circular transition. Below, the five principles are further elaborated. Additionally, figure 3.2 shows a one-page framework that comprises the five key principles, each including three subordinate principles for elaboration.

Organise reverse cycles

In a circular economy, resources should be used in circular flows. This is one of the most essential principles of the concept and presents an obvious contrast compared with the contemporary economic system. In order to close the loop, so to speak, collection and treatment systems should be organised to recover and restore value from end-of-life products. These treatment systems include processes like refurbishment and recycling that return resources back to the value chain. These are the missing links that transform the current linear economy into a circular one. Then, the output (waste) of one process becomes the input (food) for another process, which effectively eliminates the concept of waste. Ideally, a circular value chain functions as a symbiotic network of different actors. Therefore, collaboration is needed across the supply chain. The development of reverse cycles primarily relates to logistics and process innovation, but can be greatly supported by product development strategies that promote resource recovery.

Be resource effective

The circular economy aims to increase the effectivity with which resources are used in the economy. This includes, but exceeds using resources in closed loops, as covered by the preceding principle. The essence of resource effectiveness is to use resources to their full potential to create a positive impact. This suggests a focus on a desirable outcome instead of pursuing less undesirable results. By example, from this perspective the ideal would be to use resources in a way that repairs damage to the ecosystem instead of causing less additional damage. Utilising full resource potential means that resources should be applied such that they actively create value. First of all, a product or service needs to address a relevant societal need to give it right of existence. Second, the product must be constructed to use only suitable and necessary energy, materials, and components. The intensity with which the product is used by the consumer is also relevant here. A product that lies idle could be interpreted as wasted resources. This closely relates to user behaviour and to business models. For instance, a private car spends most of its time parked, serving no purpose. Sharing and leasing structures could increase the intensity of use by making one car available to multiple users. Besides considering if and how to use resources, the question of what resources to use is also relevant for effectiveness.

Think in systems

Systems are constructed from many interrelated parts whose actions influence the overall system's behaviour. Systems thinking is an approach that aids in understanding how parts of a system interact and how they relate to the system as a whole. In terms of circular economy, the global system, in its broadest sense, is constituted from the cooperating environmental, social, and economic dimensions. Within this system, sub-systems – like NGOs, businesses, governments, and consumers – operate in non-linear and interdependent ways. Sectors, companies, and processes influence each other through complex relations, which makes the outcome of actions difficult to predict. Circular economy aims to optimise the total system performance rather than that of a single component. In order to do so, it is essential to recognise the existence of complex dependencies and to adopt a holistic perspective to assessing and optimising the impact of corporate activity. For instance, by considering the complete product lifecycle in the development process or by promoting interdisciplinary problem-solving.

Prioritise the future

The circular economy offers an approach that is fundamentally different from the contemporary status quo in economy and industry. These fundamental changes need time to be properly implemented in established processes and in most cases they also need time to bear fruit. Designing a product to increase its end-of-life value, only starts to repay when the product becomes obsolete, commonly after several years. Also on the business side, changes, like shifting from one-time sales to a product lease model, can require high initial investments that only start to return after some years. Often, long-term objectives are subordinate to short-term gains. This tendency is also observed in Remeha's business and product strategies, which commonly consider a future no further than three years. However, in order to realise and benefit from the circular economy, opportunities and consequences of actions should be considered from a more long-term perspective. Also the assessment and anticipation of risk, which is an equally relevant driver for change, should adopt long-term views. Only then can imminent future issues be affectively avoided, rather than addressing just the issues that manifest today. At this moment in time, the increasing risks imposed by the prevailing linear economy motivate and necessitate a swift transition to a different, circular system. Especially in this state of transition, a long-term perspective is required to anticipate risks, to envision a desired future, and to seize advantage. But as systems continue to change, a future-oriented approach continues to be relevant when the circular economy becomes more established. Organising processes with flexibility and diversity creates a resilience that helps to anticipate constant change in the corporate environment.

Create mutual benefit

Like a linear economy, a circular economy exists to meet society's needs for goods and development. The fundamental principles of supply and demand and the free market mechanism remain unchanged. Only the methods for using resources and the ways to create benefit change. When changing these methods, it is essential to organise every activity to create mutual benefit for different stakeholders. It is vital to a healthy economic system that there is no conflict of interest. Increasing resource effectivity by extending a product lifespan, but increasing revenue by selling more products could present a conflict. Business model innovation can offer new value propositions and revenue models that align the principles of the circular economy with an organisation's profit-oriented strategies. In essence, all company processes should be organised to benefit from the transition to the circular economy. This also extends to the supply chain level. Collaboration between different actors within or across supply chains is essential in a circular economy. Such collaborations should be organised in a way that benefits all parties involved.

3.3 Implementing the circular economy

Section 3.2 has described the key principles that are characteristic to a circular economy. Now the question arises: how to implement these principles in a corporate environment? Approaching this question from an industrial perspective, three areas can be distinguished from which to practice the principles: product design, supply chain, and business model. These areas of implementation are inspired by the so-called building blocks from the Ellen MacArthur Foundation (2013). The areas of implementation are elaborated below. Each area shows particularly strong relations to

PRINCIPLES	AREAS OF IMPLEMENTATION		
	PRODUCT DESIGN	SUPPLY CHAIN	BUSINESS MODEL
ORGANISE REVERSE CYCLES	M	L	S
BE RESOURCE EFFECTIVE	L	M	S
THINK IN SYSTEMS	L	L	L
PRIORITISE THE FUTURE	S	S	L
CREATE MUTUAL BENEFIT	S	S	L

Figure 3.3 Relations between circular economy principles and implementation areas.

a subset of principles. Business activity within each area should be primarily organised according to those dominant principles. Figure 3.3 shows how the implementation areas relate to the circular economy principles. An 'L' signifies a large contribution, an 'M' a medium contribution and an 'S' a small contribution of an implementation area to realising any of the principles.

Product design

Product development is the process of defining a product: its functionality, its physical structure, and the processes for realisation. Essentially, the design process determines what type of resources are required and how they should be transformed through production processes to meet customer demands. Consequently, the product development process enables the product lifecycle and can greatly influence resource effectivity in a circular system. Designing a product and its lifecycle according to circular economy principles means that waste can be eliminated even before it occurs and products comply with the systems to recover resources at end-of-life. To understand how products should be designed to contribute to a circular economy, one core competence is systems thinking (Ellen MacArthur Foundation, 2012).

Supply chain

A supply chain is a complex network of organisations, activities and resources that are aligned to bring products and services to the customer. Linear supply chains are primarily aimed at the delivery of products to the customer, mostly disregarding the end-of-life processes that succeed product usage. Typically, companies seek to maximise their profits within their own domains, without much interest in the total scope of the supply chain. Activities involve the transformation of natural resources into finished products and delivery chain logistics. In the circular economy, the scope continues beyond product delivery to the organisation of reverse cycles so that used products can re-enter the supply chain as a secondary resource. It should be noted that a secondary resource in this respect does not imply any degradation of quality, merely a non-virgin nature. Activities should be aimed to preserve the quality of resources through processes of transformation and to restore resources from end-of-life products to their initial quality. These aims are aided by arranging accessible collection and treatment systems, tracking the whereabouts and condition of products and materials along value cycles, and seeking collaborative advantage with other parties in the supply chain (Ellen MacArthur Foundation, 2012).

Business model

A business model describes how an organisation creates, delivers and captures value (Osterwalder & Pigneur, 2010). In the circular economy, business models can provide the incentives to consumers and the industry to use and produce products more resource-effectively. By combining attractive value propositions with feasible revenue models, business models could drive better designs with longer-lasting usage (Ellen MacArthur Foundation, 2012) and motivate the return of end-of-life products to reverse cycles. Simultaneously, business models could stimulate acceptance and adoption of circular products and services by end consumers. Capturing value through business model innovation is accelerated when a systems approach is applied to assessing opportunities (Ellen MacArthur Foundation, 2012).

Create value through synergy

While the three areas can be characterised as distinct domains, they closely interrelate in the product development process. The business model defines what value should be delivered to the market, which influences requirements and priorities for product design. Alternatively, decisions for product design influence production process, suppliers, and logistics in the supply chain. In reverse, the supply chain dictates conditions for transport and reverse cycles to which the product design should be aligned. As a result of these interrelations, no area can be perceived in complete isolation when pursuing the circular economy. In fact, it is stated that all areas need to be mobilised in an organisation in order to reach the true potential of a circular economy. Figure 3.4 on the next page schematically illustrates some of the interrelations between product design, supply chain, and business model.

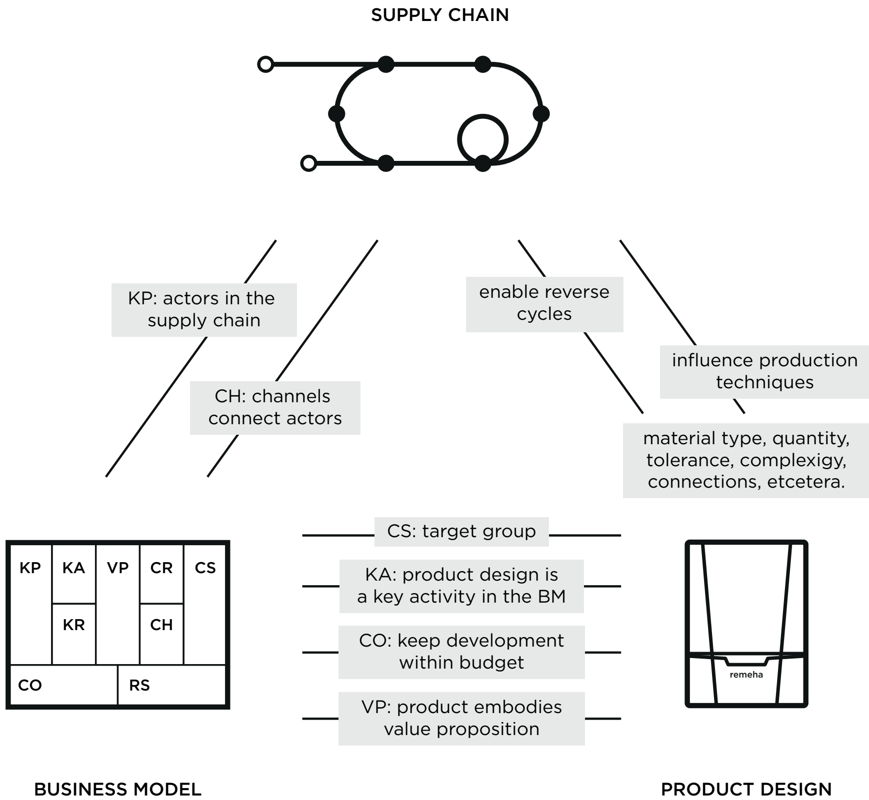


Figure 3.4 Relations between implementation areas.

3.4 Circular economy as a path to sustainability

Looking back from here, chapter 2 has identified the circular economy as the framework that is most promising to be adopted for sustainable development at Remeha. This inspired the further exploration of the circular economy, which led to the development of a clear interpretation and framework as described by this chapter. Before continuing with the in depth application of this framework, this section will briefly consider how the circular economy influences sustainability.

The Ellen MacArthur Foundation (EMF) has extensively researched the consequences of the transition towards a circular economy. They identify considerable opportunities for economic growth and innovation and benefits to society and environment. Benefits predominantly arise from improvements in resource productivity that could be exploited with circularity principles. Several conclusions[4] from this study are presented

4 Analysis is based on European figures and assumptions, but since the sustainability challenges are universal, the conclusions are assumed to apply to other regions as well.

in this section to indicate the potential of circular economy to address sustainability issues while stimulating economic growth. The indicated potential is explicitly related to the issues of over-population, resource depletion, and pollution that were previously described in section 2.3.

Net material savings reduce risk of resource depletion

The currently wasteful economic model leaves great resource potential unexploited. The circular economy allows a more efficient utilisation of material value. By enhancing resource productivity, the industry requires less input from primary raw materials. This means a greater demand can be satisfied by a smaller amount of resources. As a result, the risk of depleting natural resource reserves is mitigated. In a transition scenario – assuming conservative changes in product designs and reverse cycles – the EMF expects an annual cost saving of USD 340 to 380 billion at European level for high-potential product industries. These include eight sectors of medium-lived complex products that together represent 48.6% of the manufacturing industry's contribution to Europe's GDP.

Reduced supply risks and stock price fluctuation

Increasing demand for natural resources combined with the exhaustion of easily accessible resource reserves has caused high and fluctuating stock prices. This presents risks to the European Union, which heavily relies on external resource supply as it imports 6 times more natural resources than it exports. Control over circular material flows will lower Europe's dependency on resource supply. Moreover, the decrease in demand resulting from net material savings is likely to balance stock price increase and volatility.

Reduced CO_2 emissions[5] because of higher resource effectivity

The use of products (and the materials they are made of) causes unwanted effects, like climate change caused by, amongst others, CO_2 emission from the combustion of fossil fuels. Consuming less materials and using them in closed loops, will decrease negative externalities and their associated costs. Across mobility, food systems, and construction sectors, CO_2 emissions could drop to 48% by 2030 and 83% by 2050, relative to 2012 levels (Ellen MacArthur Foundation et al., 2015). In the Netherlands, CO_2 emission could be reduced with 17,150 Kton annually, accounting for 8% of 2010 emission (TNO, 2013).

While the circular economy does not directly influence population growth, it changes the ways of using and disposing resources. In a circular economy, less resources are needed and less waste is created in serving the needs of a population. This change will

5 It is acknowledged that CO_2 is not an inherently polluting substance or the sole contributor global warming. But given its current atmospheric concentrations (discussed in section 2.3) it imposes a substantial risk of disrupting the eco-system and its emission should be mitigated.

positively influence the carrying capacity of the earth, supporting a greater population with the same amount of resources.

Employment benefits in service-oriented industries

An area where the circular economy is expected to provide additional opportunities, is in the employment of the population, which relates to social and economic welfare. This issue has not been previously discussed in light of sustainability, but it is an important aspect to be balanced in a sustainable society and economy. The unemployment rate in Europe is estimated at around 21 million in April 2016[6]. Circular economy principles promote a shift towards a service-oriented and labour-intensive industry. Labour is regarded as a renewable resource, which should be optimally utilised. Increasing demand for new business service and a development of labour-intensive processes around reverse cycles are likely to boost employment opportunities. TNO (2013) estimates circular economy to bring 54,000 jobs in the Netherlands as a result of increased GNP.

Conclusion

The circular economy has been explained as an alternative to the exhaustive and wasteful linear economy that has prevailed since the Industrial Revolution. As such, it offers new ways of organising industrial processes like product development to use resources more effectively and in closed-loop flows. To support a structural understanding and application of the circular economy, a framework of five principles is proposed. These principles can be implemented in three areas of an organisation like Remeha, namely product design, supply chain, and business model. This theoretical framework will be projected to Remeha's activities and processes in chapter 4. Through a focus on product design, the principles of circularity eventually translate into a design strategy and tool that support the development of domestic boilers for a circular economy.

In chapter 2, sustainability has been explained as relating to three dimension that interrelate and are of equal importance: society, environment, and economy. As an approach to reach sustainability through development, the circular economy focuses at resource effectivity and industrial process. Consequently, it addresses the economy and environmental dimensions, but largely disregards the social dimension as an area to optimise. For this research, it is accepted that the social dimension is outside the scope of optimisation, but it is important to realise what this means. Therefore, an intermezzo that directly follows this chapter will provide a brief perspective on the social side of the circular economy.

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6 Based on most recent unemployment statistics by Eurostat, obtained at June 2016.

Intermezzo

THE SOCIAL SIDE OF THE CIRCULAR ECONOMY

This intermezzo elaborates on the social side to the circular economy and the lack thereof. In addition to chapter 3, it is meant to reflect on the current notion of the circular economy with respect to the three-dimensional notion of sustainability, as explained in section 2.1. This chapter does not provide any solution, it merely mentions some critical notes to acknowledge the current shortcoming of the circular economy in addressing social sustainability. The circular economy is not the perfect solution to all sustainability issues, nor does it need to be in order to be meaningful. Yet, it is all the more valuable when shortcomings are recognised.

As section 2.1 has argued, a sustainable condition occurs when the social, environment, and economic domains are in productive balance. Complex systems, like societies, industries, or eco-systems are based in one or several of these domains, but interact with all domains. When influencing systems towards a sustainable condition (for instance through sustainable development), each domain should be addressed and valued equally (Buchert, Neugebauer, Schenker, Lindow, & Stark, 2015; Gmelin & Seuring, 2014; Lozano, 2012).

However, common interpretations and practices of sustainable development have primarily centred around the environmental domain (Buchert et al., 2015; Gmelin & Seuring, 2014). Perhaps this is related to the fact that most concerns of sustainability (like the ones described in section 2.3) have manifested in the environmental domain. It is tempting to understand the issue by its symptoms, but this is a mistake when it comes to sustainability. This is because the symptoms are highly dynamic, depending on the state of interaction between society, environment, and economy. When focusing now at only solving environmental issues, the risk is to neglect or even create future social and economic issues.

The need to consider sustainability from a multi-dimensional perspective, applies to every level at which sustainable development is practiced. In policy-making, education, business development, and also product development. Understanding this is one thing, but properly acting upon it is another. Most initiatives for sustainable development are still rooted in the environmental domain. The inclusion of social considerations is receiving increasing attention in academics, but is still far from common practice. Looking at the circular economy specifically, the social side also remains rather subordinate. The focus at resource productivity is easily related to the environment and the regard for economy systems is quite explicit as well. In its application, the circular economy recognises its impact to the social domain, for instance by creating job opportunities. However, it offers no answer as to how the social domain as a whole should be influenced and optimised. In fact, this research has not found any concept for sustainable development which explicitly related the influence of product development to realising a positive impact in the social domain.

It is concluded that more knowledge and research is required to influence the social domain through product development. However, this exceeds the scope of this research. For now, the circular economy is adopted with the explicit awareness that it addresses environmental and economic systems, but does not consider an optimum influence to the social domain.

part 2

Applying the principles of circularity

chapter 04

The corporate context of Remeha

Describe Remeha's corporate context in the areas of product design, supply chain, and business model and specify the research focus in the organisation.

chapter 05

Business model innovation

Develop a new business model to support the adoption of more resource-effective strategies in design with a business incentive.

chapter 06

Design for circularity

Translate the principles of circularity into the area of product development in terms of design strategies. Analysing several strategies and choosing one for further application at Remeha.

chapter

04

The corporate context of Remeha

So far, it has been elaborated how to understand sustainability and sustainable development, how there are multiple concepts to practice sustainable development, and how the circular economy can be interpreted in this respect. These abstract notions have been addressed by the preceding chapters to provide a necessary understanding for their structured utilisation. However, the level of provided understanding remains rather theoretical, yet.

This chapter sets the first step towards practical implementation by relating the theoretical framework of the circular economy to the corporate environment of Remeha. As described in chapter 3, the circular economy framework consists of five principles, which are practiced through three implementation areas in an industrial organisation, like Remeha. How the principles should be applied to the areas of implementation, cannot be defined in general sense. Their utilisation is influenced by the particular corporate context that shapes the areas of implementation. Therefore, this chapter will describe the corporate context of Remeha in terms of the implementation areas: product design, supply chain, and business model. Also, it will be specified where this research will focus the application of circular economy principles in the organisation of Remeha. But before going into the organisational context, the boiler will be.

4.1 An introduction to boiler technology

Remeha's product portfolio consists of a diverse range of heating products, including, but not limited to, heat pumps, water heaters, boilers, and hybrid solutions. All these products essentially convert an energy source into useful warmth, but they do this in different ways. Appendix D shows an overview of the complete portfolio, including brief product descriptions. As mentioned in section 1.1, Remeha is owned by the holding company BDR Thermea. As a consequence, only the boilers are developed by the R&D department at Remeha. The other products of Remeha's portfolio are developed by R&D departments elsewhere, which will be further addressed in section 4.2. Since the R&D department at Remeha has commissioned this research, it will follow their development scope and focus at gas-fired boilers. Even more specifically, at wall-hanging boilers (WHB) for domestic use.

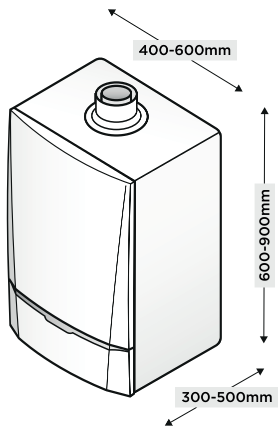
A boiler's main functionality is to generate and transfer heat in a controlled manner. In case of Remeha's wall-hanging boilers, heat is generated by combusting (fossil) gas. Through a heat exchanger component, this heat is transferred to water in two different flows. The first is the central heating flow that circulates through a closed system of boiler, pipes, and radiators. The heated water runs through and transfers heat to the radiator, which in turn transfers heat to the air in order to warm a domestic space. The second flow is the tap water flow that is used for sanitation. This is an open loop flow in which the warmed water does not return to the boiler, but runs down into the sewage system. For a more complete understanding of the boiler's technology and the components involved, appendix E offers a schematic overview of a boiler. It also indicates the product’s input and output from and to surrounding systems. Air and gas are required as input for combustion and water is required as the medium for carrying the transferred heat. The boiler’s output consists of warm water, exhaust gasses (including CO_2) that are emitted to the air, and condensate and tap water that are disposed through the sewage system.

The product’s functionality has now been explained, but it is also relevant to consider some characteristics of the product that delivers that function. To this end, figure 4.1 mentions some main features of Remeha’s wall-hanging boiler. Together with the functional description, this should provide a sufficient impression of the product that is pivotal to this research: the gas-fired wall-hanging boiler for domestic use.

Technologically matured
Boiler HE technology is matured and is about to enter the stage of decline. Secondary functions become more important in the martket

Replacement lifespan 12-18 years
Product becomes obsolete on quality (when it wears out)

Low-interest product
The product is bought out of necessity and for its function. Aesthetics or trends have only minor influence



weight 25-50kg

Wear-out lifespan 12-18 years
WHBs (in the whole sector) are designed for a 15-year lifespan

Built from technical materials
Boilers are constructed from mostly plastics and metals.

107% energy efficiency [7]
With HE technology, efficiencies cannot go much further than 107%. Only minor improvements can still be made on the tap water heating.

Figure 4.1 Main characteristics of Remeha’s domestic boiler.

7 In theory, the useful thermal output of a boiler cannot exceed its fuel energy input, which means the energy conversion efficiency cannot exceed 100%. Condensing boilers do not defy these laws of physics, but calculate the thermal output differently. Water is heated by the combustion energy and additionally by the energy that is captured in the exhaust gasses. These useful energy outputs are added in the numerator of the efficiency equation, while divided only by the energy from fuel combustion. This causes the efficiency value to exceed 100%.

4.2 Remeha’s implementation areas

A corporate transition to circular economy involves the three implementation areas of product design, supply chain, and business model. Each area relates to specific business activities that are unique for every organisation. This section provides a more specific description of these areas in the particular context of Remeha. They have been an important basis for development, implementation, or decision-making in this research, which explains their rather elaborate descriptions. As will appear from section 4.3, especially the areas of product design and business model will be further regarded for implementing the circular economy and so their current state is important to understand as a context for development. Figure 4.2 shows an organogram that includes the different departments of Remeha. Particularly relevant is the direct involvement of BDR Thermea in managing the R&D department, which results in fairly complex organisational dynamics. For this section, it is relevant to understand the involvement of the various departments in the product development process on a local (Remeha) or group (BDR Thermea) level.

At the top of the organisational hierarchy stands BDR Thermea group, a holding company that owns different brands, including Remeha. Through these brands, a broad portfolio of heating products is brought to the market. The development of that portfolio is directly managed by BDR Thermea and performed through 11 different competence centres around Europe. These competence centres are effectively R&D departments, specialised in a specific technology and domain of application. This means that all competence centres are brand-independent. Consequently, product development projects are competence-associated instead of brand-associated. The R&D department at Remeha (officially named R&D Competence Centre Apeldoorn) is dedicated to developing gas-fired wall-hanging and floor-standing boilers for commercial and domestic use. This explains the department’s development focus that was previously mentioned in section 4.1. The boilers that are developed in Apeldoorn are sometimes designed for Remeha and sometimes for other brands, like De Dietrich. As indicated in section 1.1, it is acknowledged that R&D Competence Centre Apeldoorn is organisationally separated from Remeha as it is directly managed by BDR Thermea. However, the R&D department is located at the Remeha head office and closely collaborates with local Remeha departments. Therefore, in this report it is considered part of Remeha in speaking terms.

The scope of the R&D department should be clear, focusing at gas-fired boilers and developing for different BDR Thermea brands. As for the other departments, they are all under direct management of Remeha, like shown in figure 4.2. The activities of the departments in the business area (business unit NL and business development) are directly associated to the Remeha brand. They are concerned with the complete Remeha product portfolio. The operations department is under management of

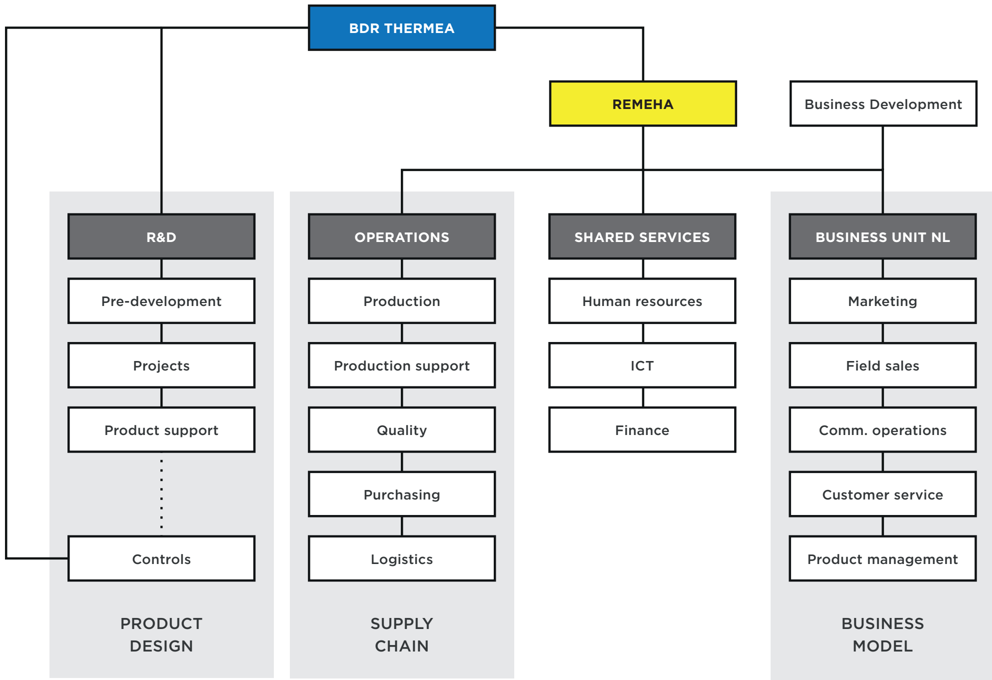


Figure 4.2 Organogram Remeha.

Remeha, but not so much brand-related. They are in charge of producing the boilers that are developed at the R&D department in Apeldoorn, which could be for Remeha or for a different brand.

Now that the organisational structure of Remeha has been elaborated, different parts of the organisation will be described on an activity level. Figure 4.2 shows how the different departments can be related to the circular economy's three areas of implementation. The shared services are more enabling activities, allowing the other processes to function. As such, they relate to all other departments, but do not have a distinct output in the industrial system. For this reason, they are not recognised as a key area for implementing the circular economy. The upcoming sections will describe the corporate context of Remeha in terms of the three areas of implementation.

Product design

The area of product design is concentrated at the R&D department, which is divided into three sub-departments: Innovation & Pre-Development (IPD), Projects, and Product Support. This organisational structure is unique to Competence Centre Apeldoorn; other BDR Thermea Competence Centres are organised differently. The IPD department is concerned with more innovative and high-risk developments on a technology level.

These developments result in feasible technologies that are ready for implementation in new products. These new products are developed by the Projects department, which delivers a marketable product that is ready for production. When a newly developed product is ready for industrialisation, the product is handed over to Product Support. This department is responsible for any changes to the product while it is in production. For instance, to improve costs or to solve any structural technical issues that arise after the market introduction.

In order to streamline the development process, BDR Thermea has formulated a New Product Development (NPD) process that must be employed by all competence centres. This development process is not merely an R&D process since it involves all disciplines in the project team, like product management, procurement, and quality. Given the organisational structure of R&D Competence Centre Apeldoorn, the NPD process literally applies to the Projects department specifically. The IPD and Product Support departments employ slightly different development processes. These are based at the NPD process, but are tailored for the respective departments as they do not primarily focus at the development of new products. Figure 4.3 shows a concise

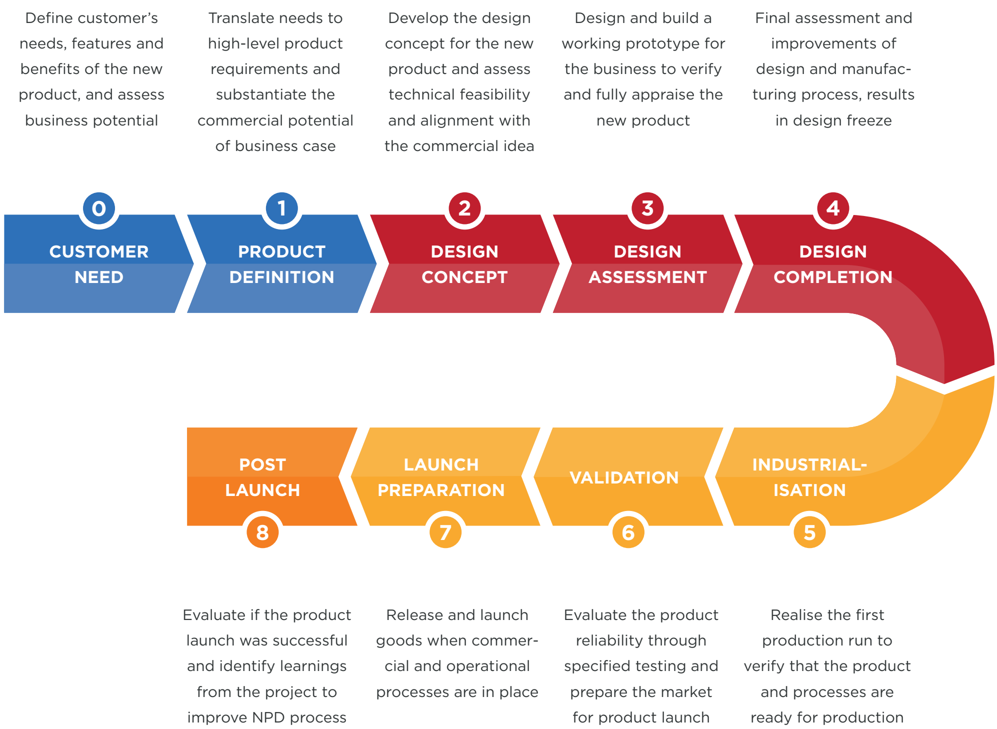


Figure 4.3 BDR Thermea's New Product Development Process.

model of the NPD process. Appendix F contains a more elaborate model that describes key activities of the development process in eight so-called workstreams.

The New Product Development process is built according to the stage gate methodology. There are nine stages in total, each succeeded by a stage gate. Through these nine stages, a project evolves from an idea or need into the production and market launch of a new product. A stage is essentially a project phase that can occupy several weeks or even months. Each stage has a pre-defined set of deliverables. The principle of the stage gate model is that the project can only continue to the next phase after these deliverables are produced. The stage gate is the moment at the end of each stage when the deliverables are assessed to decide whether to proceed to the next stage of the project. This ordered way of proceeding a project allows to reduce uncertainties and control the commitment of resources to the project.

Supply chain

Remeha's global supply chain involves a broad range of actors that source materials, transform them into components, assemble final products, and distribute them to the customer. Different products in Remeha's portfolio are assembled at and distributed from different sites in Europe. The gas-fired boilers that are developed at R&D Competence Centre Apeldoorn are also assembled in Apeldoorn (with some occasional exceptions). From there, the boilers are distributed through extensive sales channels all over Europe, major markets being the Netherlands, Belgium, Germany and England (mostly commercial).

The supply chain's predominant focus has been the delivery of products to the customer, but also the maintenance and repair of boilers during the use phase. Maintenance and repair activities are mostly performed by installers and sometimes supported by Remeha's service mechanics. Spare parts for these activities are supplied by Remeha, guaranteeing quality and availability for a reasonable period after the last production date. Figure 4.4 shows a simplified model of Remeha's current supply chain.

The end-of-life processes that succeed the use phase have so far received limited attention from Remeha. Large-scale collection and treatment systems for disposed boilers are not yet established and Remeha has little control over end-of-life products. While no information has been attained on what exactly happens to Remeha's boilers after use, an approximation of the supply chain's current end-of-life processes can be provided. A portion of disposed boilers is illegally distributed to countries in Eastern Europe to be reused, but there is no established system for intended reuse. The vast majority of disposed boilers enters local waste streams. Relative to sales numbers, the number of refurbished components is assumed to be marginal. As for recycling, Van Gerrevink estimates that about 50% of disposed boilers is processed through established recycling facilities. Still, only a portion of these boilers ends up as recycled

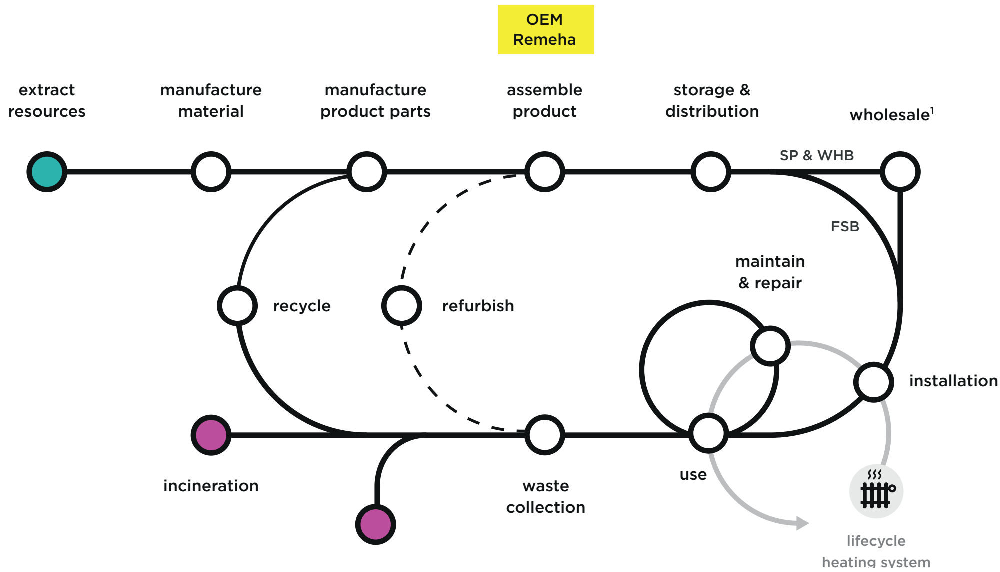


Figure 4.4 Simplified model of Remeha's supply chain.
[1] Spare parts (SP) and wall-hanging boilers (WHB) are distributed through wholesale. Floor-standing boilers (FSB) are supplied directly to the installer.

material, because many contemporary boiler components are not fit or optimised for recycling. The other roughly 50% is estimated to be disposed directly through incineration and landfill, with the probable exception of valuable components like the heat exchanger. Based on these estimates, it can be stated that Remeha's supply chain is organised in a predominantly linear fashion.

However, recent developments are increasingly oriented towards the supply chain processes that succeed product usage. In 2015, Remeha started to offer refurbished gas-air units with equal quality and warranty conditions as new components. This so-called Remeha Renewed programme is a success in the market, but is still only applied at small scale today. It offers just the gas-air unit for only the model Tzerra boiler. Additionally, Remeha is closely collaborating with Van Gerrevink, a local recycling company, to increase opportunities for recycling. Part of this collaboration has been a graduation project by Willem Haanstra on industrial collaboration to close material loops for a domestic boiler. Still, these initiatives need to be further developed and expanded to larger scales in order to realise a notable level of control and impact in post-use stages of the supply chain.

Business model

Remeha delivers a range of heating systems to serve different customer segments: building owners, consultancy firms, installers, and end users. Building owners manage the construction and maintenance of residential and non-residential real estate, which is rented by or sold to the end user. This real estate is delivered including a heating system, which is often selected on advice of a consultancy firm. The installer installs and maintains heating systems at residential and non-residential buildings, sometimes according to the consultancy firm's advisory report. He sells boilers and maintenance or repair service to end users and building owners and in some cases advises his customers in their purchasing decisions.

The company's value proposition is centred around the product, which is sold for its functionality to provide heat in a cost- and energy-efficient manner. In the current market for heating systems, competing products are very similar in functionality, performance and efficiency. When new product features are introduced to the market, competitors are quick to follow suit. Typically, Remeha takes a prominent position in the market, but is rarely leading in product innovation. By responding quickly to recent market developments, they level with competition. As there is little functional distinction between competing products, the market is highly competitive on price and warranty conditions.

Distribution and sales channels are business-to-business oriented. Remeha sells products to wholesales and installers, who resell them to the end user with a profit margin. All this through one-time sales transactions, which instantly return the costs for every delivered product or service. In this classic business model, Remeha benefits financially from high sales numbers. This motivates to sell as much products as possible, as quickly as possible. In this model, improvements to resource productivity, like extended product lifetime, are only profitable when they lead to higher sales numbers or a lower cost price.

With every transaction in Remeha's business model, the ownership of the product is transferred and eventually ends up with the end user. He now possesses the product, but also bears the risk of malfunction and the responsibility for maintenance and disposal when the product becomes obsolete. Remeha is not directly involved with the end user and has no influence or control over the product during and after its use phase.

Competitors mostly employ business models similar to the one just described. However, developments in the market demonstrate an increasing interest in leasing or renting, rather than owning boilers. Installers and boiler manufacturers like Holland Warmte, and Nefit all offer different propositions through a leasing structure[8]. Remeha also experiments with product lease for the 'nul-op-de-meter' project, be it on a small scale.

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8 Based on information obtained from the website of the respective installer or manufacturer, retrieved at 18 March 2017.

The development of new products, technologies, or variants, is planned in a product roadmap that spans three years. This roadmap is formulated, based on input from all BDR Thermea's business units. The most leading input comes from the market, provided by the product management departments. They continuously monitor market development and customer needs, which they translate into a product request. On a group level, these requests are collected and filtered and subsequently assigned to a competence centre, based on its expertise.

Product development at R&D Competence Centre Apeldoorn only accounts for sustainability considerations in terms of legislative requirements. Compliance with RoHS, Ecodesign, and Energy Labeling directives is ensured, but there are no efforts to exceed these requirements. Remarkably, the NPD process requires the consideration of 'environmental impact' at stage 2, but there is no consensus on what this means or how to deal with it.

4.3 Focus areas and departments

Ideally, all departments of Remeha are mobilised to adopt the principles of circularity. Then, product development, supply chain, and business model function in synergy and create a maximum effect. However, such a complete transition is of great impact to the organisation and is not feasible to realise within the scope of this research. Thus, in the pursuit of implementing the circular economy at Remeha, this research needs to focus at a particular part of the organisation. Based on the research objective, formulated in chapter 1, the research focus is formulated in terms of the areas of implementation. This scope is further specified and narrowed down to specific departments in the organisation. These departments lead to the identification of important stakeholders and represent the boundaries for developing the tool. Figure 4.5 shows this focus schematically. The reasoning behind this focus will be further explained in this section.

The area of product design is the primary focus of this research. First of all, this focus aligns with Remeha's need to influence sustainability through the product development process. Since product development has been identified as an area of key influence to the circular economy in chapter 3, it can be stated that this focus is justified. Moreover, a focus at product development aligns with the expertise of the author, which allows it to be substantially addressed. Translating this focus to the organisation reveals R&D Competence Centre Apeldoorn as the responsible department for product development at Remeha and the initiator of this research. As indicated in section 4.2, R&D Competence Centre Apeldoorn is divided into three departments: innovations & pre-development (IPD), projects, and product support. The projects department is concerned with the development of new products and will be the primary focus for implementing the principles of circularity. It is assumed that, by aiming at new product development (rather than variants and change management), a larger impact on

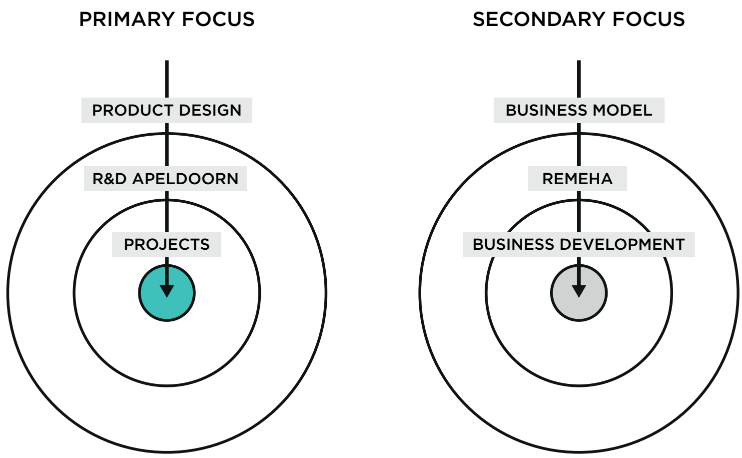


Figure 4.5 Focus areas and departments.

the product's sustainability performance can be achieved. Moreover, this research is commissioned by the Projects department specifically, which expresses the need to focus implementation at their department. Implementation in this area will be further discussed in chapter 6 and leads to a practical design tool that will be introduced in chapter 8 of this report.

Focusing at the area of product design and the R&D Projects department properly addresses the research objective that requires an implementation of sustainability in the product development process. However, Remeha's transition to a circular economy would benefit from a broader approach. For this reason, the business model area is included as a secondary focus in this research. Development in this area allows to illustrate the business potential of the circular economy and to inspire new ways of thinking about the role of the product in the value proposition. This can create new opportunities to improve resource effectivity, it will promote the adoption of the circular economy as a strategic corporate aspect, and it will result in broader support in the organisation. Eventually, this should also benefit the implementation of the design tool at R&D. Since the business area is of lower relevance to the research objective, it is addressed by this research as a secondary result. The result will be a business model, developed at a conceptual level and supported by a business case. How it should be further optimised, implemented, and organised, is beyond the scope of this research. Considering again how this focus translates to Remeha's organisation, development of the business model will be targeted at the business development department.

Stakeholders
The selection of departments leads to the identification of several key stakeholders. They come from different departments and have been involved in the development of the design tool and the business model. Their needs and interests have influenced decisions in this process. Below, the stakeholders for this project are described, mentioning their responsibilities and their key interests in relation to this research.

- **Manager R&D:** Ensure that development objectives are determined and met, logistics are coordinated and budgets maintained. Lead a team of employees from the IPD, Product Support, and Projects departments to realise the product roadmap according to BDR Thermea requirements.
  Key interests: viable business case, alignment with BDR Thermea policy, build on available expertise.
- **Manager Projects:** Manage the development of new products according to the product roadmap. Coordinate resources and lead a team of project managers and engineers to develop products that are up to standards and within planning and budget.
  Key interests: align with NPD process flow, practical results, limited impact to budget and planning.
- **Team leader Product Engineers (PE):** Responsible for the personal management of a team of product engineers. Knows about personal and professional conditions of employees to ensure that people work efficiently, to the best of their ability, and with pleasure. Personally involved in initiating this research.
  Key interests: support team in their activities, allow pro-active development for sustainability.
- **Manager Business Development:** Realise a strong market position and financial growth by defining long-term strategic goals, building key partnerships, understanding market conditions, and identifying business opportunities. Initiate and organise development to capture these opportunities.
  Key interests: align with long term business objectives and company expertise, contribute to market position.
- **Director Operations (COO Remeha):** Plan, direct and coordinate the production system - including warehousing, inventory, product assembly, and logistics to function effectively, within budget and planning, and according to specification and quality requirements.
- **CSR ambassador Remeha:** Build BDR Thermea CSR strategy and manage the implementation of this group strategy at Remeha. Support department directors in formulating and pursuing specific CSR goals. Continue to explore opportunities for business and CSR alignment.
  Key interests: align with and support CSR strategy, make CSR actionable through business practice.

The COO is involved to gain his support for the project and to prevent any conflicts with his area of expertise. However, given the previously described focus in the organisation, his interests are not leading in this research. The Corporate Social Responsibility (CSR) ambassador has been involved to align this research's approach to sustainability with his approach to corporate responsibility. In terms of developing the design tool and business model, his position and interests are less relevant.

Conclusion

This chapter has described the corporate context of Remeha in terms of three areas: product design, supply chain, and business model. The area of product design has been selected as a primary focus for implementing the principles of the circular economy. This focus aligns with Remeha's need to influence sustainability through product development and it conforms with the author's expertise. Chapter 6 will further develop this focus by translating the abstract principles of circularity into more actionable design strategies. Adopting one design strategy for further implementation at Remeha, leads to the development of a design support tool that will be introduced in chapter 7 and 8.

According to the secondary focus of this research, a new business model has been developed. This business model is meant to create new opportunities for increasing resource effectivity and to support the adoption of circular design strategies with a business incentive. The proposed business model leads to a better-founded selection of design strategies in chapter 6, which is why it is introduced first in chapter 5. But before continuing with the elaboration of the business model and design strategies, a brief intermezzo will discuss the energy transition as an external factor that influences decisions in both these areas.

Intermezzo

THE ENERGY TRANSITION

In the 1990s politicians around the globe became increasingly aware of the occurrence and consequences of climate change. As a result, the United Nations Framework Convention on Climate Change (UNFCCC) was founded to regulate international climate policies and coordinates an annual Conference of Parties (COP). At these conferences, leaders from virtually all nations gather to discuss climate change and how to address it. In 2015, the 21st Conference of Parties was held in Paris to establish an agreement on measures to limit global warming. This has resulted in the Paris Agreement, signed by 174 nations and with the primary aim to keep global warming below 2ºC relative to pre-industrial levels. Each participating country is expected to determine its own contribution to the agreement. In response, the European Union has committed to reducing GHG emissions with 80-95% by 2050, compared to 1990 levels.

As a member of the European Union, the objective to reduce GHG emissions greatly impacts the Netherlands' energy consumption. According to a study by Schepers, Naber, Rooijers, and Leguijt (2015), 95% of the buildings in the Netherlands is currently heated by products that use fossil gas, like Remeha's boilers. In order to reduce GHG emissions, different sources of energy need to be used in more efficient ways. One

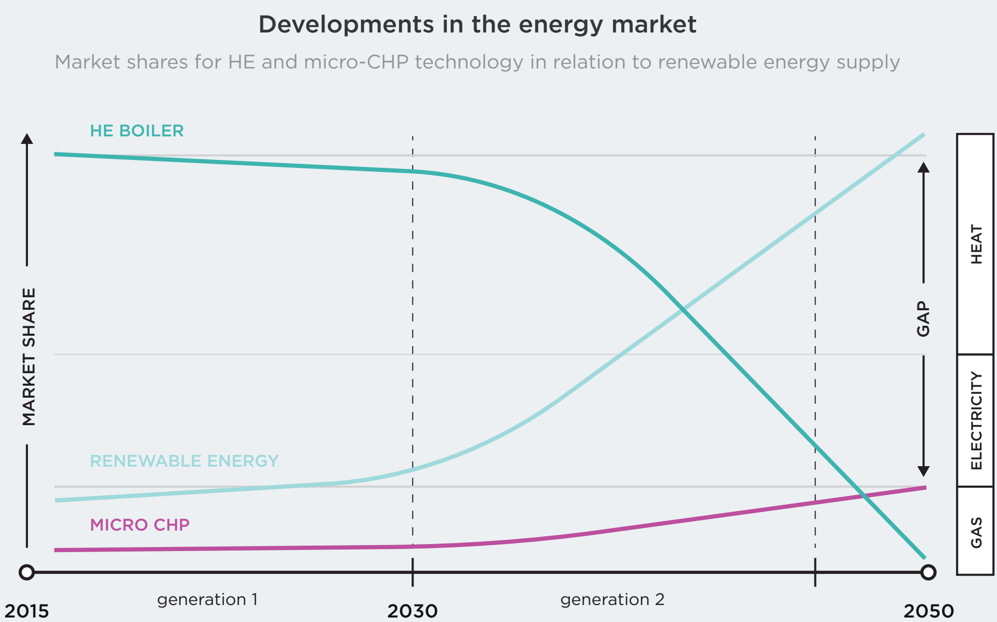


Figure I Developments in the energy market.

pivotal development in this respect is to move from fossil to renewable energy sources. How this can be organised, depends on the costs and availability of alternative energy sources and the adaptability and capacity of the energy infrastructure. Based on these influences, it is expected that in 2050 the energy supply to the built environment will consist of green gas (20%), electricity (30%), and thermal sources (50%) (Schepers et al., 2015). Ratios might turn out somewhat different, but it is reasonable to assume that the future energy market of 2050 will depend more equally on multiple sources to meet the energy demands of the built environment.

Currently, Remeha's boilers are not compatible with renewable energy sources. However, this compatibility is required if Remeha wishes to maintain its relevance in a changing energy market. What this will mean for Remeha's future product development is yet unclear. As the share of gas will shrink from 95% to about 20%, the market shares of gas-fired boilers is expected to decrease accordingly, as displayed in figure I. Within the gas domain, Remeha expects the currently dominant high-efficiency (HE) technology to lose its relevance as a result of inadequate efficiencies. Micro-CHP technology allows higher efficiencies and is expected to gradually replace HE technology. This still leaves a gap to be filled by other technologies that operate with electrical or thermal energy. For this research, it is relevant to acknowledge the approaching energy transition and its impact to Remeha. This will influence decisions on business model and design strategy in chapter 5 and 6 respectively.

chapter

05

Business model innovation

The business model has been recognised as an essential area from which to practice the principles of the circular economy. It can create a powerful incentive for companies and consumers to use resources more productively. Moreover, a new business model could inspire new ways of thinking about the role of the product in the value proposition, which can present new opportunities for circular design. This chapter proposes a new business model that allows Remeha to benefit from developing their boilers in a more resource-effective way. By proposing this business model, the aim is to create incentives and opportunities for adopting circular design strategies and create support for the implementation of a design tool at the R&D department. This way, the business model leads to a better-founded selection of design strategies in chapter 6.

First, section 5.1 identifies where the opportunities lie for business model innovation, considering opportunities of circularity but also trends in the industry and the market. In response, chapter 5.2 proposes the product-service system archetype as the new business model principle, offering various benefits over the current model. Consequently, section 5.3 uses the Business Model Canvas to describe how a business model based on a product-service system looks like for Remeha. Lastly, the financial viability of the proposed business model is assessed and verified by a business case described in section 5.4. These steps, from opportunity identification to business case, are developed in close collaboration with Remeha's business development department. This, to ensure the quality and applicability of the business model for Remeha and to establish support in the organisation.

5.1 The motivation for innovation

The identified importance of business models for a transition towards the circular economy has encouraged the exploration of opportunities for business model innovation. In this respect, the primary aim is to align circular economy principles with business objectives, focusing at resource effectiveness. Considering Remeha's current business model, as described in section 4.2, some challenges arise in light of enhancing resource effectivity. Currently, Remeha benefits from the sales of a product through a one-time transaction. Improvements to resource productivity, like extended product lifetime, are only profitable when they lead to higher sales numbers or a lower cost price. However, extending a product's lifespan is more likely to result in less rather than more annual sales numbers, because products can be used longer and the main reason for obsolescence relates to quality. Here, a conflict arises between increased resource effectiveness and increasing revenue. How about if the product were to be designed for a closed-loop resource flow? This would increase its residual value after use and could save costs for primary raw materials. But in the current business model, Remeha loses ownership of the product after sales and has no influence or control over the product during and after its use phase. This presents another conflict between resource productivity and financial benefit. Within Remeha's current business model, the opportunities to create benefit from a more productive use of resources are limited. A new business model could increase these opportunities and better align improved resource effectiveness with Remeha's business objectives.

It has been established that a new business model can provide increased opportunities for Remeha to benefit from the circular economy. Therefore, a new business model is developed for this research. However, it is interesting to consider a different perspective as well. Instead of regarding the circular economy as the incentive to adopt a new business model, a new business model can also offer the incentive to adopt the principles of circularity. At the moment when the development of a new business model was initiated, Remeha was not ready to commit to organisational changes in pursuit of the circular economy. For this reason, key trends and forces in industry and in the market are also considered in the development of a new business model. This would help to develop a model that is successful in the market and aligns with the principles of circularity. It is this combination that creates value and incentive to change.

When exploring the incentives for business model innovation other than from a circular economy perspective, the business model's environment should be regarded. A business operates in the context of competing organisations, technological innovations, changing customer needs, and international networks. Such external forces influence the business model. Understanding them will help to uncover new associations, patterns and opportunities that lead to ideas for business model redesign or innovation. Therefore, the business model's environment is mapped according to four external aspects: key trends, market forces, industry forces, and macro-economic forces. Figure 5.1 shows these aspects around the business model and briefly elaborated by several key points.

These aspects have been systematically mapped by use of the Business Model Design Space Card Deck tool by Strategyzer, available on their website. It offers trigger questions to map the business context in a structured way. Appendix G shows the result of this analysis, listing a variety of trends and forces. Three of these have particularly motivated and influenced the development of a new business model. They relate to the energy transition, a market shift from ownership to access, and legislation on resource management and are briefly elaborated below.

- The energy market undergoes a transition from fossil fuels to renewable energy sources. Currently, fossil gas accounts for 95% of the energy supply to the built environment. It is expected that by 2050, fossil gas supply to the Dutch built environment is fully shut off. The new energy market of 2015 will likely be a diverse market consisting of bio-gas (50%), heat (30%), and (green) electricity (20%). Supply will depend on local availability. In the transition towards the new energy market of 2015, the built environment will experience the impact of

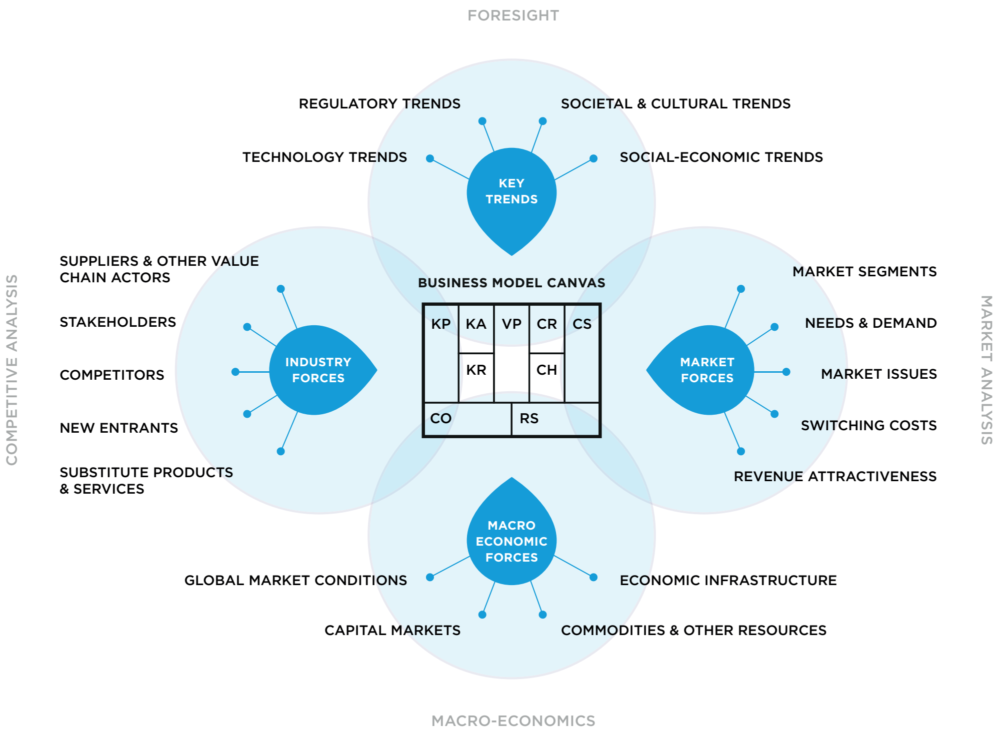


Figure 5.1 Business environment map (Osterwalder & Pigneur, 2010).

changing energy supply and infrastructure. In this situation, Remeha's current sales proposition causes risks and uncertainty for the customer. For how long can a boiler still be used when the energy market changes? And should one buy a new boiler when fossil gas supply will be terminated?

- A disruptive trend in the consumer market reveals a new generation of consumers that is willing to value products for their use instead of their possession. This shift is demonstrated by an increase of shared cars, machinery, and daily commodities (Ellen MacArthur Foundation, 2012) and is supported by sharing platforms such as Snappcar, Airbnb, and Peerby. In the heating system industry, installers and boiler manufacturers like Holland Warmte, Geas Energiewacht, ATAG, and Nefit all offer different propositions through a renting or leasing structure[9].
- Legislation is increasingly aimed at resource management and extended corporate responsibility. The WEEE Recast Directive (2012/19/EU) requires Remeha to collect and properly treat end-of-life boilers that have been placed on the market after 2005. The European Commission's circular economy Action

9 Based on information obtained from the website of the respective installer or manufacturer, retrieved at 18 March 2017.

Plan will introduce measures and product requirements to promote the effective use of resources in the whole product lifecycle. Appendix A provides a more elaborate overview of legislation that addresses sustainability and resource management. These legislative developments impose obligations, but also present opportunities to benefit from the end-of-life value of boilers. But to do so, Remeha needs control over their end-of-life boilers.

In conclusion, innovating Remeha's business model can provide a strong incentive to adopt principles of circularity in product development and provides the opportunity to align with developments in the energy market, the consumer market, and legislation.

5.2 Moving from ownership to access

When considering how Remeha's current business model is limited in stimulating the effective use of resources, one essential influence is the aspect of ownership. When a customer owns the product, he owns the benefit from a longer product lifetime and increased end-of-life value. The customer controls the product during the use phase and decides how to handle disposal. Also, he owns the risk of malfunction and the uncertainty of a changing energy market. However, customers do not necessarily want this ownership, especially in the case of a low-interest product like a boiler. Here lies the key to business model innovation for Remeha: rethinking the principle of ownership.

In a circular economy resources should be circulated within the economic system, which requires persistent control over products and components in each stage of their life cycle. When transferring ownership of a product to the consumer, Remeha resigns its influence on the return of its embedded resources. An alternative way for Remeha to supply benefit to the consumer is by selling a boiler's performance instead of its possession. As a result, consumers benefit from guaranteed product functionality without the responsibility to maintain or properly dispose. Then, use replaces consumption; durable products are leased, rented or shared wherever possible. At the same time, Remeha holds ownership of the boiler during its use phase and thereby maintains control over its resources. As a result of this business model, all incentives are aligned to create resource-effective products and services. Now, Remeha benefits from durable products instead of maximised throughput, because income from lease is proportional to the use time instead of the replacement frequency. And when designing a product for a closed-loop system Remeha takes advantage of the resources that can be recovered. The company can now control resource flows in each stage of the product lifecycle and influence disposal and end-of-life treatments like recycling.

One business model archetype that facilitates this new approach to ownership is the product-service system (PSS). This function-oriented business model integrates a tangible product with an intangible service to fulfil the customer's needs. A product-service system focuses its value proposition at selling and using functionality, rather than possession of a product. This principle of selling a product as a service closely relates to the concept of the functional service economy, introduced by Walter Stahel (2006) and also commonly referred to as the performance economy. Already in the mid-1990s the product-service system was recognised as one of the most effective instruments to improve economy's resource-efficiency in a revolutionary way (Tukker, 2015). Today, the product-service systems is still regarded for its high-potential impact on economy's resource productivity and is viewed by influential authors and policy makers as one of the most important means of creating a circular economy (Tukker, 2015). Different types of product-service systems can be distinguished. Tukker (2004) recognises three PSS classes, based on whether the core value lies with the product or service component of the business model:

- **Product-oriented:** The value proposition is mainly focused at the product, which is owned by the customer. Additional services, such as a maintenance contract or a take-back agreement, are offered in combination with the product.
- **Use-oriented:** The value proposition is still centred around the product, but ownership remains with the product provider. Use replaces consumption; products are made available to consumers through leasing, renting, sharing (sequentially used by different users), or pooling (simultaneous use of the product by different users).
- **Result-oriented:** The customer pays the provider for delivering a result, like a comfortable climate at home. The value proposition does not involve a pre-determined product to deliver this result.

In the first class, the product-service system relies on the product as its core component of value creation and service takes a secondary stand. This type of PSS is quite similar to Remeha's current business model. Proceeding from the second to the third class, the value proposition increasingly shifts from product towards service. The business model that will be proposed and further elaborated in the next sections of this chapter can be classified as a result-oriented product-service system.

5.3 New business model

The principle of the product-service system has been generally described in section 5.2, but has not yet been specified for Remeha. This section will propose a tailored business model for Remeha, based on the product-service system archetype. This business model is developed according this research's focus at domestic boilers, as elaborated in section 4.1.

The Business Model Canvas by Osterwalder and Pigneur (2010) was used as a tool for describing and developing the new business model. The canvas provides a holistic perspective on the business and its different interrelated aspects. It recognises nine categories to describe different processes and internal activities. Figure 5.1 shows a template of the Business Model Canvas. It indicates the nine categories and furthermore specifies several relations between the categories.

Appendix H describes the new business model according to the Business Model Canvas template. Each aspect is briefly elaborated by a few key points. Developing all nine categories of the business model in detail would exceed the scope of this research. Therefore, only a selection of categories is described in detail by this report. Here, the focus is on the value proposition that will be offered to the customers and how a leasing structure can be organised to deliver this proposition. This section will explicitly describe the customer segments and the value proposition by use of the Value Proposition Canvas by Osterwalder et al. (2014). This canvas consists of a Customer Profile and Value Map that can be used to structurally describe a customer segment and value proposition respectively. Subsequently, it is described how the proposed product-service system can be organised, touching upon key partners and sales channels. Section 5.4 considers the cost structure and revenue streams.

Customer segments

A business model should be built on a thorough understanding of the customers it serves. These insights help to comprehend who the customer is and what his needs are. Based on this understanding, the customer can be effectively targeted by a value proposition, addressed by customer relations, and reached through sales channels.

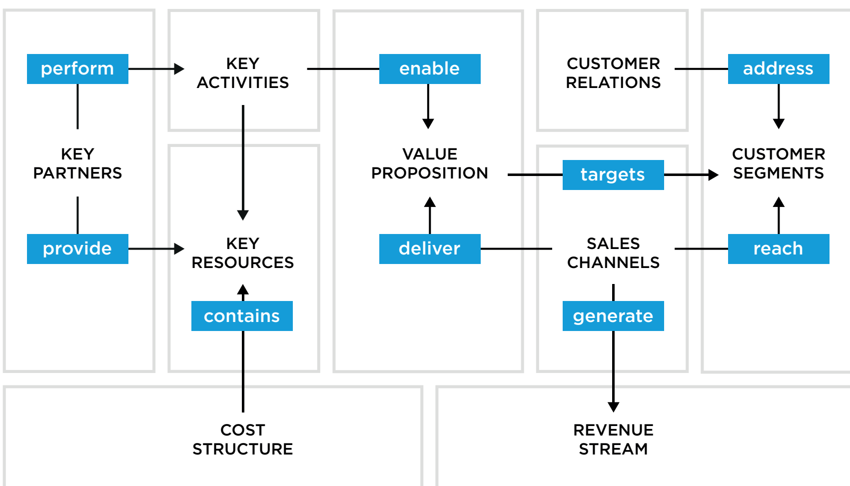


Figure 5.2 Business Model Canvas template.

Remeha serves four customer segments with their current business model: building owners, consultancy firms, installers, and end users. The proposed product-service system targets the same segments and respects the customer relations that have already been established. To keep this first stage of development manageable, only the end user and installer are regarded for now. In consultation with Remeha's business development department these segments are assumed to be most important in light of the focus at domestic boilers.

Based on Osterwalder et al. (2014), the segments of the end user and installer are explored and described by a customer profile. As shown by figure 5.3, the customer profile consists of three areas. Jobs are activities that the customer is trying to complete, pains are negative experiences that the customer might face while working on a job, and gains are the positive outcomes that the customer is trying to achieve. Additionally, the figure mentions some key points that are involved in each of the areas. According to this model, a customer profile has been formulated for the end user and installer, based on insight from Remeha's business development, marketing, and product management departments. Both profiles are described in appendix I. Within the scope of this research, their foundation on Remeha's expertise is sufficiently valid. But when Remeha should decide to pursue this business model proposal further, the profiles need to be verified by market research. Each profile lists several jobs, pains, and gains in respective order of importance, severity, and relevance. This ranking is necessary for understanding the significance of the different factors in the profile and to prioritise the value proposition accordingly.

The end user buys the domestic boiler and thermostat to be installed in his home. He benefits from warm tap water and a warm living environment, controlled through the thermostat. While the boiler itself is of low interest to the end user, its functionality highly influences the user's well-being. He expects warmth to be always available end

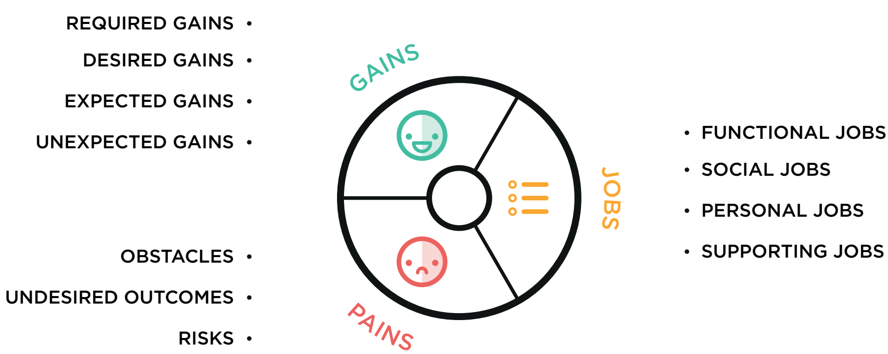


Figure 5.3 Customer Profile template, based on Osterwalder et al. (2014).

experiences great discomfort of a malfunctioning product. End users are generally most interested in low costs of acquisition and use and highly value safety, which is particularly relevant since a boiler is an inherently unsafe product. In general, the market is increasingly interested in sustainable products, but only if this does not lead to (considerably) higher costs.

The installer professionally installs, maintains, and repairs boiler for the end user. His business is centred around these activities but also includes work on other domestic installations. Maintenance work is planned in regular (typically annual) intervals. Repair activities are always incidental and are always high-priority, because the end user expects uninterrupted access to warmth. The installer benefits from a boiler that is reliable and easy to maintain and service. As the current market is organised, the end user is the primary client of the installer. He requests and pays for the services of the installer and often relies on the installer's advice when deciding on the purchase of a new boiler. Around half of the end users that own a domestic boiler have some kind of service contract with the installer, paying a fixed amount per month or year and receiving proper maintenance and repair in return. Depending on the contract, either the installer or end user is responsible for the costs of spare parts outside the warranty period. The other half has no contract and pays for each service incident separately.

Value propositions

Equipped with an understanding of the customer's characteristics and needs, a value proposition can be formulated for the product-service system. To this end, the second part of the Value Proposition Canvas is used: the value map. As visualised by figure 5.4, the value map breaks the value proposition down into products & services, pain relievers, and gain creators. The pain relievers should relate directly to the customer pains and the gain creators should relate directly to the customer gains. Then, a fit is established between the customer segment and the value proposition. Appendix J

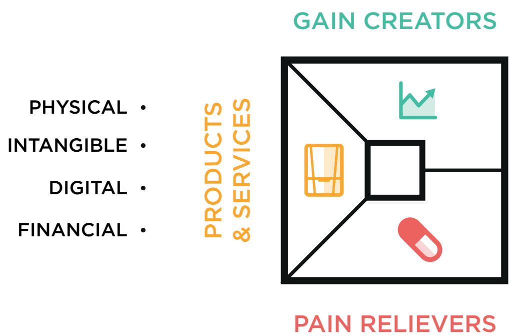


Figure 5.4 Value Map template, based on Osterwalder et al. (2014).

contains elaborate value maps of the end user and the installer. These value maps have been used as an inventory of how value can be created for the end user and the installer. Not all aspects mentioned in the value maps are explicitly included in the value proposition of the developed product-service system. Consequently, not all identified customer jobs, pains, and gains are addressed by the value proposition. Again, this is to keep this first step in business innovation manageable and focused. Possible next stages of development, after the conclusion of this research, can expand the scope of the value proposition.

The essence of the value proposition to the end-user is result-oriented, revolving around the function of the product rather than the product itself. By paying a fixed amount per month, the end user receives guaranteed access to warmth in the form of warm tap water and a warm living environment. This result is delivered through a combination of products and services, the most important being:

- The wall-hanging boiler that generates warmth;
- The smart thermostat that allows the user to control the delivered warmth;
- Energy supply (gas and electricity) to operate the boiler;
- Regular maintenance and 24/7 service to guarantee the boiler's functionality;

To the customer these products and services are no longer relevant, because he pays for their collective result: guaranteed warmth. This function-oriented proposition allows to take the user's needs as a starting point. Thereby, value is no longer confined to the product domain, which allows greater freedom in serving the needs of the customer. For a low-interest product like a boiler this is particularly relevant, because the end user is more interested in the product's function than in the product itself. Through a proposition of guaranteed warmth, the end user actually pays for what he wants, which allows Remeha to compete on value rather than costs. Moreover, this proposition relieves the end user of financial risks and responsibilities. The end user pays one fixed amount per month that includes the purchase, operation (energy), maintenance, and possible repair of the boiler. To the end user, there are no more unexpected costs when a boiler needs to be repaired or replaced and everything is arranged through one transparent contract with one reliable party.

The proposition to the installer is not particularly result-oriented and remains similar to Remeha's current proposition. The installer still receives reliable and serviceable products and can count on a dependable and quick supply of spare parts. However, organising the previously described value proposition for the end user results in some changes in the proposition to the installer as well. Because boilers are now leased from Remeha, the installer can no longer gain a profit margin on the sales of a boiler. But this minor loss is compensated for by an increased demand for service contracts, paid for by Remeha to guarantee warmth for the end user. Additionally, Remeha is accountable for the costs and supply of spare parts, which decreases financial risks and costs of a service contract for the installer. Through these service contracts, the installer has a more predictable and reliable income.

Organising a product service system

A product-service system needs to be organised differently compared to Remeha's current business model. It introduces new partners and relationships with existing partners change. This section will briefly describe how the product-service system can be arranged to deliver the value propositions to the customer segments. Figure 5.5 shows the proposed organisation, introducing various partners and their interrelations.

The described value proposition to the end user is offered through a leasing contract with Remeha. The end user pays a fixed amount each month and in return is guaranteed of warm tap water and a warm living environment. Through this leasing contract, the end user gains access to function while Remeha holds ownership of the boiler. Organising a leasing structure requires strict legal compliance and influences the financial balance since operational boilers remain assets. Therefore, it is assumed that the product-service system can be best organised through a separate business entity, here referred to as Remeha Lease B.V. This is not necessarily the brand by which to bring the lease proposition to the market. From a marketing perspective it could be preferable to associate the leasing model with the Remeha brand or rather to disassociate from it. The end user holds a contract with Remeha Lease B.V. for delivering the complete proposition of warmth. As appears from figure 5.5 this proposition is delivered to the end user through various partners. Remeha Lease B.V. supplies the boiler and thermostat and holds contracts with the energy supplier to deliver gas and electricity

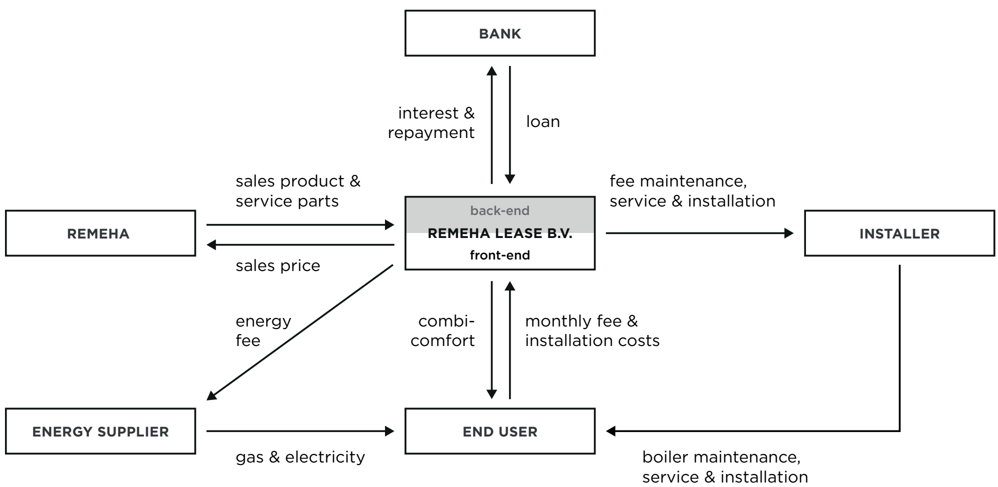


Figure 5.5 Organisation product-service system.

and with the installer to provide maintenance and service. This structure seems devious, but is essential to the value proposition. It allows the customer to receive all these the collective of products and services through one transparent contract with one accountable party.

As far as Remeha's current organisation is concerned, the company continues to sell boilers, thermostats, and spare parts. Only now, they sell to Remeha Lease B.V. who in turn leases to the end user. A consequence of leasing, is that revenue is gained over a continuous period, but with small amounts at a time. This way, it can take several years to return costs from for instance product purchase and installation. To finance such costs in advance, Remeha Lease B.V. holds a loan with an investor like a bank. This loan could be a permanent part of the model or it could be used in the start-up phase but replaced by own investments when the business model becomes profitable after several years.

Benefits of a product-service system to Remeha

A business model that is based on the principle of the result-oriented product-service system, as previously described in this section, offers a number of benefits to Remeha:

- Persistent ownership of the boiler provides control over resource flows in the complete product lifecycle. This allows financial and strategic benefit from increased resource productivity and reduced supply risks;
- Build a closer relationship with customers, being involved during the use phase and (more importantly) at the end of the use phase when the product needs replacement.
- Serve a market that prefers access to functionality over the possession of the product;

5.4 Financial business case

This chapter has so far explained the general concept of a product-service system, how this leads to a value proposition around the function of a boiler, and how a leasing structure can be organised to deliver this proposition to the customer. The previous section has briefly touched upon some costs and revenues, but not yet in a way that shows whether the model is financially feasible. Therefore, this section goes further into the business model's cost structure and revenue streams. A financial business case is developed to assess if and how the proposed business model can be profitable. The basic structure of the business case has been provided by Remeha's finance department. This structure has been further refined and extended by the author, in close collaboration with Remeha's business development department.

For this research, the business case is calculated for the combi-comfort system including the Tzerra (CW4) boiler and the eTwist thermostat. The business case's parameters and values are determined based on this scope, which influences for instance the lease period, energy costs, and service costs and intervals. As a consequence of this particular scope, developing the business case becomes more manageable and more tangible. However, it also limits the extent to which this business case can demonstrate the feasibility of the business model. When the business model is to be applied to other products or technologies (like heat pump or micro-CHP), the financial feasibility needs to be verified by different business cases. It is assumed that the structure of this business case remains largely applicable to other product scopes, only the parameter values change.

Table 5.1 Business case parameters and their values.

Parameter		Value
Contract lease fee (excl. energy)	●	€25 per month
Contract energy fee (equal to energy costs)	●	€100 per month
Installation costs	●	€350 per boiler
Installation reimbursement	●	€350 per boiler
Average gas consumption boiler	●	1500 m3 per year
Average electricity consumption boiler	●	200 kWh per year
Energy rate gas	●	€0,60 / m^3
Energy rate electricity	●	€0,22 / kWh
Labour costs for maintenance and service	●	€100 per boiler per year
Spare parts costs for maintenance and service	●	€10 per boiler per year
Cost price Tzerra CW4 and eTwist	●	confidential
Lease period combi-comfort	●	15 years
Devaluation period combi-comfort	●	10 years
Residual value boiler	●	€30
Bad debts	●	3% of the revenue
Repayment period loan	●	5 years
Interest rate loan	●	2%
Employment costs	●	€120,000 per year
Annual number of new contracts	●	50; 100; 200; 400; 800; 1600; 3200; 6400; 12800; 25600; 51200

The business case is essentially a computational model (in this instance a Microsoft Excel sheet) that defines the quantities, (periodic) occurrence, and relations of costs and earnings. Based on these parameters, the business case calculates the annual cash flow, the income statement (amount of profit or loss), and the balance sheet. Table 5.2 describes the parameters of the business case and their assumed values. A red dot indicates that a parameter relates to costs, a green dot indicates a relation to revenue and a grey dot indicates a neutral relation, considered from the perspective of Remeha. Appendix K describes the assumptions by which the parameter values are determined.

To show how costs and earnings develop over time, the business model is calculated for 10 successive years. Table 5.1 shows the values of the first year. For each next year these values increase with 2% to correct for annual inflation. Accordingly, the lease price will also increase with 2% each year, but applies only to newly-closed contracts. It is assumed that once a leasing contract is closed, the fee will remain constant over the contract period. By including a broad range of parameter, it has been tried to make the business case represent a realistic model of costs and revenue. However, it is not a comprehensive model, lacking for instance costs for logistics and marketing or the costs and frequencies of the boiler's removal or replacement. Also, certain assumed values need to be further refined, like the boiler's residual value and the costs for installation, maintenance, and service. In spite of these acknowledged shortcomings, it is assumed that the business case is useful for assessing the potential profitability of the product-service system in the current stage of development.

Outcome business case

The computational model of the business case can generate different outputs as a result of the input variables described in table 5.1. For this particular study, the aim is to determine if it is financially feasible to deliver the value proposition from section 5.3 through the organisation structure from figure 5.5. To this end, the output of the business case is described in terms of the income statement, the cash flow, and the balance sheet. These three financial statements are common indicators for a company's financial affairs. The income statement shows a company's financial performance by representing the net profit or loss that are incurred over a particular period. The income statement of a given year includes the profit or loss of the previous year. The balance sheet shows what a company owns (debit) and what it owes (credit) at a certain point in time. In this case, this includes the value of the boilers that are leased, because they are still owned by Remeha Lease B.V. Lastly, the cash flow represents the net amount of money that flows into and out of the business. A positive cash flow means that the company's liquid assets (debit on the balance sheet) are increasing. The values of these three statements are plotted in figure 5.6, ranging over several years to demonstrate how the model develops over time. Additionally, the number of contracts is plotted to indicate a relation between financial performance and the growth of the model.

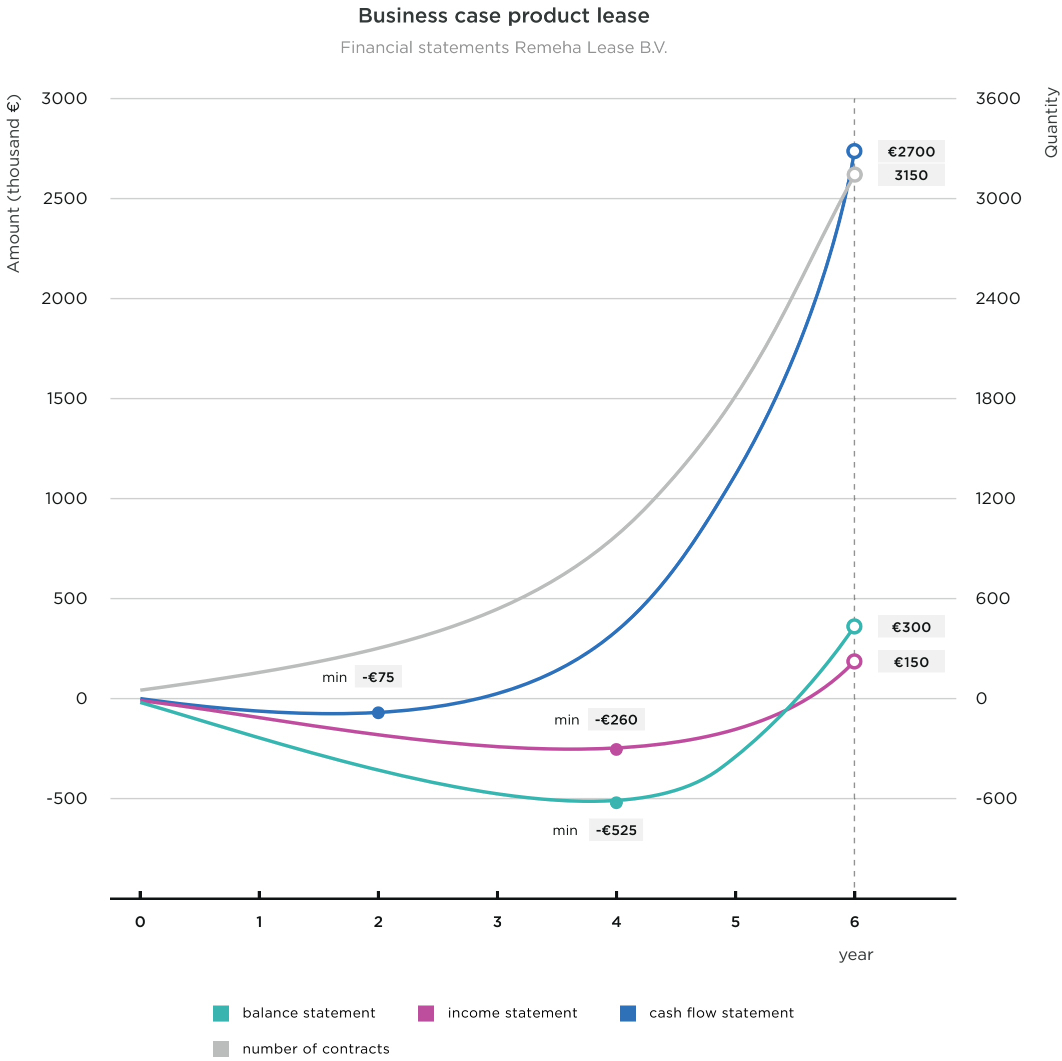


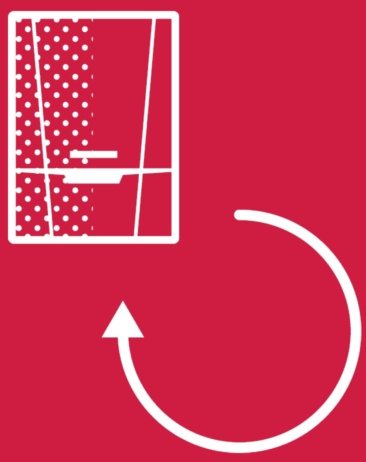
Figure 5.6 Remeha Lease B.V. financial performance.

In conclusion, it is stated that it can be financially feasible to organise a product service system according to the proposed organisation structure (figure 5.5) and parameters (table 5.1). However, it is only feasible from a long term perspective. The first years, it requires high loans to launch the proposed leasing structure. Revenue is gained over a continuous period, but with small amounts at a time. From year 4, losses start to decrease and the model first becomes profitable in the sixth year. This mostly has to do with the costs for the boiler and installation at the start of a new contract, which take time to be compensated for by a relatively low lease fee. The losses in the first six years will be repaid for through the leasing contracts, only with a delay. Once the model runs, the contracts will continue to pay out for several years after the costs for boiler and installation have been returned.

Whether or not the incurred losses in the first years are acceptable to Remeha, is a decision that needs to be made by the company's management. It is the intention of the business development department to introduce them to this business case, but this has not yet happened at the time of writing this report. In light of this decision, Remeha is advised to regard the potential of this proposal in a long-term perspective. It is inevitable to incur losses during the first years of organising a leasing structure. This is a consequence of the transition from selling to leasing and it must be endured in order to organise a successful lease model. If the organisation commits to pursuing a product-service system, they should do so with the perseverance to overcome initial losses in order to benefit from long-term gains.

Conclusion

This chapter has proposed a new business model to support the adoption of more resource effective strategies in product development. By organising a product-service system, boilers can be leased and Remeha can maintain ownership of the product and its embedded resources. This allows Remeha to benefit from developing boilers for increased end-of-life value or an extended lifespan. Moreover, the new business model offers opportunities for dealing with corporate responsibilities imposed by legislation and for controlling market shifts caused by the energy transition. A financial business case indicates the financial potential of organising a product service system. Having established the proposed product-service system for Remeha, this research's secondary focus on the business model is concluded. The following chapters will further address the implementation of the circular economy principles in the area of product development.



chapter

06

Design for circularity

A product's design determines what kind of resources it requires and how they are transformed through production processes. This makes product development a key area to influence the way in which resources are used and consumed in an economy. Acknowledging this influence, this chapter will research how domestic boilers can be designed for enhanced resource effectivity in a circular economy. A methodological analysis of design strategies will result in the formulation of a particular design strategy that aligns with the needs, expertise, and influence of Remeha. Based on this design strategy, chapter 7 and 8 will address the realisation of this strategy through a design tool.

To start with, section 6.1 will introduce several design strategies that make the principles of circularity specifically applicable to the product development process. On this strategy level, a focus is determined and further developed into a design tool. To facilitate such focus, section 6.2 proposes three strategy scenarios that each encompass several design strategies. In close consultation with R&D stakeholders, one scenario is selected for further development and implementation: closing the loop. Section 6.3 will further elaborate on this particular strategy.

6.1 Design strategy model

The principles of the circular economy need to be translated into the realm of product development. These principles, as they are described in chapter 3, offer a general description that is not directly applicable to product development activities. As a way to make the principles more actionable, they are translated into design strategies. These strategies embody the more high-level principles of the circular economy and offer specific directions to develop boilers for increased resource effectivity in a circular economy.

Literature on the circular economy mentions several potential strategies for design. Bakker, den Hollander, Van Hinte, and Zijlstra (2014) focus at the potential of long-life products and mention concepts such as design for disassembly, upgradability and ease of maintenance. The Ellen MacArthur Foundation (2012) speaks of modular product structures and standardised components to enable circularity through design. In a more recent study the Ellen MacArthur Foundation mentions strategies relating to circular product design, such as dematerialisation, material substitution, and increased product efficiency (Ellen MacArthur Foundation, 2015). These studies offer various possibilities for improving a product's design for the circular economy. However, the performed literature research reveals no studies that present design strategies on a holistic level, addressing the multiple facets to circular product development. Often, publications take a selective viewpoint, focusing at, for instance, long life or end-of-life treatment.
A more holistic view on design strategies for a circular economy would promote their effective selection and application. To this end, a design strategy model is proposed, represented by figure 6.1. The model offers a structured representation of design strategies and indicates their relevance to circular economy principles. Literature study

has been an important source for formulating the model, building on studies like Bakker et al. (2014) and the ReSOLVE framework by the Ellen MacArthur Foundation (2015). Moreover, an ideation process based on the circularity principles from figure 3.2, has provided additional input for the model. Appendix L shows an unstructured collection of design strategies that have resulted from the first stage of literature research and ideation. A process of selecting, fine-tuning and categorising these strategies has resulted in the proposed model of figure 6.1, dispayed on the next page.

Before going into the contents of the model, the process of selection deserves some more explanation. The utility of design strategies highly depends on the context to which they are applied. One especially relevant aspect of this context is the kind of product that is to be designed. For instance, a strategy to design for cascaded use cycles is only appropriate to a product that consists of biological materials, like a wooden table or bed frame. And design for disassembly hardly applies to products that consists of a single component, like plastic cups or paper trays. Given these dependencies, it is not feasible to develop a comprehensive and generally applicable set of design strategies within the scope of this study. Instead, the design strategies in the proposed model have been selected for their applicability to the domestic boiler. This means the strategies relate to, amongst others, energy consumption, technical resources, and a product structure that consists of multiple components and materials. As a result of this focus, the proposed design strategy model is applicable to the development of domestic boilers. Considering the similar characteristics of other products in Remeha's portfolio, it is assumed that the model can be applied to their development as well. Furthermore, it is probable that the model also (partly) applies to products from different industries, like refrigerators or washing machines. However, this requires more analysis to state with certainty.

This section has so far explained why and how the design strategy model is developed and what the constraints are to its applicability. Now, the contents of the model will be briefly discussed in terms of the six categories that are shown in figure 6.1.

- **Design for long life:** When products can be used longer, it generally requires less products (and resources) to serve a need over a given amount of time. When designing a product for a longer life time, it should be able to offer persistent benefit in the most resource efficient way. This does not always mean the longer the life time the better. For instance, a boiler from 25 years ago is considerably less energy-efficient than today's technology. From a resource perspective, its replacement could be more effective as the enhanced efficiency of new boilers compensate with energy savings in the long run.
- **Design for product-service system:** New business models could inspire new value propositions to meet the customer's needs. This, in turn, influences what and how products are designed. The product-service system, as discussed in chapter 5,

CATEGORY		DESIGN STRATEGY
DESIGN FOR LONG LIFE	1	Upgrade components during the use phase to increase performance
	2	Design a product to function over multiple consecutive use cycles for various users
	3	Maintain and repair the condition and functionality of components during the use phase
DESIGN FOR PRODUCT-SERVICE SYSTEM	4	Design new value propositions to meet customer needs
	5	Incorporate service development in de product development process
	6	Apply user-centred design techniques to specify and validate solutions
	7	Monitor products across the lifecycle to direct service and innovation
INCREASE DESIRABILITY	8	Adapt product functionality to changing customer needs and technological developments
	9	Create new relations between the customer and the product
	10	Configure product features for individual customer demands
DESIGN FOR REVERSE CYCLES	11	Design the product for easy dis- and re-assembly of components
	12	Standardise product features within product portfolio, between supply chains or across sectors
	13	Design a modular product architecture
REDUCE RESOURCE INTENSITY	14	Improve product performance to reduce energy consumption
	15	Dematerialise/virtualise product functionality
	16	Influence user behaviour to use energy efficiently
	17	Apply advanced technologies and materials
SELECT LOW-IMPACT MATERIALS	18	Create value from restored resources
	19	Design for reduced GHG emission
	20	Design energy-using products to operate on renewable energy input

LEGEND CIRCULAR ECONOMY PRINCIPLES

organise reverse cycles · be resource effective · think in systems · proritise the future · create mutual benefit

Figure 6.1 Design strategy model.

focuses not at the product itself but at the function it delivers. Moreover, service becomes a more integrated part of the proposition. This new position of the product in the value proposition argues for a reconsideration of the product definition, more fundamentally centred around the customer's needs.

- **Increase desirability:** Designing a product for a long lifespan is about a product's qualitative and functional relevance. Increasing the desirability of a product focuses at relating the product to the customer's (changing) needs. This promotes the usefulness of the product and motivates the customer to use the product for its full lifespan.
- **Design for reverse cycles:** In a circular economy, it is essential that products and their embedded resources can return to the value chain at the end of their lifecycle. Reverse cycles are the processes that treat end-of-life product to recover and restore their value in terms of function, material, and energy. How a product is designed, greatly influences the options for restoring value through reverse cycles. For instance, glued components are difficult to disassemble for reuse and composite materials can hardly be recycled.
- **Reduce resource intensity:** Reducing resource intensity is a more traditional approach that aims to simply use less resources in the first place. Can a boiler be made from fewer resources while preserving its necessary function and quality? Functions could be delivered in more integrated ways or advanced materials could be used to realise the same structural integrity with fewer materials.
- **Select low-impact materials:** the use of certain materials can have a negative impact to surrounding systems in different stages of the product lifecycle. For instance, toxic substances can enter the environment when certain materials are incinerated or disposed to the soil. Also, more waste is produced or more energy consumed for the mining and production of certain materials. From this perspective, recycled materials are generally preferred over virgin materials.

Having established the design strategy model, the question remains how it should be applied to Remeha's product development. It has been stated that all strategies are suitable for Remeha's development, but their relevance varies for different projects in in light of different objectives or constrains. Moreover, in terms of implementation it is assumed not to be feasible or effective to utilise all strategies at the same time. Therefore, specific strategies need to be selected for particular situations. In this regard the design strategy model represents the elective space. Within the context of this research, two approaches to selecting an appropriate strategy from the model seem particularly interesting. The first is to develop a structured method that relates design strategies to context variables like product characteristics or development objectives. Such method would help Remeha to select appropriate strategies for particular situations. However, this direction would leave less room within this research to specify how a selection of a design strategy translates into design decisions. The second approach is to select a specific design strategy that is relevant to Remeha's current situation and needs. This direction allows to go deeper into the actual realisation of a particular strategy through design decisions, but it does not equip Remeha to select a different strategy for a different situation in the future.

Both directions answer to the need for implementing sustainability in the product development process, but they result in solutions that operate on different levels. One more strategic and the other more practical. The R&D stakeholders preferred a result that could be utilised by their engineers and would help them to develop tangible product solutions. Therefore, it has been decided to adopt the second approach. A specific design strategy will be selected from the model and a tool will be developed that enables the realisation of this strategy through design decisions.

6.2 Design strategy scenarios

As stated in the previous section, numerous design strategies can be applied to develop boilers for a circular economy, but it is not feasible to implement them all at once. Therefore, it has been decided to select a limited number of synergetic design strategies that will be further implemented through a practical design tool for product engineers. This selection will be further addressed by the current section.

Considering the design strategy model of figure 6.1, the strategies it contains are formulated in a rather abstract terms. This makes them more widely applicable, but simultaneously challenges a good understanding of what it means to apply strategies in a certain context. Especially for those who do not have extensive knowledge of the circular economy, like the stakeholders for this research. To involve these stakeholders in identifying the appropriate strategy, three scenarios have been formulated. Each scenario encompasses several design strategies that are applied for a certain objective in a context that is relevant to Remeha. The formulation of scenarios serves a two-fold purpose. First, it supports the selection of an appropriate design strategy for Remeha. Second, it demonstrates the synergetic advantages of applying several strategies in unison. The scenarios are described below. Each scenario mentions the strategies it encompasses point by point, relating to a number that refers to figure 6.1.

Scenario 1: Closing the loop
Resource depletion and pollution of the ecosystem are pressing issues of sustainability that directly relate to industrial activity. The prevailing linear economic system builds on high material throughput and wastes resource productivity. Thereby creating scarcity of the resources it depends on for value creation. The circular economy presents an alternative model that circulates resources in a closed-loop system where resources are used, restored, and re-used in continuous cycles. In this model, products in fact become resource carriers and they should be designed as such. This perception widens the

scope from performance in the use phase to include end-of-life scenarios as a priority for design. Accordingly, products are designed such that the resources they embed can be recovered at end-of-life and re-utilised for new value creation. This focus impacts the product at a structural level: the embodiment by which it performs its function. Remeha could adopt new design strategies to enable the recovery and utilisation of resources from end-of-life products by design:

11 Design components for easy dis- and re-assembly to recover embedded resources at high quality;
12 Apply standardised components or materials (within product portfolio or across industries) to enhance the applicability of recovered resources.
13 Design products with a modular structure;
18 Create products from resources that are recovered through reverse cycles.

Scenario 2: redefine product proposition

The circular economy brings a fundamental shift in the way products are made to fulfil customer needs, which closely relates to business model innovation. One potential new business model diverges from the classical perception of products as possession and aims to offer customers their performance instead. This model, also referred to as the product-service system, aligns with circular economy objectives and has been identified in chapter 5 as a promising business innovation for Remeha. In order to exploit the full potential of this business innovation, product design should be aligned to new value propositions that revolve around product-service systems. This impacts the fundamental product proposition, since customer needs are met by an integrated combination of product and service. Moreover, the product functionality, rather than the embodiment of that functionality, now takes a central part in delivering the value proposition. Remeha could adopt new design strategies to develop these new function-oriented and service-included product propositions:

2 Design for multiple users and use cycles.
5 Integrate product and service development in the design process;
6 Create new relations between customers and products through user-centred design;

Scenario 3: adapt to change

Products are designed to operate in a specific context where they provide benefit to the user. The relevance of the product depends on this context and on the customer's needs, which directly translates to either success or failure in the market. However, these conditions - context and needs – are highly dynamic. Rapid technological development and changing needs can render a product prematurely obsolete. Some products are even designed by intention to become obsolete after a certain period to ensure high throughput and sales. This strategy is also referred to as planned obsolescence and is a classic example of wasteful and destructive industrial behaviour. In the circular economy products should be designed to prevent obsolescence rather than artificially creating it. To this end, products could be designed with a certain degree of flexibility, which allows them to be adjusted to changing conditions and thus preserve their relevance. Performance-related components could be upgraded when technological development allows increased performance and efficiency. Or components could be added to the product to provide additional functionality. Flexibility can also be used either to conform with market developments or to push new innovations to the market without the need to replace complete products. Considering the context of Remeha, one particularly relevant and changing condition is the energy market. Between now and 2050, the energy infrastructure will change drastically, which highly influences the relevance of Remeha's gas-fired boilers. Remeha could adopt new design strategies to increase relevance to the user and prevent premature obsolescence:

1 Upgrade product components during use.
8 Adapt products to a changing energy infrastructure;
10 Configure product features according to individual customer demands;
20 Design energy-using components to operate on renewable energy source.

Scenario selection

The three described scenarios each apply to Remeha and relate to the circular economy in a specific way. Closing the loop presents great potential to increase resource effectivity because it allows to transform Remeha's predominantly linear supply chain into a circular one. It provides more control over resource flows, which can save raw material costs and decreases supply risks. Redefining the product proposition for a product-service system innovates the product at its fundamental level. A performance-oriented value proposition stimulates to develop a resource effective product-service combination that aligns to the customer's needs. Adapting a product to changing conditions increases its relevance to the customer and thereby prevents early obsolescence. It offers a way to address the approaching energy transition in a competitive and resource effective way.

It should be clear that all scenarios offer a potential to increase resource effectivity in a circular economy in a way that is relevant and beneficial to Remeha. To determine which scenario will be further pursued by this research, each scenario is assessed according to three criteria. These criteria are described below, including an explanation of their relevance.

- **Be influenced by Remeha R&D personnel, preferably by product engineers**
  As indicated in section 6.1, the R&D stakeholders for this research have expressed to prefer an outcome that can be used by their engineers and leads to practical results.

- **Help to anticipate developments in market and legislation**
  Developments in market and legislation have been identified in chapter 1 as important drivers for this research. Selecting a strategy that aligns with on-going or expected developments in these areas will create benefit for Remeha.
- **Address high-potential opportunities to enhance resource effectivity**
  From the perspective of the circular economy, it is important that the design strategy leads to considerable improvements in resource effectivity. There is a pressing need to drastically change current ways of development in order to reach a sustainable condition.

The assessment has led to the identification of several positive and negative aspects of each scenario, displayed in table 6.1.

Based on the assessment in table 6.1 and close consultation with the R&D stakeholders, the 'closing the loop' scenario has been selected as a focus for further implementation. This particular strategy allows to anticipate a changing resource market and developing legislations on increased corporate responsibilities, like the WEEE Recast Directive. The strategy embodies the central principle of the circular economy to transform linear into circular resource flows. Given Remeha's predominantly linear supply chain (described in section 4.2), this strategy is expected to result in considerably enhanced resource productivity. And while the further implementation of this strategy will be focused at Remeha's domestic boilers, its principle is generally applicable to Remeha's complete portfolio. Moreover, designing for closed-loop flows relates to a product's structural

Table 6.1 Positive and negative aspects of the design strategy scenarios.

	Scenario	Positive	Negative
1	**Closing the loop**	Offers a way to meet legislative obligations and exploit potential advantage	Focus at incremental development based on the existing product proposition
		High potential to improve resource productivity and generally applicable	
2	**Redefine product proposition**	Improve value for the user that aligns with market trends for share/lease	Effectiveness depends on the adoption of a new business model
		Support revolutionary product innovation	Exceeds current expertise of product engineers
3	**Adapt to change**	Establish a position in the shifting energy market	Added complexity for design and management
		Improve product relevance for the user	Effect depends on future developments and requires long-term perspective

characteristics; what components it contains, how they are connected, and from what materials they are made. These aspects can all be directly influenced by the product engineers. However, this strategy takes the existing product definition of a boiler as a starting point, which allows only incremental changes. The second scenario, focusing at redefining the product proposition for a product-service system, would allow more revolutionary changes. This would increase the opportunities of using resources more productively, but the effect would depend on the adoption of a new business model like described in chapter 5. At the moment of this research, the Remeha was not yet ready to commit to such an impactful business innovation, which is why scenario 2 was not further developed. Should Remeha decide to adopt the proposed product-service system in the future, then the implementation of scenario 2 should be reconsidered.

6.3 Closing the loop by design

The preceding section has identified the 'closing the loop' scenario as a focus for further implementing the circular economy in product development. This scenario encompasses four synergetic design strategies that can be adopted to develop boilers for closed-loop resource flows in a circular economy. These strategies combined have so far been referred to as 'scenario', but in the context of their implementation the term 'strategy' is believed to be more accurate and will be adopted from now on. In these terms, this research will focus at the implementation of the 'closing the loop' (high-level) design strategy that consists of four subjacent (more specific) design strategies that offer different ways to realise closed-loop flows by design. This section will describe the 'closing the loop' strategy in relation to reverse cycle processes and in terms of its subjacent design strategies.

In a circular economy, industrial processes are designed to use, recover, and reuse resources in a continuous cycle, rather than a single flow. An essential aspect of realising these closed-loop flows is organising reverse cycles that recover and restore value from end-of-life products. This perception broadens the scope from performance in the use phase to include end-of-life scenarios as a priority for design. Consequently, products in the circular economy become resource carriers and they should be designed as such. This implies that there is value in the product as a collective of functional components, but also in components separately and in the materials they are made of. End-of-life scenarios should not only be considered for the product as a whole, but for its enclosed modules, components, and materials as well. The aim of the 'closing the loop' design strategy is to leverage design so that resources from end-of-life boilers can be recovered and restored through reverse cycles so they can be used again. As introduced in section 3.1, the circular economy recognises several distinct reverse cycles in the biological and technical resource flows. Given the technical nature of a boiler's embedded resources, three reverse cycle processes are especially relevant: reuse, refurbishment, and recycling. This focus is shown schematically in figure 6.2, marked by the black arrows. It is within this scope that the selected design strategy aims to increase resource effectivity.

A product enters a revers cycle when it becomes obsolete in the use phase. While the product no longer serves the needs of its user, it still holds value in several forms: function, material, and energy. Reverse cycles are meant to recover and restore embedded value from end-of-life products, such that this value can be re-utilised in industrial processes. Table 6.2 on the next pageshows a brief overview of these processes in terms of their objective, their focus at the product, and their output. After collecting an end-of-life boiler, the first priority is to consider if it can be reused. In this cycle, the aim is to find a new user for the product in its used condition. This process is mainly logistically oriented and does not involve reprocessing to change the condition of the product. When reuse is not an option, for instance when the product's quality has deteriorated too far, a product enters the refurbishment process. In this process, the product is disassembled into functional components that are reprocessed to improved or initial OEM quality. Processes could involve cleaning, repair, or replacement and are only applied selectively. The refurbishment process seeks to preserve a component's quality and functionality as much as possible and only reprocesses when and where necessary. The last option for recovering and restoring value is to recycle the materials that are embedded in the product. During this process, a product is disassembled, not

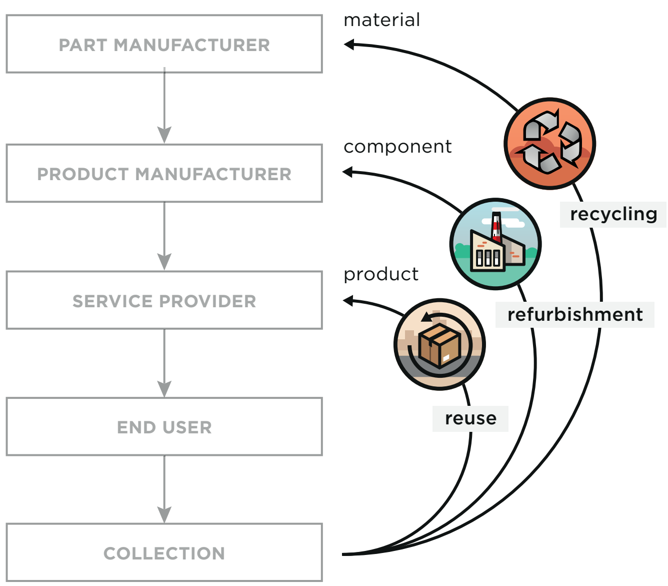


Figure 6.2 Circular economy system diagram scope.

based on function, but based on its material content. Material batches are separated and reprocessed into secondary raw materials that are used for the production of new parts. Ideally, all materials that are embedded in the product can be separated into pure streams and restored back to initial quality. For more detailed information, appendix M contains flow diagrams of the reuse, refurbishment, and recycling processes.

Table 6.2 Reverse cycles, based on Desai and Mital (2003).

Reverse cycle	Objective	Level of disassembly	Output
Reuse	Apply product in current condition for a different user	Product/ component	Product or component is used again without reprocessing
Refurbishment	Restore component to initial OEM performance specifications or improved quality	Component	Some parts of components are repaired or replaced Used and new components in new products
Recycling	Recover pure materials from products so these materials can be used again as secondary resources	Material	Materials are used for production of new parts

Design strategy explained

The possibilities for resource recovery and re-utilisation through each of the discussed cycles can be greatly influenced through product design. This is the focus of the selected design strategy that proposes four specific strategies to support reverse cycles by design. These strategies are further elaborated below after which their relation to the reverse cycles is explicitly addressed. The first two strategies, concerning disassembly and modularity, relate more strongly to the recovery of the resources that are embedded in the boiler. The latter two strategies focus more at the reutilisation of those recovered resources.

- **Design the product for easy disassembly and reassembly**
  When a boiler is manufactured, it is assembled from many components that are each constructed from a variety of materials. It is these components and materials that still hold value when a product is retired. Designing a boiler such that its components and materials can be easily separated, promotes value recovery through reverse cycles. Disassembly should be enabled in a way that maintains product integrity so components can be reassembled with preserved quality. This this supports disassembly procedures for refurbishment and recycling and further promotes life extension strategies such as maintenance and repair.

- **Design a modular product architecture**
  Modular products are constructed from a series of detachable modules that can be manufactured, (dis)assembled, and serviced separately. Modules consist of several components and are connected through standardised interfaces. They can be applied in different systems and combined in numerous ways to build customised products. This combined leverage of standardisation and customisation increases a boiler's possibilities for reuse. It furthermore supports product disassembly and serviceability and incorporates a flexibility in design, which allows to complement and adjust product functionality. In the circular economy, modules should be designed while considering not only the interaction between components, but also end-of-life options.

- **Create value from recovered resources**
  Remeha's boilers are currently made from virgin materials mostly. Some part specifications even literally require the application of virgin materials, which excludes the application of recycled materials in advance, not based on quality, but based on origin. When boilers are designed for their embedded resources to be recovered, Remeha should be able to use these resources for their own value creation. Consequently, boilers should be designed so they can use recovered resources.

- **Standardise product features for compatibility**
  When pursuing an economy in which product components and materials are reused, their application is no longer confined to the context of a single product. Standardisation of product design can enhance the usability of recovered resources because it provides a broader scope of application. Standardisation can be regarded within a company's product portfolio, allowing the exchange of components between different product variants. It can also be perceived in a broader sense between supply chains or across industries.

Relation between design strategy and reverse cycles

When a boiler is designed for disassembly and reassembly, it can be more easily and accurately separated into functional parts for refurbishment or into different material batches for recycling. It is essential that design makes this separation not only possible, but also easy to execute as this influences the costs for reverse cycles and thus the incentive to restore value. When a boiler has a modular architecture, easy (dis)assembly is further promoted. Also, a boiler's modular structure could provide a basis for standardisation, which increases its options for reutilisation in reuse or after refurbishment. Creating value from recovered resources is what closes the circle after resources are recovered. It creates a demand for secondary resources, which is a further incentive to organise reverse cycles on a large scale. A boiler can be specifically designed from recycled materials or for compatibility with refurbished components.

Finally, using standardised components or materials stimulates the usability of recovered resources. For example, PP is a commonly used plastic. Because of this, it appears in high quantities in waste streams, which motivates recycling processes or organise its recovery. Furthermore, once PP is recovered, it can be easily repurposed since it is in high demand. The description of the four strategies reveals their synergetic potential in realising products that comply with reverse cycles. Considering their impact on product development, all strategies relate to the structural characteristics of the product. This means that, from a product development perspective, these strategies allow an integrated implementation in product development.

Validity

The proposed design strategy is focused at the end-of-life stages of the product lifecycle to enable the recovery and re-utilisation of resources from disposed boilers. When Remeha applies this strategy to their product development, circular resource flows are enabled through product design. The products that follow from this strategy are expected to offer benefits through enhanced resource productivity, because their embedded resources can be again after the product becomes obsolete. This particular strategy enables circular resource flows, which is an essential step towards realising the circular economy.

In spite of the relevance and benefits of the proposed strategy, it should be acknowledged that designing products for closed-loop material flows is not the only way for Remeha to realise circular economy objectives, nor does it make their boilers fully circular. Other strategies can be applied to product design, like optimising the product lifespan or developing new product propositions that fit new function-oriented business models. Such alternatives do not replace the proposed strategy or reduce its validity, but they can further improve resource productivity and offer additional benefits.

part 3

Supporting product development for reverse cycles

chapter 07

Design guidelines: a principle solution

Formulate a coherent set of guidelines to support product engineers in realising the circular design strategy.

chapter 08

Dedicated design tool

Develop a digital design tool that provides interactive access to the guidelines to promote their application.

chapter 09

Evaluation

Evaluate the design tool with the product engineers to assess its usability and applicability for the development of domestic boilers.

chapter

07

Design guidelines: a principle solution

Developing products for the circular economy is a challenge that requires new ways of thinking about design. These have been described in chapter 6 in terms of design strategies. Each strategy offers a particular direction to develop boilers that are more resource effective in a circular economy. In the previous chapter, a design strategy aiming to enable closed-loop resource flows by design has been selected for further implementation at Remeha. According to this strategy, boilers are designed so that their embedded resources can be recovered, restored, and used again.

The design strategy provides a clear line of thought for development that is substantiated in terms of design for modularity, standardisation, disassembly. But the strategy itself does not answer how it could be realised by design. This presents a challenge to Remeha's engineers, because they are unfamiliar with designing products for a circular economy. To this end, a design tool is developed that guides engineers in realising the proposed strategy through their design decisions. This chapter describes the backbone of the tool. The characteristics and needs of Remeha's product engineers are explained and guidelines are introduced as a means of support to offer prescriptive recommendations for design decisions. Based on literature study, user feedback, and an iterative development process, a set of dedicated and practical design guidelines is proposed. They represent the information that is to inform and inspire Remeha's engineers to design domestic boilers for closed-loop resource flows. Subsequently, chapter 8 will introduce a digital design tool that embodies the information backbone of the design guidelines. Guidelines and supporting information are presented by the tool in an accessible and interactive way that promotes their adoption in the design process.

7.1 Target group

The design tool is specifically developed to support product engineers in their design activities. It is acknowledged that outside this target group people in other roles and departments offer a relevant contribution to circular development as well. However, a target group focus is required as a necessary boundary for this research.

In chapter 4 it has been explained how the focus of this research lies with the R&D Projects department that is specialised in the development of new products. Within the Projects department, people operate in different roles. There are R&D managers, project managers, (lead) appliance engineers, (lead) product engineers, and a team leader. As briefly indicated in chapter 6, the R&D stakeholders prefer the tool to be applicable by the product engineers of the department. The product engineers are primarily responsible for defining the physical properties of the product. When they are enabled to put the design strategy into practice, it leads directly to tangible results. Because of the stakeholders' preference and the impactful influence of the product engineer, the design tool will be specifically aimed at supporting product engineers. It is possible to further expand or supplement the design tool to support other roles in the future, but this is beyond the scope of this research.

As the target group, product engineers make the decisions and develop the solutions that should embody the principles of circularity. They are able to bridge theory and practice and to realise tangible change. This is a key position of responsibility and opportunity in which they will be supported by a dedicated tool. For the development of this tool it is essential to understand who the product engineer is so that the provided support aligns with his needs and activities. Below, the target group is described in terms of responsibilities, expertise, and workflow.

Responsibilities: A product engineer is responsible for developing technically feasible solutions that meet the product requirements, formulated in the Detailed Product Request (DPR). Commonly, a product engineer takes responsibility over particular product parts in a project, like the control box or the front cover of a boiler.

Expertise: Product engineers are specialised in technical product solutions and are focused at engineering activities. Design of aesthetics or user experience is no focal point for development and is typically no expertise. Within the R&D department, engineers have commonly developed a particular area of expertise that is oriented at a certain boiler component or functionality, like the heat exchanger or packaging. Most engineers have encountered considerations of sustainability in current or previous work environments, but there is no experience with developing products for a circular economy.

Workflow: A development project follows the structure of the New Product Development (NPD) process. Over various stages, a boiler is developed from a conceptual idea into an industrialised product. Considering how a product develops through these stages, it is difficult to describe one specific workflow for the engineer. He encounters various design cases in different contexts that require different outcomes. Also on the level of problem-solving methodology, engineers work in various ways to solve design problems. Typically, a potential solution is quickly conceptualised and further iterated upon.

Based on the target group description, it can be stated that the product engineer is capable of influencing a boiler's technical characteristics, but is unfamiliar with developing boilers for a circular economy. The target group will benefit from a design tool that helps to broaden their expertise and fits their development process and workflow.

7.2 Guideline inventory and conceptualisation

An engineer has the skills and the influence to define product characteristics, like functions and materials, and thereby has a significant influence on resource usage in a circular economy. Remeha's product engineers ground their decisions mainly in considerations of costs, manufacturability, quality, and serviceability. End-of-life processes are not actively considered or promoted by design. As a result of the adopted design strategy, end-of-life considerations now become a priority in design. To successfully act on this priority, the product engineer needs knowledge about the relation between product characteristics and the reverse cycle processes. Currently, Remeha's product engineers are not equipped with this knowledge and do not have adequate access to relevant information through available tools or methods. This research aims to provide product engineers this information to guide their design decisions. Such information can be formulated and provided in different ways, for instance through serious gaming, animated videos, or a reference book. For this particular research, guidelines are adopted as a means to inform and inspire product engineers in their engineering activities. Guidelines can offer prescriptive recommendations for design decisions and are frequently used to guide actions towards a desirable result (Nowack, 1997). Accordingly, guidelines are routinely used by Remeha's product engineers in support of their daily activities. In conclusion, guidelines are identified as an appropriate way for product engineers to acquire information about designing for reverse cycles and it is a way of support that Remeha's engineers are already accustomed to. In this respect, the proposed guidelines are meant to be used as a source of information and inspiration and not as a fixed set of rules that needs to be obeyed. It is up to the engineer to decide what guidelines to apply, depending on the design case scope and constraints.

Considering the progression of a product design through various stages of development, the stage at which the guidelines are available and applied, influences their impact. Product characteristics are mostly determined in the early stages of the development process. Decisions in these early stages have the greatest influence on the product's sustainable performance (Bhamra et al., 1999; Bhander, Hauschild, & McAloone, 2003; Dewulf, 2013), which includes the recovery of resources in reverse cycles. It is also in the early stages of development that the process allows flexibility in dealing with changes at relatively low costs. Therefore, the guidelines are developed to be applied in the early stages of BDR Thermea's New Product Development process that was introduced in section 4.2. In particular, between stage 1 and stage gate 4. Product engineers are involved in the project from stage 2 and by exception already from stage 1. From stage gate 4 the design is frozen and the project focus shifts to industrialisation. Figure 7.1 visualises the described focus in the NPD process in relation to the costs for change and the design freedom.

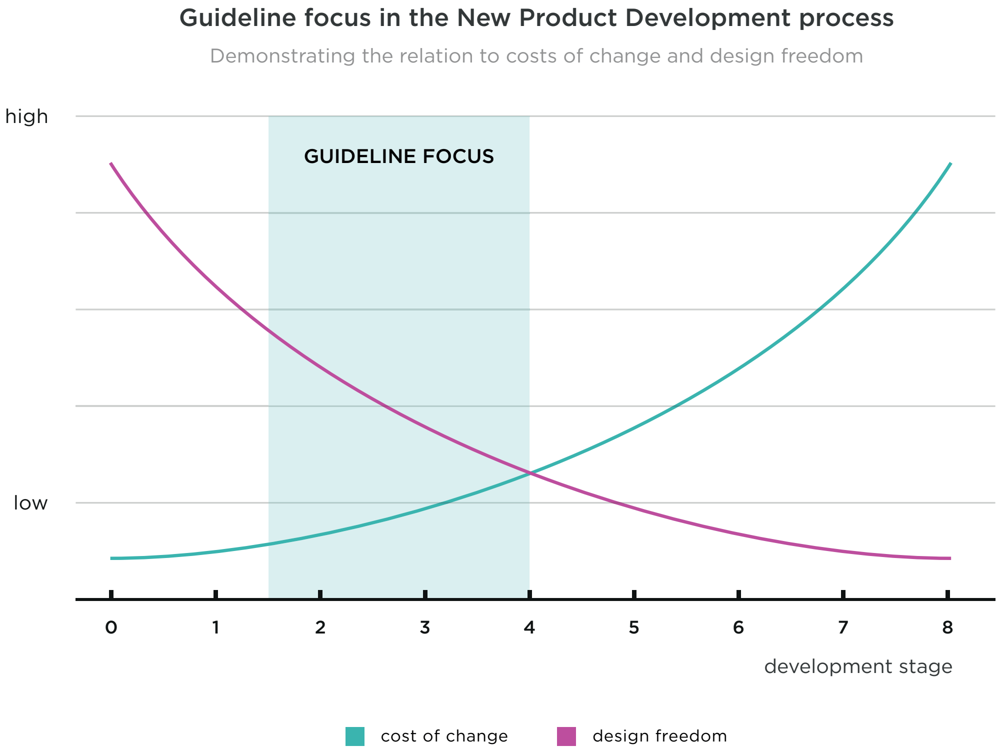


Figure 7.1 Focus guidelines in New Product Development process, informed by Bhamra et al. (1999) and Dewulf (2013).

So far, it has been argued that the design tool will be targeted at product engineers of the R&D Projects department, that guidance will be provided to them by means of design guidelines, and that these guidelines are to be applied in the early stages of development. Together, these decisions comprise the core of the design tool's solution principle, which can be described as:

> A coherent set of design guidelines that support product engineers in the early stages of the NPD process to design domestic boilers such that their embedded resources can be recovered, restored, and reutilised through reverse cycles in a circular economy.

Having established this solution principle, a set of guidelines is needed that aligns with the defined constraints. Extensive literature study has not revealed an existing set of consistent guidelines that adequately support design for reverse cycles. Van den Berg and Bakker (2015) propose a design framework for the circular economy, but formulate guidelines in a rather abstract way that is regarded insufficiently practical for this research. The Circular Design Guide by the Ellen MacArthur Foundation was released in 2017, after concluding the development of this research's design tool. Consequently, the methods proposed by the EMF's design guide have not been considered for this research. Because no existing design guide was found that meets the scope and objective of this research, an iterative process is initiated to develop a collection of specific and coherent guidelines.

Drafting a dedicated design guide

Formulating a custom set of guidelines requires a confirmed information base to substantiate the provided recommendations. Such information could be found in practical experience or based on relevant expertise. For this research, literature study has provided the primary source for establishing an adequate information base. Some studies report on product design for a circular economy and numerous publications have been found on more particular fields, such as design for (dis)assembly, recyclability, modularity, and remanufacturing. Literature on these domains has been studied for established information and design guidelines. To supplement the findings from literature, a brainstorm was organised with Remeha, Van Gerrevink (recycler), and HR Recycling/Premium Parts (recycler/refurbisher). The goal of this brainstorm was to formulate design guidelines or requirements that would help to develop boilers in compliance with end-of-life processes. This session was intended to contribute to a collaborative project from MVO Nederland in which Remeha participated, but it also aligned with the scope and direction of this thesis. Appendix N contains some background information on the workshop session and describes the most important insights from this session.

Based on literature study and the workshop session, over 150 guidelines have been identified that relate to the scope of this research. By merging similar guidelines and an initial selection on relevance, the first inventory has been reduced to a manageable collection of about 50 guidelines, described in appendix O. To give an idea of the inventory, some of the guidelines it contains are mentioned below.

- Concentrate compatible material groups in separate subassemblies of a product;
- Specify renewable and abundantly available resources;
- Avoid aging and corrosive material combinations;
- Allow for spare part harvesting;
- Avoid fixed connections;
- Simplify and standardise component fits;
- Make the location and handling of fasteners and disassembly points easily identifiable;

While these guidelines represent useful information, they are not yet sufficiently applicable in Remeha's product development process. Certain issues have been found to hinder practical application and could potentially be improved:

- Guidelines are displayed in an unstructured list, which makes it hard to distinguish mutual relations and to judge possible relevance for a certain design case.
- Guidelines are mostly formulated in an abstract way. They articulate high-level aspirations and are not actionable to improve a product by design or to inspire new solutions.
- Guidelines are often formulated in a negative way that imposes restrictions, specifying what should *not* be done.
- Guidelines do not inform about their rationale, which makes it difficult to make informed trade-off decisions for their application.

These issues have been addressed in the next development step that focuses at organising, reformulating, and supplementing the guideline inventory. A proposed way of organising the guidelines is to categorise them based on the different levels of product definition: structure, module, component, connection, and material. The overall product structure is built from a combination of modules that contain a cluster of components that are fixed by connections and constructed from materials. By linking the guidelines to the product definition, they implicitly relate to the design decisions that influence the product at different levels, concerning overall layout, type and form of components, and selection of materials. This motivates the relevance of adopting the proposed categorisation. As for supplementing the guidelines, some additional guidelines have been formulated based on new insights. But mostly the established guidelines have been elaborated with explanations of their purpose and underlying logics. This has resulted in a draft version of a structured set of guidelines, described in appendix P. The draft has deliberately been developed selectively with respect to the initial inventory. Some guidelines have been reformulated or combined, some have been elaborated, and others have not been changed at all. This is because the determined course for development as just described, needs to be verified by the target group as a meaningful direction before it is applied to all the guidelines. The draft version shows the contrast between a developed and an undeveloped guidelines and allows to test the user's preference. The next section will show if users agree with the solution principle, if the proposed course of development adds value, and how the guidelines can be further improved.

Evaluation and alignment of guidelines to user needs

The draft version of the selected and structured guidelines has been evaluated with six product engineers from Remeha in individual sessions. The goal of this evaluation has been twofold: to verify if product engineers consider guidelines a useful way of support and to identify how the guidelines can be further developed for increased usability.

During this evaluation session, the engineers were first introduced to the circular economy by means of a brief presentation. The fundamental idea of the circular economy was explained as a systemic change in relation to Remeha's current way of development. It was clarified how this new way of organising translates into new perspectives on product development and how this puts the engineers in a key position of influence. Based on this theoretical introduction, the drafted guidelines from appendix P were introduced as a way to support the engineers in designing boilers for a circular economy. Once the context for interpreting the guidelines was set, the engineers were presented with the guidelines. First the categories (structure, module, component, connection, and material) were shown to evaluate if this way of organising would be clear and useful to the engineers. Then, the guidelines of two categories were shown in more detail; the material category and one other. The guidelines of the material category contained the most elaborate descriptions and were most developed compared to the initial guideline inventory. They were shown in relation to less-developed guidelines to demonstrate their contrast and assess the engineers' preference. While studying the presented guidelines, the engineers were asked to express their thoughts, considering if what they read was understandable and applicable. For each evaluation session, the feedback results are reported in appendix Q. The most important conclusions from these results are described below.

- Overall, product engineers believe guidelines to be an appropriate and useful way to support their work. Engineers at Remeha are already used to working with guidelines, only they are regularly interpreted and applied as strict rules.
- Dividing the design guidelines over the proposed categories is experienced by the engineers as useful. The meaning of each category is clear, only the distinction between component and module is ambiguous to some engineers.
- Terminology used in the guidelines is in some cases complex or ambiguous and is not always consistently applied.
- The explanation with each guideline helps engineers to understand what the guideline means, but the increased amount of information decreases its accessibility.
- Product engineers recognise the potential of representing design guidelines through a digital design tool. Representing information at different levels (category, guideline, explanation) is experienced as a pleasant and orderly way to access information.

Based on these conclusions, it can be stated that guidelines are an appropriate way to support the design decisions of Remeha's product engineers, which verifies the solution principle. Moreover, the assumed directions for further development have been confirmed by the product engineers:

- Organise the guidelines in different categories;
- Reformulate guidelines more explicitly and practically to align with the product engineer;
- Explain the rationale of each guideline;

These directions have already been partially applied in the guidelines draft. Now that their potential has been confirmed by the product engineers, they will be more consistently applied to developing the guidelines further. The result of this last stage of development is described in the next section.

7.3 A coherent set of guidelines

This chapter has proposed guidelines as the principle solution to support Remeha's product engineers in designing boilers for reverse cycles. Literature has provided an information base for established guidelines, which has been further developed to improve applicability and usability. A user research has verified the potential of guidelines as a solution principle and has confirmed the assumed directions for further development. Based on these insights a coherent set of design guidelines is developed as the design tool's information backbone. This result will be described in the current section. First, the guidelines are described in general sense, referring to how they are structured, phrased and supplemented by explanations. At the end of this section, it will be elaborated how the guidelines relate to the design strategy that they are to realise.

The collection of guidelines is structured into four categories: architecture, component, connection, and material. This structure follows the same logic as the previous previously proposed categories in section 7.2, only it is refined to better suit the product engineer. Modules have been removed as a separate category and merged with the architecture guidelines, because product engineers do not generally develop specifically at a modular level and they experience the distinction between module and component to be ambiguous. Moreover, product structure is now referred to as architecture since this is a more commonly used term at Remeha. The overall architecture is built from components that are fixed by connections and constructed from materials. Each category is shortly elaborated below.

- **Architecture:** describes how the functional elements (components) of the product are structured and grouped in the product assembly. It concerns the positioning of components, their space claim, and their interfaces.
- **Component:** describes the characteristics of the components that build the product, concerning their functions and physical properties.

- **Connection:** relates to the physical attachments that connect parts, components, and modules in the product assembly.
- **Material:** expresses the materials from which the connections and components of the product are constructed.

The categories do not only provide overview in a broad collection of guidelines, but also give a specific context for the interpretation and application of the guidelines. As each category represents a particular aspect of the product definition, the guidelines are related to the product through their categorisation. Table 7.1 provides a list of all guidelines that have been developed for this research, structured according to the proposed categories. Every category includes about 10 guidelines. Occasionally, a guideline contains several secondary guidelines that offer more specific recommendations. Secondary guidelines should not be interpreted as less relevant or effective, but merely as operating on a more detailed level. Considering the guidelines in table 7.1 and how they are phrased, they can be characterised by three distinctive features:

- **User-oriented:** guidelines apply to the interpretation and influence of the product engineer in the product development process of Remeha;
- **Actionable:** guidelines propose practical directions for design activity to improve products.
- **Positive expression:** guidelines stimulate a positive approach to problem-solving, aiming at opportunities instead of what *not* to do.

These features have been deliberately instilled to promote the application of the guidelines by the engineers. They relate to how information is communicated through the guideline. A final feature to describe, relates more to the contents of the provided information. Each guideline is supported with a specific explanation that clarifies the rationale behind the guideline. The reason for adding these explanations is to make the user more aware of why certain actions are recommended. This increased understanding supports the application of a guideline and provides a basis for making trade-off decisions in design. In table 7.1, explanations are mentioned for the first guideline of each category (arc 01, com 01, con 01, and mat 01). These serve as an impression of the provided guidance, but mentioning all explanations here would result in an overly excessive list. The complete list of guidelines and their explanations is described in appendix R.

Table 7.1 Structured guidelines to support the design of boilers for reverse cycles.

	Architecture	
arc 01	Specify the space claims to allow easy access to components The accessibility of components in the assembly is influenced by the empty space around them. Sufficient space can support visual inspection, the placement of testing equipment, and the positioning of tools without the need for (extensive) disassembly.	
arc 02	Organise components into a modular structure	
	arc 02.1	Combine components with similar end-of-life options
	arc 02.2	Standardise the interfaces between modules
	arc 02.3	Concentrate PCBs in a module to make hem easily removable
arc 03	Position modules and components to make parallel disassembly possible	
arc 04	When disassembly cannot be parallel, indicate the preferred sequence	
arc 05	Position components and interfaces for an intuitive (dis)assembly direction	
arc 06	Mark components that have similar end-of-life protocols	
arc 07	Mark the boiler with information about its performance characteristics	
	Component	
com 01	Integrate multiple functions into a single component When boiler components perform multiple functions, like insulate heat and enclose technology, less individual components are needed to fulfil the combined product functionality.	
com 02	Seek to apply or iterate upon existing components	
com 03	Design new components to fit boilers from different generations or families	
com 04	Design to identify the functional condition of a component	
	com 04.1	Indicate the malfunction of parts
	com 04.2	Indicate the degree of wear of a part
	com 04.3	Monitor the product during its lifecycle
com 05	Mark components with information about their characteristics	
	com 05.1	Inform about end-of-life protocols
	com 05.2	Inform about performance and features
com 06	Design surfaces and geometry to prevent the collection of filth	
	com 06.1	Design components with smooth surfaces
	com 06.2	Design out crevices that are difficult to reach for cleaning
com 07	Shape parts so that they can be mounted in a fixture for testing or processing	
com 08	Reduce wear to individually separable components	

	Connection	
con 01	Specify connections that can be detached and re-attached, repetitively When boiler parts can be disconnected, operations like repair, refurbishment and recycling can be carried out more easily and effectively. After a part is disconnected, it must be possible to re-assemble it, preferably using the same connections. When applying this guideline, prioritise (economically) valuable components that are fit for reuse, refurbishment, or maintenance.	
	con 01.1	Ensure the possibility to easily detach PCBs in one piece
	con 01.2	Use mechanical fasteners rather than adhesives
	con 01.3	Prefer separable snap-fit joints for plastic components
	con 01.4	Prevent moulding different types of plastic together
con 02	When permanent connections are necessary, guide destructive action	
	con 02.1	Provide markers that indicate where to apply force
	con 02.2	Include breaking lines to control the breaking points
con 03	Make it easy to identify the position and handling of connections	
con 04	Ensure open access to (detachable) connections in the boiler assembly	
con 05	Use common connections that are widely applied in industry	
con 06	Enable the replacement and repair of connections	
con 07	Design connections to allow (dis)assembly by hand or with standard tools	
con 08	Minimise the number of connecting elements in the boiler	
con 09	Limit the variety of connections within the boiler	
con 10	Prevent the use of permanent magnets in boiler components	
con 11	Do not mould metal threaded inserts in plastic parts	

	Material	
mat 01	Increase the use of common materials Standardised materials are widely applied in industry and they appear in regular and high quantities in waste streams. Recycling systems are generally specialised in processing these materials so they can be recovered at high quality. Also, there exists an established market to reuse common materials as a secondary resource.	
mat 02	Design with recycled materials	
	mat 02.1	Prefer standard grade recyclates that are offered by the supplier
	mat 02.2	Reconsider tooling equipment when replacing virgin with recycled material
	mat 02.3	Apply a (higher than normal) safety factor to select recycled material

mat 03	Design parts to be made from mono-materials	
	mat 03.1	Prevent using composites that consist of different materials
	mat 03.2	Prevent blending plastics with additives or other types of plastic
	mat 03.3	Limit the use of colourants in plastics
	mat 03.4	Prevent the use of uncommon metal alloys
mat 04	If an additive is necessary, apply one that gives the plastic a unique density	
mat 05	Design boiler components with a limited number of different materials	
mat 06	Ensure that different materials are compatible for recycling	
	mat 06.1	Use material for connectors that is compatible with the host part
	mat 06.2	When using metals, ensure that ferrous metals are magnetic and non-ferrous metals are non-magnetic
mat 07	Whenever possible, limit the use of coatings	
mat 08	Mark components with a permanent and visible identification of their material type	
	mat 08.1	For plastics, adopt the ISO 11469 to indicate material type
mat 09	Ensure that suppliers comply with laws on the use of hazardous substances	
mat 10	When using plastics, prefer thermoplastics over thermosets and elastomers	

7.4 Relating guidelines to the design for reverse cycles strategy

Section 6.3 explains the selected design strategy as relating to three reverse cycle processes: reuse, refurbishment, and recycling. These processes recover and restore their value from end-of-life boilers so it can be used again in the economy. Reverse cycle processes are influenced by the structural characteristics of a product, which are determined in the product development process. The strategy suggests four synergetic ways to realise a positive influence on reverse cycles by design:

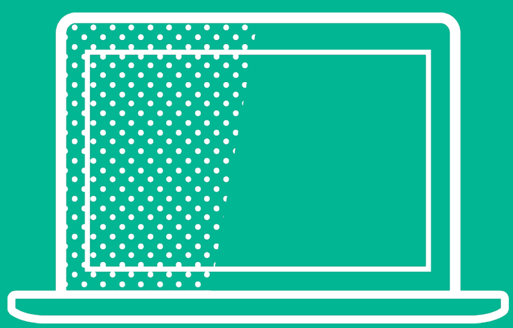
- Design for easy dis- and re-assembly
- Design a modular product architecture
- Create value from recovered resources
- Standardise product features

The guidelines have been selected and formulated based on these aspects of the design strategy. All four aspects are addressed through the collective set of guidelines. In some cases, this relation is explicitly expressed. For example, guideline arc 02 in table 7.1 literally refers to a modular structure and guideline mat 02 specifically prescribes the use of recovered materials. In most cases, however, the relation between guideline and design strategy is rather implicit. In general, the guidelines in the architecture category encourage the easy separation of components so they can be further processed in reverse cycles. Guidelines in this category relate to the positioning (arc 03), grouping (arc 02), and identification (arc 06) of components in the product assembly. On the component level, guidelines endorse the development of features that make a component easy to treat in reverse cycles and broadly applicable after treatment. Relating guidelines stimulate to identify a component's characteristics (com 05) and condition (com 04), design standardised features (com 03), and to allow reprocessing (com 07). The connections of a boiler are addressed by guidelines that benefit to easy and repetitive disassembly in a way that preserves a component's functional and material quality. Connections are advised to be applied in limited numbers (con 08), to be recognisable (con 03) and accessible (con 04), and to be easily detached (con 01). Finally, the guidelines in the material category promote the recovery of materials through the recycling process. For instance, by recommending the use of pure materials (mat 03) that can be easily identified (mat 08) and separated (mat 06). But guidelines in this category also stimulate the reutilisation of recovered materials by advising to make components from recycled materials (mat 02) and to use standardised materials (mat 01). From this elaboration it should be clear how the guidelines collectively contribute to realising the design strategy from different focus points. While these guidelines are specifically developed to stimulate reverse cycles by design, they also relate to other design strategies to increase resource effectivity. For instance, easily separable and accessible components and connections support maintenance and repair activities to extend a product's lifespan. Likewise, a product with a modular structure can be flexibly configured and upgraded to support a longer lifespan or a more resource-efficient performance. These relations are important to recognise even while they are not specifically addressed by the guidelines within the scope of this thesis.

Conflicting guidelines

As elaborated in the previous paragraph, the combined application of the guidelines contributes to realising the design strategy, but every guideline contributes from a specific focus. While they all commit to the same objective, their specific approach to realising this objective can cause conflicts. For example, integrating multiple functions into one component can support disassembly procedures, but it can make a component more application-specific which could reduce the options for reutilisation. Broadening the scope beyond designing for reverse cycles, reveals more probable conflicts. For instance, using a coating can pollute a recycling stream, but it can significantly extend a component's lifespan.

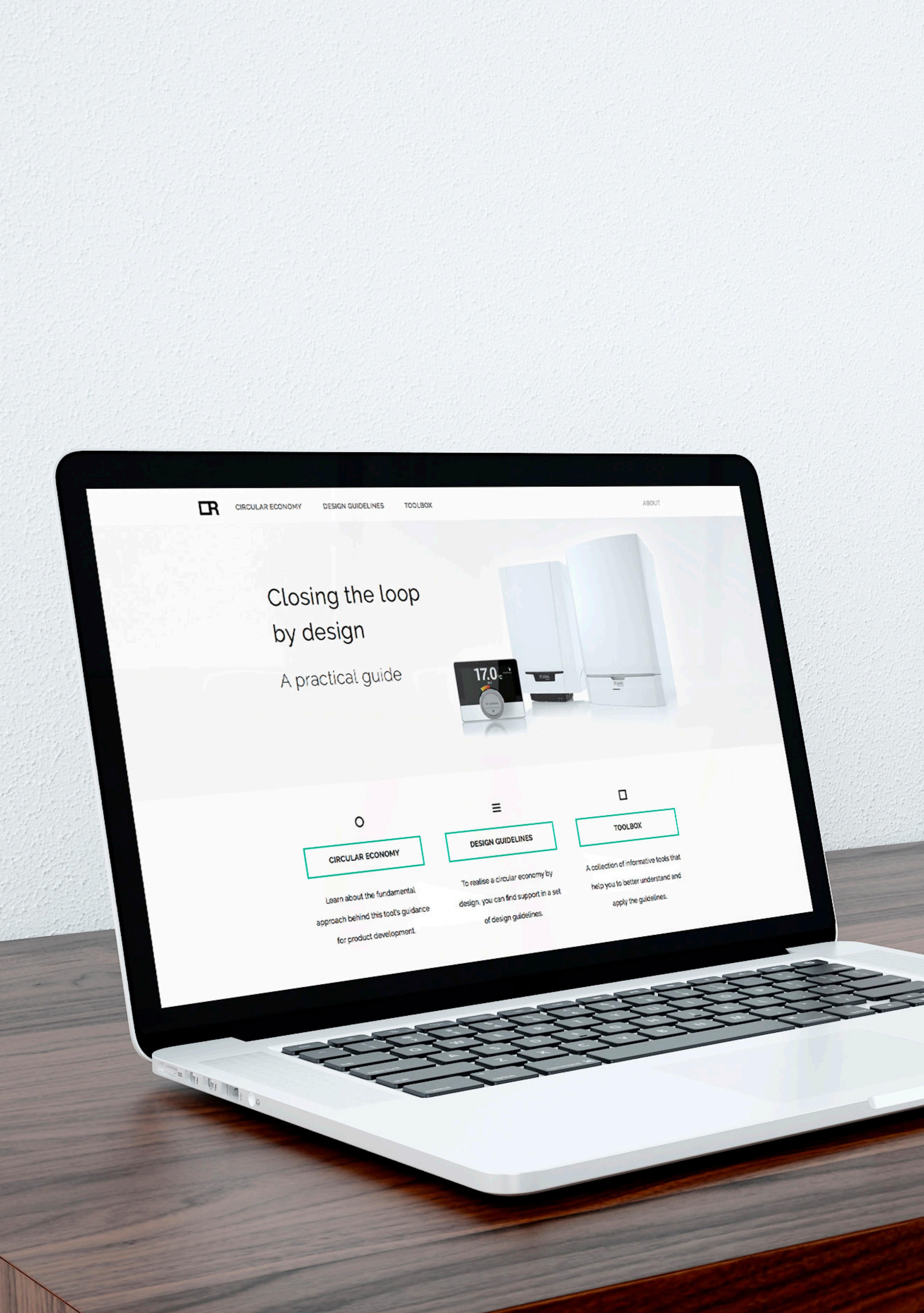
The existence of conflicts is not regarded as evidence of a guideline's invalidity or irrelevance. Instead, it is stated that the occurrence of conflicts is a logical consequence of combining several strategies into a holistic approach to increasing resource productivity. Designing for a circular economy will naturally lead to conflicting guidelines, which leads to trade-off decisions. Such a trade-off cannot be generalised, but depends on the context in which the conflict arises and the desired outcome of a development decision. This issue requires a decision-making solution that helps to make situation-specific trade-off decisions. Such solution could improve the applicability of the design guidelines, especially when their scope extends to include a broader range of circular design strategies. However, this exceeds the scope of this theses and will not be further addressed by the design tool that will be introduced in chapter 8. Within the proposed set of guidelines, the number of conflicts is limited and the explanations with each guideline support product engineers to make informed decisions on their application. Support in trade-off decisions is not essential to using the guidelines in the current stage of development and implementation.



chapter

08

Dedicated design tool



CIRCULAR ECONOMY
DESIGN GUIDELINES
TOOLBOX
ABOUT
Closing the loop
by design
A practical guide
17.0
CIRCULAR ECONOMY
Learn about the fundamental approach behind this tool's guidance for product development.
DESIGN GUIDELINES
To realise a circular economy by design, you can find support in a set of design guidelines.
TOOLBOX
A collection of informative tools that help you to better understand and apply the guidelines.

In a circular economy, products can be designed for enhanced resource effectivity in different ways. These are described in chapter 6 in terms of design strategies. One particular strategy has been selected for further development and implementation, focusing at the recovery of resources from end-of-life product so they can be used again. To support product engineers in realising this strategy, chapter 7 has proposed a set of coherent guidelines. Guidelines offer practical recommendations for design decisions, meant to inform and inspire new solutions. Basically, these guidelines provide the substantive support to develop boilers for closed resource flows. But besides the knowledge that the guidelines represent, the shape in which they are provided to the user highly influences their application. Therefore, a digital tool is developed to presents guidelines in an interactive and accessible way. As an embodiment of the guidelines described in chapter 7, the design tool is developed for the same users and scope. Product engineers of the R&D Projects department are the target group for the tool and its implementation will be focused at the early stages of development, from stage 1 to stage gate 4.

This chapter describes the digital tool; how it provides access to different kinds of information and how it should be implemented in the product development process. As the result of this research, the tool includes the guidelines that were formulated in the previous chapter. Because these guidelines have already been described, this chapter will focus more at the shape and structure of the tool than at its design guide content.

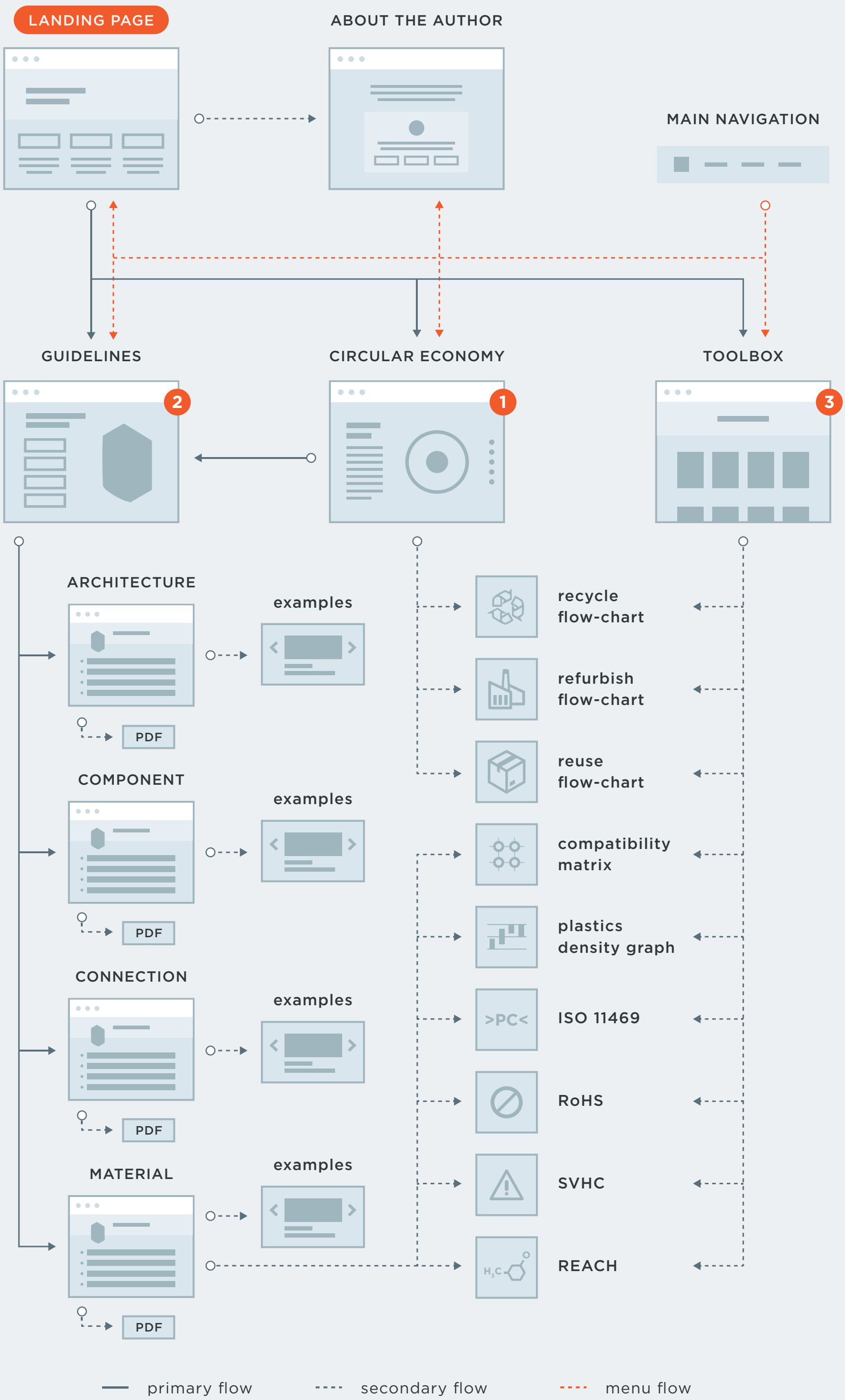


Figure 8.1 Design tool structure

8.1 Tool structure and interface

The design tool consists of a digital user interface that provides access to different kinds of information at different levels. It could be compared to a website where data is displayed on different pages. The user can navigate through these pages and can determine what information he wants to access. This way, a broad scope of information is provided in an accessible and focused manner. Figure 8.1 shows a schematic wireframe of the tool's different data screens, clarifying the various kinds of data and how they are layered. The lines that link the screens represent three flows of navigation to access information at different levels in the tool. The primary flow leads past the key information in the tool, mainly consisting of the explanation of the circular economy and the design guidelines. The secondary flow represents sidesteps from the primary flow to access more specific knowledge like examples or information tools. And third, the menu flow shows how different screens can be accessed through the main navigation menu.

The landing page is the opening screen of the tool where the user starts his workflow. Three buttons on this page provide access to the three main data screens that contain distinct types of information to support the user. The first screen (1) shows a brief explanation of the circular economy and how it relates to the proposed guidelines. The second screen (2) provides an overview of four categories into which the design guidelines are grouped. Each category links to a separate page where the guidelines are listed. The third main screen (3) offers a collection of information tools that support the application of particular guidelines. These three main areas of the tool are further elaborated in this section.

Explanation circular economy

The design guidelines have been developed from the specific perspective of the circular economy, focusing at enhancing resource effectivity in the end-of-life stages of the product lifecycle. This approach is implicitly embodied by the guidelines, but it is not explicitly communicated from a holistic perspective. However, a holistic understanding of the circular economy would benefit an adequate interpretation and application of the guidelines. Because product engineers are currently unfamiliar with the circular economy, this understanding will be provided by the tool. The explanation assumes no prior knowledge of the circular economy and is written as a stand-alone explanation in the context of the tool. Hereby, product engineers do not depend on any additional information before being able to use the guidelines. This supports the initial implementation of the tool at the R&D department and it allows new employees to use the tool regardless of their previous experience.

The explanation is formulated and displayed in an easily accessible way. The storyline consists of five distinct parts, explaining the fundamental idea of the circular economy, how it applies to Remeha's product development, and how the tool supports its realisation. Each story part is represented in the tool by a full-screen slide that contains a short text and a key visual. Figure 8.2 illustrates how this looks like by showing the first slide of the story line. The user can navigate through the five slides by scrolling, by using the arrow keys, or by clicking the bullets at the right of the screen. The story line starts with explaining the circular economy as a new way of organising industrial processes to use resources in closed loops. The second slide introduces reverse cycles as specific ways to close resource flows by restoring value from end-of-life boilers. Next, the third slide explains that product development can create new opportunities to recover and restore value in reverse cycles. In this respect, the product engineer offers an essential contribution to realising a circular economy by design, as stated by the fourth slide. Finally, the fifth slide acknowledges the challenge to adopt new ways of thinking about product development and introduces the design tool as a means of support for the product engineer. The full story line, as it is mentioned in the tool, is described in appendix S. The language is deliberately more colloquial and written from a second-person perspective to address the reader directly.

Design guidelines

Equipped with a contextual understanding of the circular economy, the product engineer can access the design guidelines in the second main section of the tool. This is the heart of the tool and the essence of its support to the engineer. As explained in chapter 7, the guidelines are grouped into four categories: architecture, component, connection, and material. These categories have been adopted in the tool as a filter to show the collection of guidelines in four separate data views. When navigating to the guidelines section, the user is first asked to select a 'design guide category' to access a specific selection of guidelines. In the tool's interface, each category is supported by a visualisation to clarify its scope in the product definition, as illustrated by figure 8.3.

By making the guidelines accessible through the categories, the tool can show a measured amount of information. This promotes the usability and accessibility of the guidelines and at the same time provides a product-related context in which the

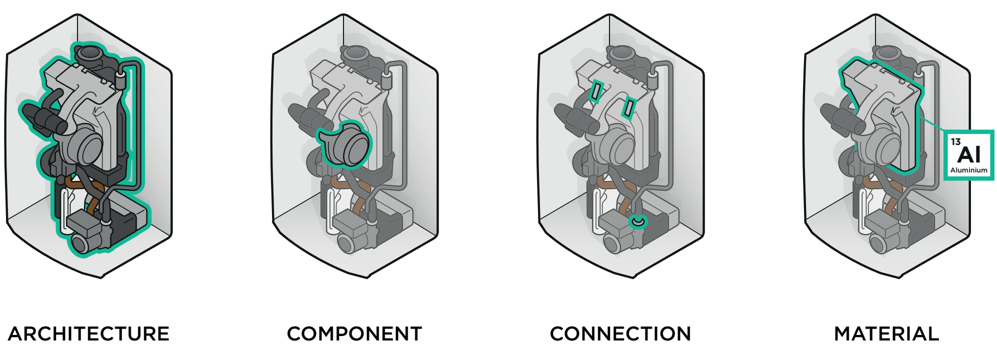


Figure 8.3 Design guide categories.

Figure 8.2 Mock-up screen circular economy.

guidelines can be interpreted and applied. Based on the general preference of the target group, the categories are listed in an order that starts with a broad scope on the product at the architecture level and converges towards a more detailed scope at the material level. Because the relevance of each category is different for each design case, the tool prescribes no fixed order in which the categories should be accessed.

After selecting a category, a next page presents the guidelines that relate to this category. Briefly recapitulating, guidelines offer prescriptive and practical recommendations for design decisions without prescribing specific solutions. As such, guidelines are meant to be used as a source of knowledge and inspiration and not as a fixed set of rules that needs to be obeyed. It is up to the engineer to decide when to apply which guidelines, depending on the project's scope and constraints. Herein, the user is supported by the explanations that accompany each guideline to clarify the underlying rationale of recommended actions. This section will further refrain from describing the content and formulation of the guidelines as this has been elaborately discussed in chapter 7. Instead, the current section will further describe how the guidelines are represented by the tool and how they are further supported by examples and additional resources.

Figure 8.4 shows how the guidelines are displayed in the design tool interface. The guidelines are represented as items in an expendable list. Initially, the list items are collapsed, showing only the guidelines and their reference number. This default display mode provides a clear overview of the available guidelines. When clicking a list item, its view expands to show more information about the clicked guideline and in some cases to reveal relating secondary guidelines. Clicking an expanded list item again will collapse it back to the default display mode that shows only the guideline. By toggling between these view modes, the user is free to access information at different levels based on his preference. This can be controlled for each separate list item. Besides the occasional secondary guideline, the following information reveals when expanding a list item:

- Explanation of the design guide's underlying rationale;
- Reference to examples that illustrate the guideline with good and bad practices;
- Reference to resources like graphs or standards to aid a guideline's application;

The references to examples and informative resources are displayed as clickable buttons below the explanations in the expanded list item, like demonstrated for guideline *arc 01* in figure 8.4. Clicking the button will present the example or resource in a new screen overlay. The examples are meant to promote the user's understanding and application of a guideline by illustrating good and bad practices. Currently, the tool contains roughly 70 examples that relate the guidelines to the features of a domestic boiler and occasionally to products from another industry to encourage creativity. In the tool's interface, the examples are shown in an image slider format that communicates

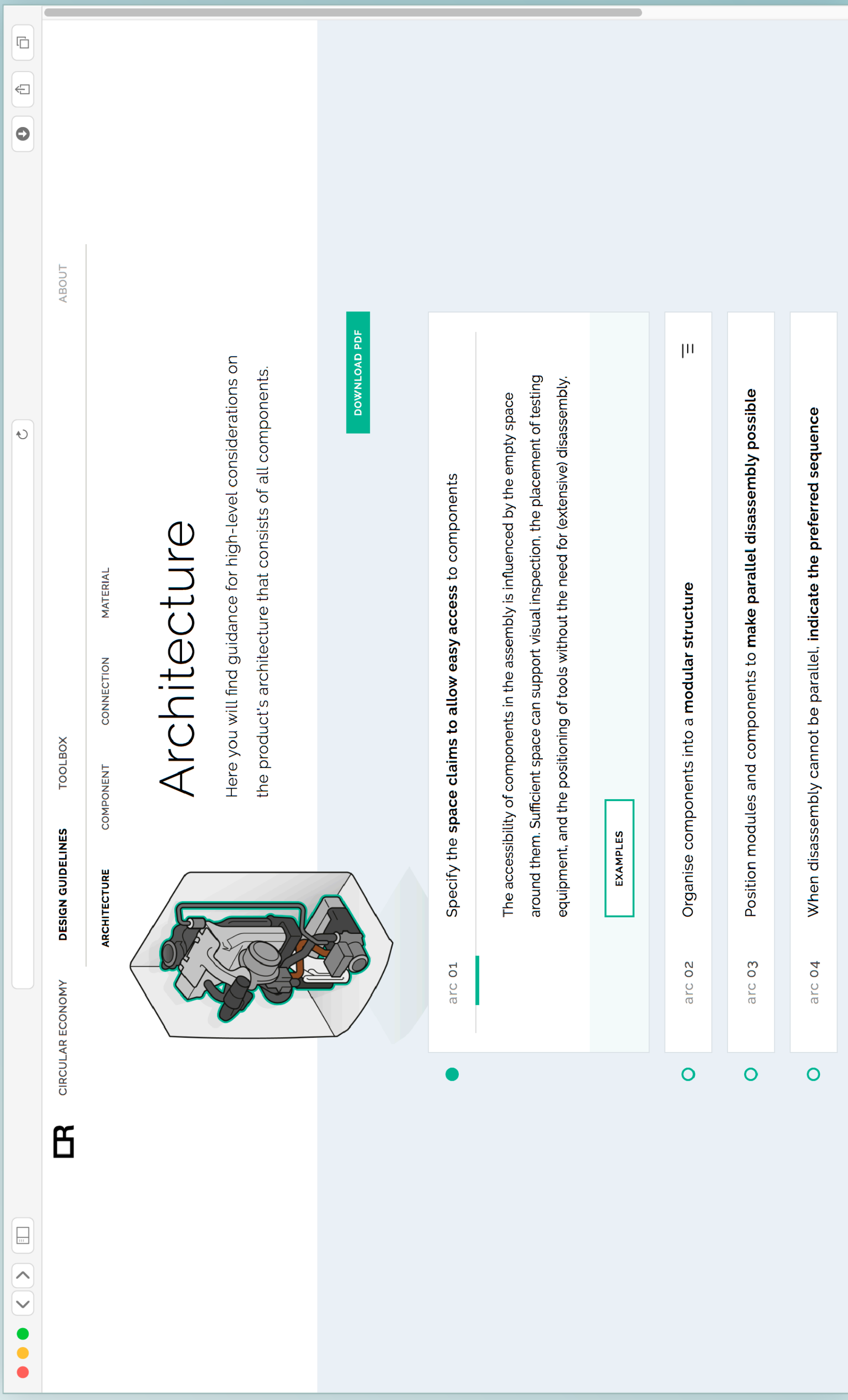


Figure 8.4 Mock-up screen guideline overview.

through a strong visual and some lines of explanation. They are linked to specific guidelines and can only be accessed through the reference buttons in the guideline overview. In addition to the examples, the informative resources offer supplementary information on a specific guideline that supports its application. For instance, guideline *mat 04* advises to apply additives in a way that gives a plastic a unique density and is supported by a graph that shows the densities for the most common plastics. Like the examples, informative resources are linked to specific guidelines and can be accessed from the guideline overview. Additionally, these resources can be accessed from another part of the tool, as will be discussed in the next section. The informative resources and examples that have been included in the tool represent just a small portion of the possible resources that can be provided. The current content is not meant to be comprehensive, but should be seen as dynamic content that can be further expanded, as will be addressed in section 8.3.

Toolbox

The third and final main screen of the design tool is the toolbox. As mentioned in the previous section, the overall design tool contains several informative resources to aid the application of particular guidelines. In the guideline overview discussed in the previous section, these resources are directly linked to the guidelines to which they apply. When a user is still unfamiliar with the tool, this direct relation confronts the user with the existence of the resources and facilitates an understanding of why and how they should be applied. Once a user becomes more experienced, he grows aware of the availability of resources and how to use them. When purposively looking for a specific resource, they are not particularly easy to find in the guideline overview. Therefore, the toolbox provides an alternative way of accessing the same informative resources. The toolbox screen does not contribute any new content, but it serves as a more centralised way to access existing content.

Figure 8.5 shows how the toolbox is displayed in the design tool. Each resource is represented by a box that contains an icon and brief description. All boxes are organised in a grid that provides an overview of available resources. Clicking a box will open a new screen that displays the resource. This could be a flow-chart or graph that is embedded in the tool, but it could also refer to an external website or PDF document. For example, there is a matrix that shows what materials are compatible in the recycling process and a reference to the ISO 11469 standard that prescribes a generic identification and marking of plastic products.

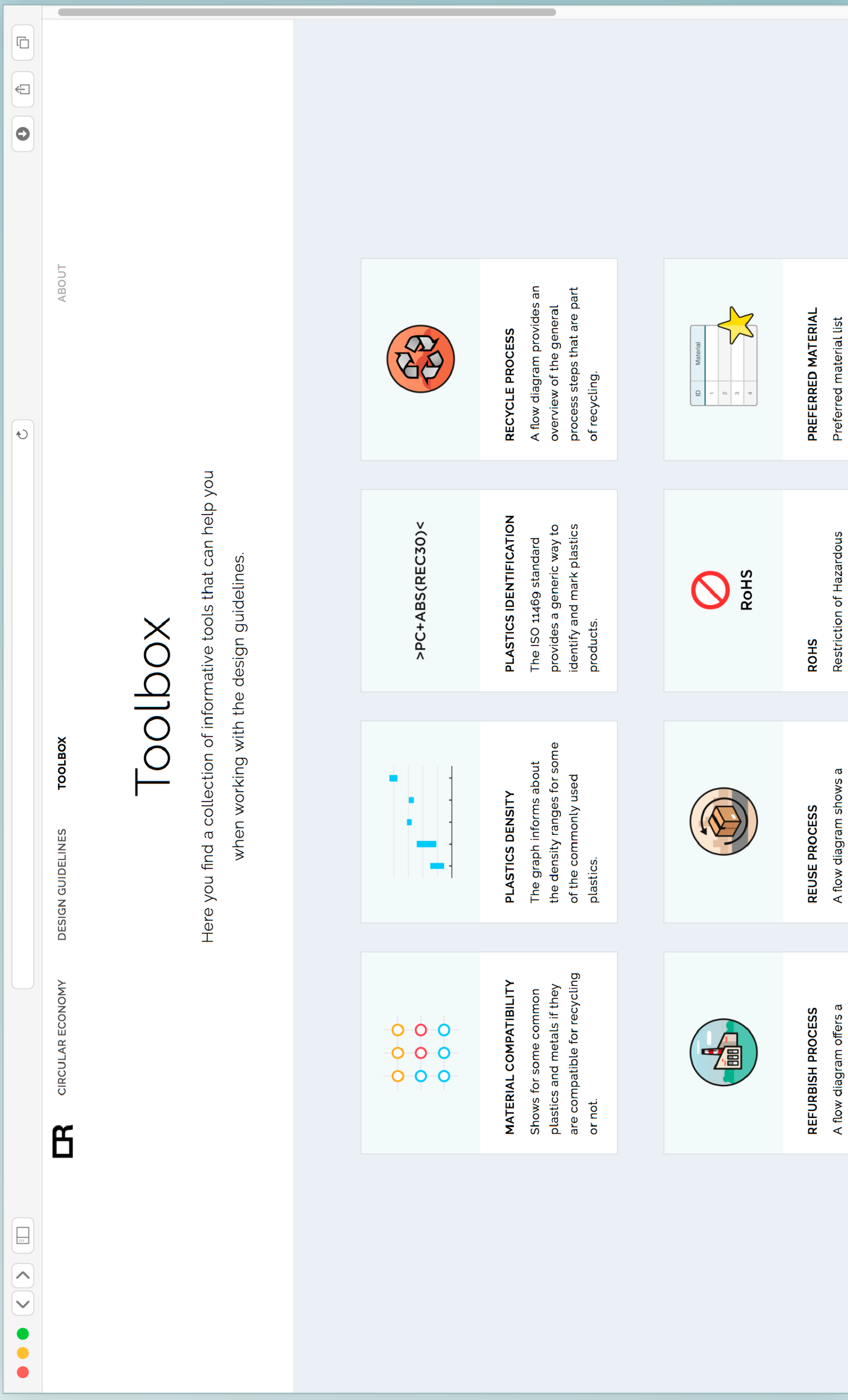


Figure 8.5 Mock-up screen toolbox.

8.2 Code script backbone

Section 8.1 has described the tool as a digital user interface that provides access to information. This digital interface has been built from coded scripts that are written in computer language, in this case specifically HTML5, CSS3, and JavaScript. These languages allow to create a customised and interactive solution and were already familiar to the author. They are often used concurrently and are each responsible for particular aspects of the tool's structure and behaviour. The computer code is interpreted by a web browser, which technically makes the tool not a program but a web application that is very similar to a website. The current section will explain the technical foundation of the tool and its relating features.

HTML is known as a markup language and is used to describe how the data content of the tool is structured. In HTML, the data structure is described by pre-defined elements that represent a particular kind of content such as a heading, list, image, paragraph or section. These elements are delineated by tags that encapsulate data, like shown in the example below.

```
<!DOCTYPE HTML>
<html>
  <head>
    <link rel="stylesheet" href="_css/style.css">
    <title>Example script</title>
  </head>
  <body>
    <ul class="list">
      <li>option 1</li>
      <li>option 2</li>
    </ul>
  </body>
</html>
```

The web browser interprets the HTML code and renders the data in a default layout that adopts standard fonts, alignments and spacing. This layout can be adjusted with HTML code, but this is not a common practice. Instead, the style sheet language CSS is used to customise how the structured data is displayed by the browser. By using CSS, the HTML code that defines the data structure is separated from the presentation semantics that define the visual layout of the data. This allows to create code that is more accessible, efficient, and flexible. CSS code defines the style of a particular HTML element, referring to a tag name, class, or ID. Below, an example of CSS code is shown that applies to the <ul> tag in line 8 of the previous HTML example.

```css
.list {
  list-style: bullet;
  font-size: 12pt;
  padding: 10px 0 0 5px;
  position: relative;
}
```

HTML and CSS have been explained as a markup language and style sheet language respectively. They are limited to expressing the structure and presentation of data, but do not prescribe any system behaviour. Strictly speaking, this makes them no real programming languages. In contrast, JavaScript is an established programming language that does define behaviour. It is used to define interactions in the interface, which allow to shape a dynamic user experience. Without JavaScript, the tool would just be a digital approximation of a written document.

The particular coded structure that has been described in this section gives the design tool a number of particular features that are relevant to its application. The tool is not an autonomous program, but needs to be accessed through a web browser such as Internet Explorer or Google Chrome. This dependency is not regarded as a limitation since contemporary smart phones, tablets, and personal computers contain a browser by default. Moreover, all major browsers support HTML, CSS, and JavaScript without requiring any additional plug-in software. At the moment, the design tool is available from Remeha's local network where it can be accessed off-line by the product engineers and all other employees. Because of how the tool is designed, it can also be published on a web server where it can be accessed from any device or location. Potentially confidential information could be shielded from public view through a login authentication. Such broad availability could for instance be beneficial during off-site meetings with suppliers. Because the tool is digital it can contain an interactive user interface that presents content dynamically. This allows for an engaging user experience through which a great amount of information is available in an accessible way. Moreover, the tool is flexible to be expanded with new functionalities or content. At this moment, content needs to be changed in the HTML code, which naturally requires some programming skills and a thorough understanding of the tool's code. In a next development step, the tool could be supplemented with a specific user interface for content management.

8.3 Implementation

It has been elaborated by the preceding sections of this chapter what the characteristics of the design tool are. The current section will address how the tool is to be implemented at the R&D Projects department. As described in section 4.2, development at the Projects department is organised according to the New Product

Development (NPD) process. The design tool is meant to be used in the early stages of this process, when the project allows the most freedom to influence a product's characteristics and their effect on reverse cycles. In terms of the NPD process, the tool should be applied from stage 1, when the product definition is specified, up to stage gate 4 when the design is frozen and the project's focus shifts to industrialisation. During these project stages the tool is available to the product engineers from their own work stations or laptops. The tool's source files are placed at the internal server and can be accessed from the so-called Product Engineers (PE) Overview that engineers use as a central portal to access knowledge documents at the server. The use of this overview is part of every engineer's workflow, which makes it an easy and intuitive way to make the tool available.

The proposed tool is to be used by product engineers to inform and inspire the development of new design solutions for domestic boilers. The knowledge that the tool provides, should become an integral part of the engineer's design activities. The application of this knowledge, addressing the development of domestic boilers for closed-loop resource flows, should not be confined to one isolated development step. Instead, it should be part of all development steps that shape a product: sketching the outlines of the product description, generating design solutions, conceptualising product proposals, and refining the integrated final solution. In all these stages, the tool should be included to support the product engineers. It is probable that different guidelines are relevant to different stages of development. For instance, guidelines on the boiler's architecture are more relevant for the product definition in stage 1. Whereas a more detailed perspective on the boiler's connections and materials becomes more relevant in stage 2 and 3 of the NPD process. However, on a more detailed level, each project sets a different context and focus for development and product engineers work with varying constraints and targets. These conditions require a flexible use of the tool. For this reason, the tool does not link guidelines to a particular part of the development process or prescribe a specific workflow. It is up to the engineer to decide when he uses which guidelines and in what order.

To stimulate the use of the tool and the consideration of its underlying strategy, the stage gate deliverables of the NPD process have adjusted with additional specifications. The NPD process formally defines several deliverables that must be met by the project team before proceeding to the next stage. The projects department further specifies a deliverable into actions that must be carried out by the product engineer in order to meet the respective deliverable. In stage gate 2, 3, and 4 an existing deliverable has been supplemented with specifications on the consideration of end-of-life value recovery and reutilisation. These specifications and their relation to the existent process deliverable are shown in table 8.1. The specifications have been defined in consultation with the product engineers' (PE) team leader and they will be officially included in

Table 8.1 Implementation New Product Development process deliverables.

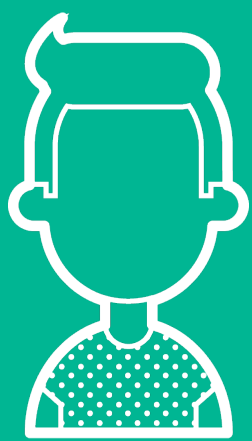
Stage gate	Deliverable	Specification product engineer
2	Environmental impact reviewed	Consider the options for developing a product so that its embedded resources can be recovered at end-of-life and use again.
3	Product and component specification made	Make a deliberate choice how to include end-of-life considerations in the project and translate these into product and component specifications. Specify how the product's embedded value can be recovered through reuse, refurbishment, and/or recycling when it becomes obsolete.
4	Specification updated and design frozen	Update specification of how the product's embedded value can be recovered through reuse, refurbishment, and/or recycling when it becomes obsolete.

the NPD process of the R&D Projects department. Through these specifications, the developed tool and its embodied strategy are formally implemented in the product development process of Remeha.

In addition to the NPD deliverables, the implementation of the tool is supported by creating awareness of the tool's existence and purpose amongst the target group and across the R&D department. At the management level, the manager R&D, manager Projects, and PE team leader have been closely involved in the development of the tool. The product engineers have been introduced to the tool in the final stage of this research project by means of two workshop sessions. The first session was mostly intended as a usability test for the tool, but was organised in a way to stimulate the tool's implementation. This session will be further elaborated in chapter 9. The second session was initiated and organised by one of Remeha's product engineers in response to his participation to the first workshop session. He was motivated by the applicability of the tool and positive energy of the first session and believed in the importance of considering the tool's knowledge in the development of boilers. As will appear from chapter 9, all product engineers that participated in the usability test were willing to use the tool in their regular engineering work. This demonstrates a basis of support amongst the product engineers to build the tool's implementation upon.

Scalability and maintenance

The knowledge content of the design tool has been customised for the product engineer's current state of knowledge and experience with developing products for a circular economy. Some guidelines will provide new insights to the user and others will be seen as logical or familiar, but need to be mentioned since they are currently not part of the user's structural considerations about design. As Remeha's product engineers become more experienced with the tool, its knowledge will become more familiar and their needs for support change. Moreover, a regular use of the tool is likely to lead to new insights that can supplement its content. For instance, by including more examples, refining guideline explanations, or even adding new guidelines. Because of the tool's digital nature and how it is designed, it is possible to adjust and supplement its content. However, within the limits of the tool's current structure and interface, changes to its content are limited to: guidelines and explanations, examples, and informative resources. Also, the order of navigation menus and guidelines are susceptible to changes. These adjustments are technically possible and allow the tool to flexibly adjust to changing user needs. However, such change management is currently not supported by a user interface and needs to be conducted in the tool's HTML scripts. This requires some programming skills and knowledge of the tool's code structure. It would be possible to develop a user interface for change management, but this is recommended for future development as will be discussed in chapter 11.



chapter

09

Evaluation

As described in chapter 8, a design tool has been developed for the product development environment at Remeha. The tool is applicable to the development of domestic boilers, a key product in the company's portfolio, and it is aligned to the preference and knowledge of Remeha's product engineers. This chapter will discuss how the tool is experienced by the target group and how it influences their design decisions.

9.1 Usability test setup

The tool's performance has been assessed by means of a qualitative usability test with the target group. This test is meant to verify the usability of the tool's structure and interface and the applicability of its design guidelines to the development of domestic boilers. To verify these aspects, the usability test has been organised as a workshop session in which nine product engineers participated. During this session, the participants are introduced to the idea of the circular economy, work with the tool to generate design solutions, and share their experience through a questionnaire. These three parts of the test session will be briefly elaborated below.

- **Introduction circular economy and design strategy**
  The session starts off with a general presentation on the circular economy to the whole group of participants. This introduction discusses the idea of enhanced resource effectivity in a circular economy and how this can be realised in through several design strategies. In this respect, the tool is introduced as a means to support the product engineers in realising one particular design strategy. Through this introduction, product engineers become aware of the general concept of the circular economy, the important role of product development, and the function and scope of the design tool. The specifics of the design tool, how its interface looks like or how it works, are deliberately not explained.
- **Case study boiler component**
  Having been introduced to the concept of the circular economy and the scope of the design tool, participants are asked to use the tool in a 45-minute case study. During this case study, participants work with the design tool and apply its guidelines to create a redesign of a boiler component. To promote creative solutions and to allow discussion about the tool's content, the case studies are executed in three groups of each three participants. Every group is assigned their own boiler component as a scope for their case study: a heat exchanger, a gas-air unit, or a front cover. To provide some structure and direction to the case study, each group received a design brief, containing detailed instructions and deliverables. The elaborated design brief can be found in appendix T. Amongst others, it instructs that every participant should have worked with the tool during the case study and that guidelines from multiple categories should be applied. To further support the case study, each group receives a physical example of their assigned component and one laptop from which the tool can be accessed.

- **Evaluation user experience**
  After completing the case study, each participant is asked to individually fill out a questionnaire about their experience with using the tool. The results of this questionnaire provide the basis for evaluating the tool's usability and applicability for product engineers.

The described test setup is meant to offer the participants sufficient background information and experience with the tool to qualify them for evaluating its performance. The case study simulates a probable use case and allows participants not just to read the tool's knowledge but to apply it for generating solutions, as it is meant to. This allows a good evaluation of the tool's practical applicability and the use experience prepares the participants for using the tool independently during their regular engineering work. Moreover, the design solutions that result from the case study can reveal potential improvements that can be considered for implementation in development projects. For this purpose, the boiler components that were assigned as subject of the case studies have been selected in consultation with lead engineers and are open to changes in projects that are on-going or about to start.

9.2 Test results

After performing the case study, the participants completed a questionnaire that assessed how they experienced working with the tool. The questionnaire first asks for general information about the participant's department, case study subject, and skill level. Subsequently, the participant is asked to rate 11 statements on a 5-point Likert scale, evaluating if the tool's provided information was experienced as useful and accessible. Finally, four open questions asked for more specific feedback on how the tool was used and what aspects were regarded positive or negative. Appendix U contains the template of the questionnaire as it was handed out to the participants. The results from the completed questionnaires are described in appendix V. This section presents a summarised overview of the most important test results.

The response on the general questions show that product engineers indicate to have an intermediate skill level when it comes to designing products for sustainability, with the exception of one beginner and one experienced. Due to the formulation of the question, this estimation probably reflects not just their experience with sustainable development, but includes their capabilities as a product developer. This would explain the relatively high estimated skill levels compared to the results of the interim evaluation of the draft guidelines, described in appendix Q, which indicated limited experience with design for sustainability.

Figure 9.1 shows how participants valuate the statements on how they experienced working with the tool during the test session. Participants unanimously agree or strongly agree that the guidelines are clearly formulated, were applicable to their case study, and can be used for their regular engineering tasks. Likewise, participants all agree or strongly agree that the tool is pleasant to work with, provides easy access to information, and provides useful insights on how to design products for a circular economy. The usefulness of the examples and explanations that accompany the guidelines is generally agreed on and some indicate to have no opinion. As a final indication, one participant strongly prefers guidelines on a written document, while other participants indicate to disagree with this preference or have no opinion.

The results from the open questions provide more specific feedback on the use of the tool. For each open question, the results are summarised below.

- **How did you use the tool during your case study?**
  Generally, the tool was first explored to see what information it contained and where that information was located. The guidelines were mostly used to assess the opportunities for a component's redesign and to generate new solutions. Some participants chose to walk through all categories in (reversed) order of appearance in the tool, others did not adopt a specific order for using the guidelines.
- **What do you like about the tool?**
  Participants found the information in the tool clear, accessible and practical. They valued the guidelines and their explanations as useful way to consider sustainability.
- **Is there anything you missed or did not like about the tool?**
  There were some remarks about the navigation in the tool. When returning from an example back to the guidelines the list was 'reset' to a collapsed list. Some suggested a specific different order in which to present the design guide categories: from architecture down to material. One participant indicated to prefer a more structured workflow in the tool and one suggested a more explicit relation between the guidelines and their effect on the reverse cycles.
- **Would you be willing to use this tool for your projects?**
  All participants indicated to be willing to use the tool for their projects. Some supported this statement with a remark on the usefulness of the tool and the positive energy it provides.

Besides the results from the questionnaire, some results from the author's observations during the case study are worth mentioning.

- At the start of the workshop, the participants were given 10 minutes to explore the tool, without previous explanation about its interface or functionality. After these 10 minutes, there was an opportunity for questions or further instructions, but this turned out not to be necessary. After their 10 minutes of independent orientation, all groups were ready to start applying the tool to their case study.

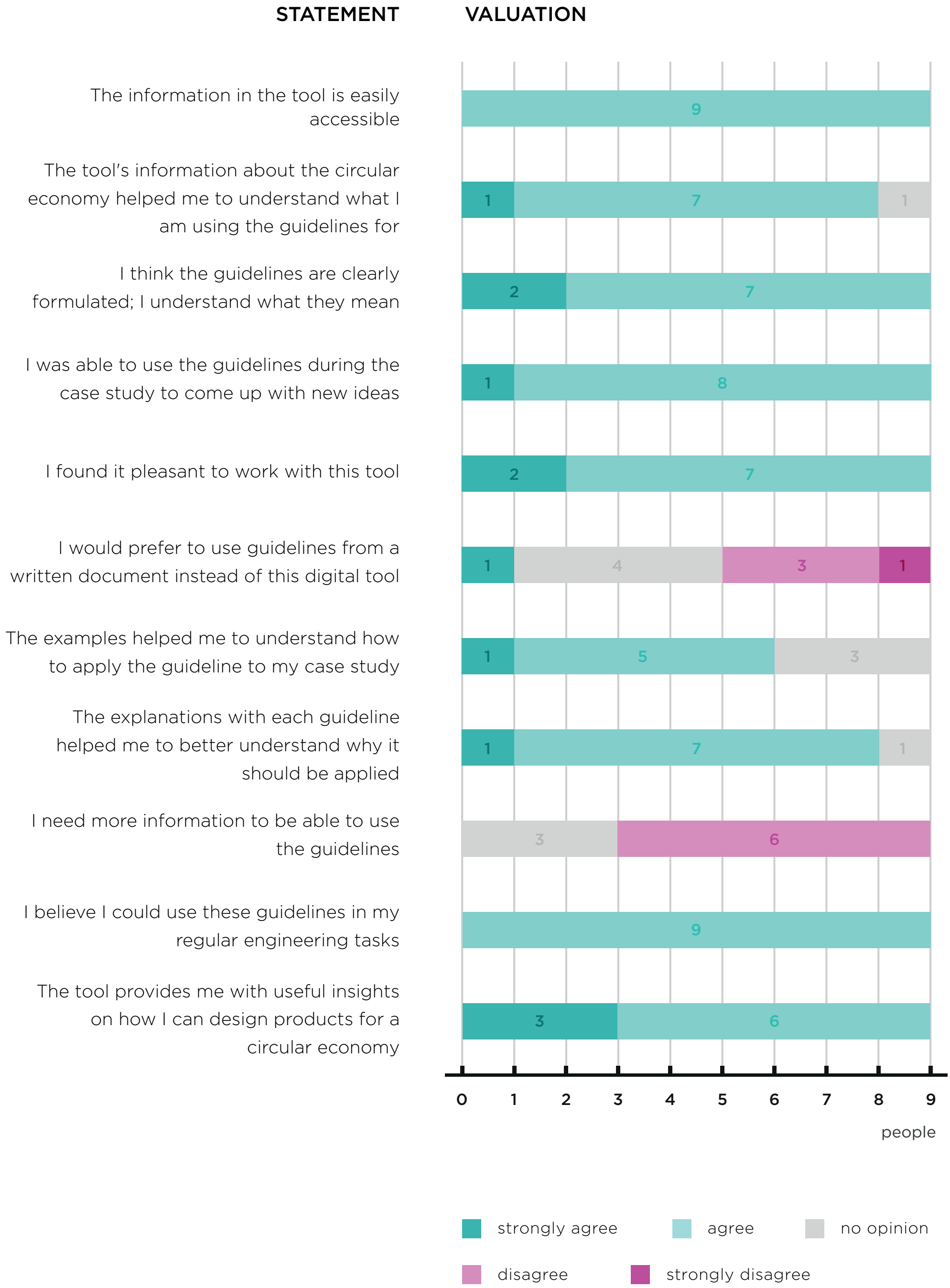


Figure 9.1 Evaluation results statement valuation.

- During the workshop, the tool sparked meaningful discussion amongst collaborating product engineers about how the application of particular guidelines influenced reverse cycle processes. They discussed the effects on for instance refurbishment compared to reuse and found that a guideline did not always present the optimum outcome for both processes. Moreover, some engineers identified conflicts with a product's lifespan and recognised the need for trade-off decisions.
- Participants worked on the case studies with enthusiasm and expressed positive response about the practical insights that the tool provided and the pleasant way of working with it.

As a final result, there is the outcome of the case study. At the end of the case study each group has delivered a clear description of their conceptual design proposal, supported by a specification of their process and design rationale. These results demonstrate the applicability of the guidelines and can be used as input for on-going or future development projects. Appendix W lists the design ideas that resulted from the case study.

Conclusion

Based on the test results, it can be stated that the tool can be intuitively used by the product engineers, without prior training or experience with the tool or circular product development in general. Product engineers found the tool's content to be accessible and the use experience to be pleasant. Users have demonstrated a considerable understanding of the guidelines and underlying philosophy, inspired by the tool but also credited to the abilities of the product engineer. This is reflected by lively discussions during the case study and the concrete design proposals that resulted from the case study. Based on these results and the personal assessment of the product engineers, it can be concluded that the guidelines provide useful and practical insights that are applicable to the development of domestic boilers. Product engineers have shown enthusiasm about using the tool and are willing to use it for their regular engineering tasks. This way, the design tool has been verified as an accessible and practical solution that is accepted by the user and leads to new and concrete design solutions for domestic boilers.

chapter

10

Conclusion

This research has started off to develop a tool for structurally considering sustainability in the product development process of Remeha. Adopting the circular economy as an approach to sustainable development, this research has centred around the question how to implement the circular economy in Remeha's product development process. This question has been addressed by three secondary research questions that will each be answered in the current chapter, leading to conclude this thesis.

What is the circular economy?

To understand the circular economy, it needs to be regarded with respect to the overarching notion of sustainable development. Sustainable development is understood as a strategy for organising temporal processes to realise a productive balance between society, environment, and economy. This perspective on pursuing sustainability argues not for a stagnation of growth but for adopting different ways to attain it. This perception aligns with society's demand for persistent technological progress and therefore with Remeha's intrinsic business interest in delivering that progress. There is a multitude of different concepts available to help organisations pursue the abstract notion of sustainable development. For this research, the circular economy has been adopted as a way to interpret and practice sustainable development at Remeha.

The circular economy is essentially an economic model that aims to use resources in fundamentally different and more effective ways. It offers a viable alternative to the currently predominant and wasteful economic system that extracts, uses, and disposes resources in linear way that builds value on high throughput. Inspired by concepts like Cradle to Cradle and Biomimicry, the circular economy proposes new ways for organising industrial processes to recover and restore the sources of energy and material that are used, so they can be used again. This research characterises the circular economy in terms of five fundamental principles: organise reverse cycles, be resource effective, think in systems, prioritise the future, and create mutual benefit. These principles combined, offer a holistic and accessible understanding of the circular economy that provides a basis for its implementation.

How should the principles of the circular economy be applied to Remeha's product development?

The fundamental principles of the circular economy offer a general and high-level description that is not directly applicable to the realm of product design. In order to apply the principles of circularity to Remeha's product development, they are translated into design strategies. A design strategy offers more specific and actionable ways to develop boilers for increased resource effectivity in a circular economy. Different design strategies represent varying approaches to increasing resource effectivity. Some focus at extending the product lifespan, some at recovering value from end-of-life products, and others at providing function in a less resource intensive manner. The relevance and effectiveness of a design strategy highly depends on the type of product and corporate environment to which it is applied. For this research, one specific design strategy was selected for further implementation, aiming to enable closed-loop resource flows by design. It allows to transform linear into circular flows and is expected to have a considerable impact to resource productivity. According to the design strategy, domestic boilers are designed so that the value they embed, can be recovered, restored, and used again through reverse cycle processes. It proposes four ways to do this: design for dis- and re-assembly, design for a modular architecture, design with recovered resources, and design for standardisation. Their combined leverage enables circular resource flows by design, which is an essential step towards realising the circular economy. It should, however, be recognised that this strategy represents a limited perspective on designing for a circular economy and thus results in boilers that are only partially optimised for resource effectivity.

To support of the adoption of a more resource effective approach to design, a new business model is developed. The business model no longer sells ownership of the boiler, but provides the customer access to warmth, which is delivered by a product-service combination. This new business approach allows financial and strategic benefit from developing boilers in a more resource-effective way, which aligns incentives for profitable and more sustainable development. This creates new opportunities to improve resource effectivity, it promotes the adoption of the circular economy as a strategic corporate aspect, and it stimulates broader support in the organisation. Eventually, this should also benefit the implementation of the design tool at the R&D department.

So, to apply the principles of the circular economy to Remeha's product development, they are translated into design strategies that can be realised through engineering activities. One design strategy is selected for further implementation, aiming to enable closed-loop resource flows by design. A new business model is proposed to support the adoption of a more resource effective approach to design with business incentive.

How can the development of boilers for a circular economy be supported by a dedicated tool for product engineers?
Remeha's product engineers are unfamiliar with developing boilers for closed-loop resource flows. Therefore, a digital tool has been developed to support product engineers in the early stages of development, when their decisions have the most significant impact. The tool's key principle of support is a coherent set of guidelines that is presented through an interactive and accessible user interface. The guidelines offer prescriptive recommendations to inform and inspire design decisions and are specifically formulated to be user-oriented, actionable, and to reflect a positive expression. The tool further supports the application of the guidelines by providing examples, informative resources, and background information on the circular economy. Formal stage gate deliverables of the product development process have been

supplemented to prescribe the consideration of value recovery and reutilisation from end-of-life boilers. Through these specifications, the tool and its underlying strategy for circular product development have been officially implemented in the product development process of the R&D Projects department. The usability of the tool and the applicability of the guidelines have been evaluated with nine product engineers from Remeha's R&D department. During the test session, the participants have applied the tool to redesign a boiler component for reuse, refurbishment, and recycling. Based on this evaluation, it can be concluded that product engineers are able to use the tool intuitively without needing an explanation on its workflow or functionality. They have shown to be able to understand the guidelines and apply them to generate new solutions for domestic boilers. Moreover, product engineers indicate unanimously that the tool is accessible and pleasant to work with and provides them with useful insights that are applicable to their regular engineering tasks.

These conclusions have answered how the circular economy can be implemented in Remeha's product development process. A characterisation of the circular economy in terms of holistic principles has been translated into the realm of product development through design strategies. Pursuing the implementation of the reverse cycle strategy, a design tool has been developed to support product engineers in realising this strategy through their design decisions. The tool has been confirmed to be applicable to the development of domestic boilers and to inspire new design solutions. This way, the result of this thesis meets Remeha's need for a way to structurally consider sustainability in their product development process.

chapter

11

Recommendations

This thesis has been been conducted from a specific scope and solution direction. The result has been concluded to meet Remeha's need for a more sustainable way of development, but the research results can be further improve upon and supplement beyond the scope of this thesis. This chapter discusses some recommendations for further development, relating to the function and implementation of the tool and more generally to the adoption of the circular economy at Remeha.

Commit to change

Implementing the circular economy in an organisation brings new ways of thinking and organising that are different from the established status quo. In order for these changes to have effect and bring benefit, it is essential that Remeha commits to pursuing circular objectives as an organisation and invests in structural change. This requires support from top management and alignment between departments. At this moment, the R&D department wishes to employ the tool, but cannot afford to prioritise circular product development as it no part of the official project deliverables or criteria. During this thesis, people in top management, like Remehas management board and the R&D manager of the BDR Thermea group, have been involved to encourage their support and commitment. They recognise the relevance of the circular economy and support the outcome of this thesis, only it takes more time to bring about official commitment and development objectives. Given the established basis of support, it is recommended that the R&D department continues to advocate the circular economy in the organisation. For instance, the manager of the Product Development department is aware of this research and recognises the circular economy as a movement in the market. A discussion between Product Management and R&D on the implications of the circular economy could lead to include development targets formally in the Detailed Product Request. Then, circular development becomes a justified endeavour and a priority in design.

Content management interface

The digital nature of the tool makes it flexible to change, which allows the tool to adjust to developing experience and needs of its users. However, the way the tool is developed now, its content is part of the coded HTML scripts. As a result, supplementing or changing content requires some experience with programming and knowledge about the tools particular code structure. Programming experience is available with the controls engineers of the R&D department, but not with the people that have so far been involved with the initiation, development, or implementation of this research.
In order to make the content management of the tool less dependent on specific knowledge, it is possible to expand the tool's interface with a content management interface. To this end, it seems sensible to store the tool's content in a database (like MySQL). Then, the user interface will access and display this data while the content management interface allows to manipulate this data. This functionality can be realised

with an additional HTML interface, JavaScript functionality and server sided scripting for data processing. This is a feasible development that can supplement the tool while preserving its current structure and functionality.

Support evaluation of boilers and design proposals

The tool that is developed for this research is meant support the development of new design solutions. Guidelines introduce new considerations into the development process that inform and inspire product engineers in their design activities. However, the tool does not provide a way to quantify or even judge the generated solutions based on their performance on increased resource effectivity. Such a valuation could support the selection and refinement of design solutions and is recommended as a focus point for future development. A structured and objective evaluation of design solutions could be facilitated by a specific tool. It could be integrated in the developed design tool or in Remeha's Alternative Solutions Table, which is commonly used tool (Excel sheet) to compare different design proposals. It is advisable to identify several indicators based on the adopted circular design strategy. A design solution can be scored on each of those indicators, for instance through a questionnaire that supports the user in determining an objective score. This is suggested as a possible approach, but further research should demonstrate what the best method and application is for evaluating solutions.

Develop a more structural implementation strategy

When Remeha commits to structurally developing products for a circular economy, it is recommended to implement the tool's underlying design strategy not only at the engineering level but also at the product strategy level in the R&D department. This requires the development of knowledge and the support of a dedicated methodology or strategic tool. Part of this product strategy could be to determine specific end-of-life objectives per product component, possibly formulated in a lifecycle scenario and included in the Product Roadmap. Focusing at the component level allows more specific strategies for end-of-life treatment and broader opportunities for reutilising value, which is expected to be more effective. The objectives could be expressed by KPIs (key performance indexes) and explicitly relate to the performance in end-of-life processes like refurbishment or recycling. An objective could for instance describe a target for a certain percentage or quantity of boilers of which a certain percentage of materials is recycled. Or it could formulate targets for the employability of refurbished components in the product portfolio. These objectives could be specifically related to the guidelines of the design tool, supported by further research on their effect on reverse cycle processes.

Adopt new design strategies in addition to the one proposed in this thesis
This research has focused on the implementation of a specific design strategy. As indicated in chapter 6, designing boilers for closed-loop resource flows is an important step towards realising a circular economy, but it is not the only way to increase resource effectivity through design. Other strategies have been presented in a design strategy model and can be adopted in addition to the strategy that has been elaborated by this thesis. It is advised that, when Remeha commits to developing boilers for a circular economy, other design strategies are reconsidered and further implemented. Especially an additional focus at optimising the product's lifespan is expected to offer considerable opportunities for using resources more effectively. This would require research on the optimum between economic and ecological lifespan and relates to strategies on the introduction of new technologies in anticipation of the energy transition. In this respect, an extended lifespan is not necessarily the most effective option and it would be fruitful to regard the lifespan not just of the complete products but of its modules and components, like referred to in the previous paragraph. Moreover, it is recommended to consider a redefinition of the product proposition from the perspective of the circular economy, possibly in combination with a new value proposition. Whereas this thesis supports more incremental development, such approach would lead to more revolutionary ideas that are expected to present considerable opportunities for increasing resource effectiveness.

Implement the principles of circularity in areas of business and supply chain
The research has focused on the influence of product design in the circular economy, but it has recognised the necessity to mobilise areas of supply chain and business model as well. Only when all three areas are mobilised and aligned, can the true potential of the circular economy be realised. This research has aimed to include the business area by proposing a new business model that allows benefit from end-of-life strategies. Further developments in this area are required to further align the value proposition to the market, to organise the leasing structure, and to translate the new value proposition into specific objectives in design. In the area of supply chain management, collection and treatment systems should be organised to actually recover and restore value from end-of-life boilers. Remeha already runs a refurbishment programme on small scale and is exploring other opportunities to organise reverse cycle processes. These initiatives should be further built upon and organised in close collaboration with partners. Also, it is essential that departments in the different areas of Remeha's organisation collaborate and align their initiatives and processes to a shared vision and objective.

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appendix

Developing a dedicated tool to support the development of domestic boilers for a circular economy

Master thesis Industrial Design Engineering

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appendix

Developing a dedicated tool to support the development of domestic boilers for a circular economy

Master thesis Industrial Design Engineering

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APPENDIX A
European legislation on sustainability

Legislation presents an important driver for Remeha to consider sustainability concerns with respect to their development. This appendix describes several European directives and initiatives that relate to sustainability concerns, like pollution or global warming. The European Commission's Circular Economy Package even specifically translates the principles of the circular economy into legislation.

WEEE Recast Directive (2012/19/EU)
Collect and properly treat waste from electrical goods to reduce waste
Waste of Electrical and Electronic Equipment (WEEE) includes a diverse waste stream of electrical goods, like laptops, lighting, fridges, medical devices, and vacuum cleaners. The WEEE Recast Directive aims to improve the management of WEEE and to "contribute to a circular economy and enhance resource efficiency" (European Commission, 2016).

The first WEEE Directive (2002/96/EC) was introduced in February 2003. In response to fast-growing waste streams, a revised directive (2012/19/EU) became effective in February 2014. The directive states that the manufacturer (Remeha) or distributor of electrical equipment is responsible collecting and properly treating end-of-life equipment that was placed on the market after 2005. Collection should be organized in a way that is free of charge and accessible to the end user. Proper treatment should be interpreted as processes aimed at recovering value, for instance recycling or reuse.

Several product categories are identified to which the directive applies and for which specific recovery and recycling/reuse targets rates are formulated. The European Directive does not specifically mention boilers as Electrical and Electronic Equipment (EEE). However, the Dutch Ministry argues that even though a boiler's primary heat source is gas, the product requires electricity to function and should therefore be seen as EEE. Consequently, boilers should be classified under Large Household Appliances in the category of "other large appliances for heating rooms, beds, seating furniture".

The WEEE Recast Directive sets targets for the collection and recycling of all kinds of electrical goods. The most recent directive formulates targets for two timeframes: from Augustus 2015 to Augustus 2018 and from Augustus 2018 onwards (European Parliament & Council of the European Union, 2012).

- 2016 to 2018: collect and properly treat 45% of EEE put on the market*
- 2019 onward: collect and properly treat 65% of EEE put on the market*
  ** calculated on the bases of the total weight of WEEE collected in relation to the average weight of EEE put on the market in the three preceding years.*

The complete list of targets for different product categories of WEEE can be found in Article 11 of the WEEE Recast Directive 2012/19/EU. The scope of the Directive will be extended from January 2019 to cover a broader scope of electrical equipment.

RoHS Recast Directive (2011/65/EU)

Restrict the use of hazardous substances in electrical goods

In addition to the WEEE Recast Directive, the Restriction of Hazardous Substances (RoHS) Recast Directive (2011/65/EU) specifically aims to manage the use of harmful substances in Electric and Electronical Equipment (EEE). As there is a substantial and increasing amount of waste from EEE (see previous section on WEEE Recast Directive), hazardous substances impose an increasing risk to environmental systems and human health. Moreover, controlling the use of hazardous substances is likely to increase the potential of recycling waste from EEE (European Parliament & Council of the European Union, 2011). This way, the RoHS and WEEE Recast Directives are meant to work in cohesion.

The directive describes a list of specific substances that are restricted from use in Electrical and Electronic Equipment. The RoSH Recast Directive (2011/65/EU) mentions six substances that are to be regulated, four heavy metals and two flame retardants:

- Lead (Pb);
- Mercury (Hg);
- Cadmium (Cd);
- Hexavalent Chromium (chromium VI, Cr^{+6});
- Polybrominated bephensyls (PBB);
- polybrominated diphenyl ethers (PBDE).

An amendment of the RoSH Recast Directive (2011/65/EU) has recently been accepted in March 2015, introducing four additional restricted substances:

- Bis(2-ethylhexyl) phthalate (DEHP)
- Widely used as a plasticiser (for instance in PVC) in food packaging and products like shower curtains, garden hoses, rainwear, toys and shoes.
- Butyl benzyl phthalate (BBP)
  Used as a plasticiser for vinyl foams or PVC. Applications are floor tiles, food conveyor belts, and artificial leather.
- Dibutyl phthalate (DBP)
- Commonly used as a plasticiser and as an additive to adhesives or printing inks
- Diisobutyl phthalate (DIBP)
  Odourless plasticiser that has excellent heat and light stability. Can be used as a substituted for DBP, but has lower density and freezing point.

The specified substances are restricted to a maximum concentration of 0.1% (1000 ppm) by weight per homogeneous material. This implies that the limits apply to any single substance that can be mechanically separated, not to the weight of a component or finished product. Cadmium is an exception and is only permitted to be applied at maximum concentrations of 0.01% (100 ppm).

REACH Regulation (EC No 1907/2006)
Restrict the overall use of hazardous chemical substances and commit to registration
Registration, Evaluation, Authorisation, and Restriction of Chemicals (REACH) addresses the production and application of chemical substances in relation to their impact on human and environmental safety. The European regulation entered into force in 2007 (with phased implementation over 9 years) and is managed by the European Chemicals Agency (ECHA). The difference with the RoHS Recast Directive is that REACH focuses merely at chemical substances, but it applies to the total industry rather than to specific electrical and electronic equipment. REACH describes an elaborate list of restricted chemicals. Companies using these substances are obliged to register with the ECHA and prove their compliance with permitted concentrations. Annex XVII of the REACH Regulation contains the list of substances which are restricted or even banned under the regulation.

Besides these restricted substances, the ECHA maintains a list of Substances of Very High Concern (SVHC). Listing a substance as a SVHC is the first step in the official procedure of restricting the use of a chemical. Annex XIV of the REACH Regulation contains a list of SVHCs that are subject to authorisation by the EACH, both for import and application in the EU. Additionally, the ECHA maintains a public SVHC Candidate List. All substances placed on this list are candidates for inclusion in annex XIV of the REACH Regulation

ErP Directive (2009/125/EC)
Reduce product's energy consumption along the lifecycle
The European Directive for Energy related Products (ErP) targets products that use, generate, or transfer energy or products that do not use energy, but have an indirect impact on energy consumption (like windows or water-saving taps). The ErP Directive primarily aims to reduce energy consumption along the product lifecycle, but also touches upon other environmental considerations including water use, material use, and pollution. Thus, it specifically addressing the Europe 2020 strategy objective of 20% reduced energy consumption by 2020. The directive prescribes requirements for product design and energy labelling through two specific directives: the Ecodesign Directive and the Energy Labelling Directive.

Ecodesign Directive
The European Commission's Ecodesign Directive (2009/125/EC) aims to stimulate manufacturers to reduce a product's energy consumption and environmental

impact at the design phase. The directive establishes a framework to set out minimum requirements for the energy efficiency of products. It does not prescribe explicit standards itself. Instead, specific implementing measures are formulated for particular product groups, like dishwashers, televisions, and heating appliances. The measures apply to the manufacturer of the product. Since the introduction of the Ecodesign Directive (2009/125/EC) in 2009, implementing measures have been adopted continuously, gradually increasing the number of product groups that is covered by the directive. In 2015, an implementing measure was adopted for all heating and hot water products with heat outputs between 70kW and 400kW (EU Regulation No 813/2013). Consequently, heating products developed by Remeha and BDR Thermea must comply with this regulation in order to be sold in the European Union. The requirements for boilers are specified in table A1.

Table A1 EcoDesign requirements for the heating efficiency of boiler products.

	Ecodesign requirements
Boilers with rated heat output £70kW	Minimum seasonal heating efficiency is 86% GCV*
Boilers with rated heat output >70kW and £400kW	Minimum useful efficiency at 100% of the rated heat output is 86% GCV* Minimum useful efficiency at 30% of the rated heat output is 94% GCV*

* gross calorific value

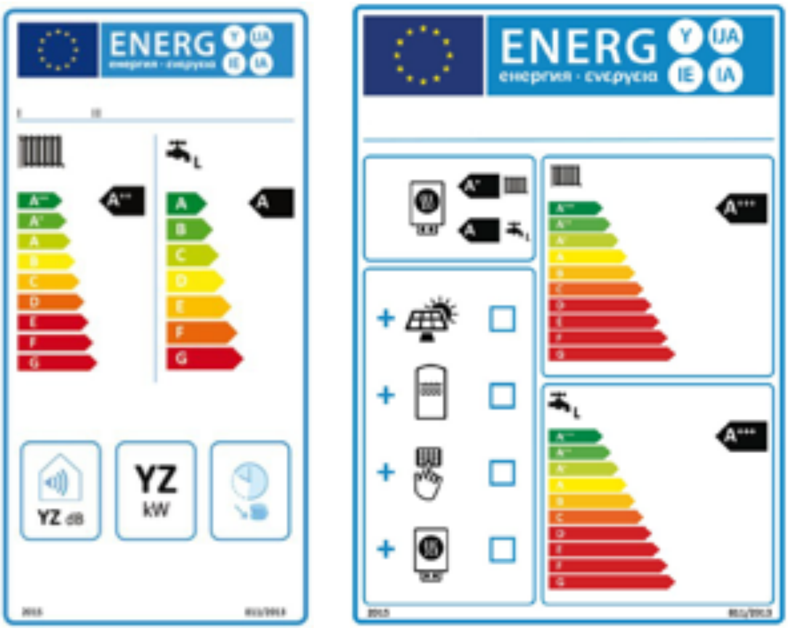
Additionally, requirements for the maximum emission of nitrogen oxides are set and require compliance from 26 September 2018: 56 mg/kWh fuel input in terms of GCV for gas-fuelled boilers. Also maximum sound power levels for heat pumps are prescribed.

Energy Labelling Directive

The Energy Labelling Directive (2009/125/EC) complements the Ecodesign Directive (2009/125/EC) by formulating requirements for product energy labelling, which are often adopted alongside Ecodesign implementing measures. The directive aims to support customers in the selection of energy efficient products and to promote their understanding of these efficiencies. Concurrent with the adoption of Ecodesign requirements in 2015, the Regulation (EU) No 811/2013 entered into force, setting standards for labelling space and water heaters. The regulation prescribes heating products and systems to be rated from A+++ to G based on their energy efficiency. Two energy labels are required:

- Product label for the boiler, showing the boiler's space heating and/or water heating efficiency (figure A1a). The product manufacturer is responsible for providing the Energy Label for the product.

- Package label for the installed heating system, showing the space heating and/or water heating efficiency of the entire installation, taking into account how the system is controlled and if it is combined with other components like solar heating (figure A1b). The installer is responsible for calculating system's efficiency and providing the Energy Label for the heating system.



(a) (b)

Figure A1 product label for a boiler (a) and package label for heating system (b).

Renewable Energy Directive (2009/28/EC)

Promote the use of energy from renewable sources in the European Union

The European Commission's Renewable Energy Directive (2009/28/EC) prescribes a policy for the production and use of energy from renewable sources in the European Union. According to the directive, the European Union should meet at least 20% of its overall energy demand with renewable sources by 2020. This should be achieved through the collective realisation of binding country-specific targets. Based on the member state's initial starting points, renewable energy potential, and economic performance the individual national targets vary from 10% in Malta to 72% in Iceland. The Netherlands have committed to a share of 14% renewable energy use, yet had only realised a share of 5.5% in February 2016, a mere 3.1% increase since 2005 (Eurostat, 2016). Additionally, every EU member state must ensure that at least 10% of its transport fuels is sourced from renewables by 2020. It enforces the Europe 2020 strategy's target of realising an overall share of 20% energy from renewables in Europe. By reducing the use of fossil energy sources, the directive furthermore contributes to a reduction of GHG emissions.

European Commission's Circular Economy Package

Closing the loop of product lifecycles

In December 2015, the European Commission adopted the Circular Economy Package. It aims to stimulate Europe's transition towards a circular economy in order to promote competitiveness, economic growth, and employment opportunities. The package includes revised legislative proposals on waste and an EU Action Plan containing concrete steps to be undertaken by the European Commission. Overall, the Circular Economy Package focuses at utilising maximum value from resources and (end-of-life) products and thereby realise energy savings and reduced GHG emissions. Proposed measures cover the whole cycle from production and consumption to waste management and secondary raw materials.

The revised legislative proposals on waste set clear targets for reduction of waste and establish an ambitious and credible long-term path for waste management and recycling. Some key elements of the revised waste proposals include:

- Recycle 65% of municipal waste and 75% of packaging waste by 2030;
- Reduce landfill to maximum of 10% of municipal waste by 2030;
- A ban on landfilling of separately collected waste;
- Simplified definitions and harmonised calculation methods for recycling rates in the EU;
- Concrete measures to promote re-use and stimulate industrial symbiosis - turning one industry's by-product into another industry's raw material;
- Economic incentives for producers to put greener products on the market and support recovery and recycling schemes.

The EU Action Plan argues that the adoption of the circular economy through the proposed action plan increases coherence of European policies and is instrumental (and possibly essential) to the realisation of EU Member States' commitments, like the United Nations' 2030 Agenda for Sustainable Development (particularly goal 12 of ensuring sustainable consumption and production patterns) and the G7 Alliance on Resource Efficiency (European Commission, 2015). The EU Action Plan outlines several measures that are planned for further elaboration or implementation in the future (European Commission, 2015). Such measures include:

- Develop product requirements relevant to the circular economy under the Ecodesign Directive, promoting the durability, upgradability, reparability and recyclability of products;
- Provide economic incentives for better product design and extend producer responsibility;
- Provide guidance on best waste management and resource efficiency;
- Develop quality standards for secondary raw materials and help research on material flows;

- Step-up action to mobilise stakeholders on the circular economy and support the development of circular economy projects;
- Develop a monitoring framework for the circular economy to measure progress effectively on the basis of reliable existing data.

These measures will be developed and implemented over the course of several years with regular updates on progress, deliverables and future (short-term) focus areas. The latest publication on this action plan was published on 26 January 2017, indicating a priority in 2017 on the Plastic Strategy (enhancing reuse and recycling opportunities), the monitoring framework, and development of the Ecodesign working plan to focus on resource efficiency beyond energy efficiency (Commission, 2017).

Europe 2020

A strategy for smart, sustainable and inclusive growth

In 2010, the European Commission accepted the Europe 2020 strategy as a succession to the Lissabon strategy. It is a long-term strategy spanning 10 years to realise a robust and sustainable European economy. The Europe 2020 strategy focuses on three priorities, supported with headline targets (European Commission, 2010):

- Develop an economy based on knowledge and innovation
    - 3% of the EU's GDP should be invested in R&D.
- Promote a resource-efficient, green and competitive economy
  Targets on this priority are adopted from the 2020 Climate and Energy Package that was accepted by the European Commission to combat climate change and increase energy security and became law in 2009. The package's key targets, also known as the 20-20-20 targets, are formulated as follows:
    - Reduce energy consumption with 20% compared to 2005 levels
    - 20% of total energy consumption should be from renewable sources
    - Reduce GHG emission with 20% compared to 1990 levels
- Foster a high-employment economy that promotes social cohesion
    - 75 % of the population aged 20-64 should be employed.

Member states of the European Union are expected to translate European priorities and targets to national targets, based on different starting points on priority topics.

2030 Climate and Energy Framework

The 2030 Climate and Energy Framework seeks to drive continued progress towards a low-carbon economy and a secure energy system. It builds on the 2020 Climate and Energy package, proposing more ambitious targets to be realised by 2030 in the same three areas:

- At least 40% cuts in greenhouse gas emissions (from 1990 levels)
- At least 27% share for renewable energy
- At least 27% improvement in energy efficiency

The framework was adopted in 2014 and aligns with the longer term perspective set out in the Roadmap for moving to a competitive low carbon economy in 2050, the Energy Roadmap 2050 and the Transport White Paper.

APPENDIX B

Concepts for sustainable development

This appendix presents an overview of different concepts for sustainable development, describing their goals and contribution to the three sustainability dimensions (social, environmental, and economic). The relations are indicated by symbols: 🟢 = full contribution, 🟠 = limited contribution, 🔴 = no contribution.

Table B.1 Concepts for sustainable development

Method	Goal	so	env	ec	Literature
Biomimicry	Approach to innovation that applies ecological concepts to the development of industrial systems to create products, processes, and systems that are adapted to life on earth in a sustainable manner. It resolves conflict between nature and technology	🔴	🟢	🔴	Benyus (1997); Kibert (2008)
Blue economy	Succeeds the green economy by stimulating the evolutionary path (growth and regeneration) of environmental and economic systems. Create entrepreneurial opportunity to eliminate waste, increase productive capacity and achieve full employment to realise a shift to a macro-economic system.	🔴	🟢	🟢	Pauli (2010)
Carrying Capacity	Quantify the environment's capacity to support a (regional or global) population and its activities within the limits of the ecosystem and without degrading the social and economic environment.	🟠	🟢	🔴	Kibert (2008)
Circular Economy	Establish a circular model for economy in which material and energy resources are circulated at maximised utility to eliminate waste and develop a regenerative mechanism. Enable the private sector in achieving this transition through a framework for systems level product design and new business models to balance environmental preservation with social and economic growth.	🟠	🟢	🟢	Ellen MacArthur Foundation (2012)
Cleaner Production	A systematically organized approach to production activities, which has positive effects on the environment. These activities encompass resource use minimisation and improved resource productivity and energy efficiency.	🔴	🟢	🟢	Glavič and Lukman (2007)

Corporate Social Responsibility (CSR)	A management concept to expand a business' responsibility and efforts beyond its own benefit and operations to improve social and environmental benefit. CSR relates to ISO14000 certification.	●	●	●	
Cradle to Cradle	Provide a design paradigm for industrial design to create a closed-loop system of material flows that accommodates the reuse of resources in a way that creates positive ecological effects rather than reduces negative impact.	●	●	●	McDonough and Braungart (2002)
Eco-design; Environmentally Conscious Design (ECD); Design for Environment (DfE)[1]; Green design	Integrate environmental aspects into product design to improve the environmental performance of the product throughout its whole lifecycle while meeting consumer needs and business-oriented design goals. Aims to realise recycling and reuse through front-loaded design. Tools shift focus between management and design practice.	●	●	●	Karlsson and Luttropp (2006)
Eco-efficiency	Deliver competitive goods and services that satisfy human needs while progressively reducing ecological impacts and resource intensity throughout the life cycle, to a level at least in line with the earth's estimated carrying capacity. Emphasises production processes and services.	●	●	●	Glavič and Lukman (2007)
Ecological Footprint (EF)	Assess and quantify human impact on eco-systems by comparing society's natural resource consumption with nature's ability to provide for this consumption. CO_2- and water footprint are based on this concept. Footprint is expressed in ecological area and is the inverse of carrying capacity.	●	●	●	Rees and Wackernagel (1996); Robèrt (2000)
Ecological Management Systems (EMS)	Administrative business tool to control and improve an organisation's environmental performance through business management. A widely accepted system is described by ISO 14001 and EMAS	●	●	●	Robèrt (2000)

1 Bhander, Hauschild, and McAloone (2003) argues that Eco-design, Environmentally Conscious Design, and Design for Environment are all based on the same concept.

Ecological Rucksack	Determine the resource productivity by quantifying the units of natural resources used to produce one unit of material. The rucksack indicator represents a factor of mass. Intends to demonstrate that human activities are only achieved through the destruction of natural resources.	🔴	🟢	🔴	Kibert (2008); Robèrt et al. (2002)
Factor X	Approach for monitoring activities aimed at reducing the materials and energy usage of diverse industrial and societal processes to achieve quality of life while limiting environmental degradation. Factor X represents X times more efficient use of resources in the future as compared to the usage today. Common concepts are factor 4 and factor 10.	🔴	🟢	🟠	Robèrt et al. (2002)
Global Warming Potential (GWP)	A relative measure to quantify the amount of heat a greenhouse gas traps in the atmosphere, commonly expressed in CO_2 equivalent	🔴	🟢	🔴	Intergovernmental Panel on Climate Change (IPCC) (1990)
Industrial ecology	Optimise resource consumption within the industrial system and across supporting ecosystems by studying material flows and their effects to surrounding systems and thus improve and maintain environmental quality. Considers ecosystems a model for industrial activity and focus on the interrelations in the industrial system.	🔴	🟢	🟢	Lifset and Graedel (2002)
Life Cycle Analysis (LCA)	Assess and quantify the environmental impact of a product design through systematic assessment of the product life cycle.	🔴	🟢	🔴	Bhander et al. (2003)
Life Cycle Engineering and Design	Focusing product development on designing the product life cycle through choices about product concept, structure, materials and processes. LCA visualises the consequences of these choices. Builds on the principle of product stewardship which extends a manufacturer's responsibilities beyond its own operations to the complete product life cycle.	🔴	🟢	🔴	Alting (1995)
Life Cycle Sustainability Analysis (LCSA)	Assess (and quantify) sustainable development across its social, economic, and environmental dimensions through a transdisciplinary integration framework of models (S-LCA, LCC, and LCA) that describes the complex mechanisms and linkages between dimensions.	🟢	🟢	🟢	Zamagni, Guinée, Heijungs, and Masoni (2012)

Material Intensity Per Service unit (MIPS)	Assist in understanding the efficiency of material usage by relating the material intensity to the service delivered by the product. Can be used to expand LCA towards a wider sustainably assessment and is an indicator for eco-efficiency.	🔴	🟢	🔴	Kibert (2008); Robèrt et al. (2002)
Natural Capitalism	Define and describe means to connect human institutions including business within the flow of natural cycles including ecosystem services. It describes a set of fundamental assumptions necessary for the integration of economy, ecology and societal demands in economic decision making	🔴	🟢	🟢	Lovins, Lovins, and Hawken (1999)
Total Material Flow (TMF)	Knowledge of total material flows within a specified period of time and for defined economic areas (e.g. country or region) can be used to monitor dematerialisation at a macro- economic level.	🔴	🟢	🔴	Robèrt et al. (2002)
Triple Bottom Line	A framework to address the social and environmental dimensions in relation to business to achieve environmental progress and evaluate business performance on sustainability. Focus on balancing the negative effects of the conflicting dynamics between economy, environment, and society.	🟢	🟢	🟢	Elkington (1994); Hall (2011)
Triple Top Line	An accounting framework that focus on design and value creation through products to enhance the well-being of nature and culture while generating economic value. Rather than balancing negative effects, it aims to maximize value through the dynamics of economy, environment, and society	🟢	🟢	🟢	McDonough and Braungart (2002)
Waste hierarchy	Prioritise strategies of resource handling through a hierarchy for managing and minimising waste. (e.g. 3R: Reduce, Reuse, Recycle)	🔴	🟢	🔴	
Zero-waste	A holistic approach to design and manage products and processes systematically to recover all resources from the waste stream and thus minimise waste towards zero. It not only encourages recycling of products but also aims to restructure their design, production and distribution to prevent waste emerging in the first place.	🔴	🟢	🔴	Zaman and Lehmann (2013)

APPENDIX C

Evaluating approaches & frameworks for sustainable development

The sustainable development initiatives that have been classified in the approach & framework class are evaluated to identify one most meaningful to be adopted by Remeha. For a structured and objective evaluation, the approaches are rated against four criteria:

1. Accommodate all three dimensions of sustainable development: society, economy, and environment (Elkington, 2004);
2. Provide a strategic framework for sustainable development that can be translated to implementation in Remeha's product development process.
3. Allow a pro-active position in sustainable development to anticipate societal and political movements.

A grading method is applied to rate how the approaches align to each criterion. The grading scale is determined to range between 1 and 3, 1 being the lowest score and 3 the highest. This scaling is assumed to allow a sufficient level of distinction, without exaggerating the level of detail. Multiple approaches can be assigned equal grades. The approach with the highest cumulative score on all criteria, proves the best choice as a strategic framework for this research.

Table C.1 scoring of approaches & frameworks on the four evaluation criteria.

Concept	1	2	3	Total score
Biomimicry	1	3	2	6
Blue Economy	2	2	2	6
Circular Economy	**2**	**3**	**3**	**8**
Cleaner Production	2	2	2	6
Cradle to Cradle	1	2	2	5
Eco-design	1	3	3	7
Industrial Ecology	**2**	**3**	**3**	**8**
Natural Capitalism	2	2	2	6
Zero-waste	1	3	2	6

On the criterion of addressing all sustainability dimensions, concepts score differently and overall low. While it is generally recognised that all three dimensions are interrelated and important to consider, most initiatives focus at one or two dimensions. Cradle to cradle places primary focus on environmental aspects of sustainability. Circular economy regards sustainable development more broadly, aiming at environmental and economic aspects and recognising, but not yet concretely managing, the social dimension.

For the second criterion, approaches are graded at how they specifically align with Remeha's product development. A concept like circular economy is particularly fitting, since it aims to organise industrial processes to realise both economic and sustainability advantage. Biomimicry is in this respect less suiting since the connection between industrial and natural processes is often abstract and business aspects are not addressed.

All approaches contribute to a pro-active position on sustainable development fairly well. Circular economy and eco-design are graded highest, because they are specifically related to legislative developments. For instance, the Eco-Design Directive that is part of the ErP guidelines and the Circular Economy Package that has been adopted by the European Commission (see appendix A for more information on legislation).

Lastly, it should be noted that the high-scoring approaches actually share similar characteristics and do not contradict each other. The framework of circular economy incorporates principles that are shared by industrial ecology, blue economy, and natural capitalism, just to name a few.

APPENDIX D
Product portfolio Remeha

The brand Remeha offers a diverse range of heating solutions to the market. In general, every product delivers heat for either domestic or commercial application. Varieties between products arise from a difference in energy input (like electricity, solar, or gas), difference in output (tap water or heating system), and heating capacity. Figure D.1 shows the different product categories that make up Remeha's total product portfolio. The different techniques are briefly elaborated in this appendix.

1. **Micro-CHP:** Combined heat and power (CHP) systems generate both heat and power from a single source (like eVita). These units meet the demand for space heating and hot water while providing electricity to supplement or replace the grid supply. Micro- CHP refers to small-scale application for individual buildings.
2. **Wall-hanging boiler (WHB):** A boiler supplies central heating and warm water to a domestic or commercial building. Wall-hanging boilers are typically used for domestic applications (like Avanta, Calenta and Tzerra), but can supply high power in a cascade setting for commercial use (like Quinta Ace).
3. **Regulator:** Several solutions are offered for controlling the heating system, like Remeha's eTwist smart thermostat. Specific regulators are available for modulated control of cascaded systems.
4. **Floor-standing boiler (FSB):** A boiler supplies central heating and warm water to a domestic or commercial building. Floor-standing boilers are traditionally used for commercial applications (like Gas 210). In general, their heating capacity is higher relative to wall-hanging boilers.
5. **Hybrid solution:** Hybrid solutions improve the energy efficiency of the boiler by combining it with a heat pump.
6. **Solar thermal:** Solar energy is used to heat up water for domestic use. It can supply 60% of the home's annual hot water demand. The solar thermal system consists of three parts: the collector obtains solar energy, the controller transfers solar energy to thermal energy for heating water, and the water tank contains the heated water. The water flows from the tank, through the boiler, to the system.
7. **Water heater:** A water heater provides hot water for sanitary use and can operate stand-alone or in combination with a central heating boiler. The water can be heated directly by an electric or gas-fired immersion heater, or indirectly by a heating coil that is warmed by an external boiler, heat pump, or solar system.

Figure D.1 Product types in Remeha's portfolio.

APPENDIX E
Main boiler components and their functionality

This appendix offers an explanation of the boiler by means of a schematic overview of primary components, presented in figure E.1. The water flows are represented by blue (cold water) and red (warm water) lines. The black lines represent other flows, like condensate or exhaust fumes.

The components that are mentioned in figure A, are briefly described below. The numbers for each component refer to the numbers in figure A.

- **Gas-air unit:** Creates a mixture of gas and air, which is the fuel for the burner. A fan creates an airflow to suck in air from the (outdoor) environment. Gas is pulled to this airflow through a pressure difference (venturi-effect).
- **Primary heat exchanger:** The gas-air mixture is burnt in the combustion chamber whose walls function as the heat exchanger. Water flows around the combustion chaimber and absorbs the heat.
- **Secondary heat exchanger:** The heat exchanger that warms the tap water. Its heat comes not from gas combustion, but from warm water that is first heated in the primary heat exchanger
- **Pressure vessel:** Compensates for any pressure variation in the heating system. It is connected to the heating system circulation, but the water does not flow through it.
- **3-way valve:** Determines the water flow. Either the central heating system flow is active, or the secondary heat exchanger flow is active, but not both at the same time
- **Pump:** Drives the water through the system.
- **Syphon:** Prevents the exhaust air to leave the system through the water drain.

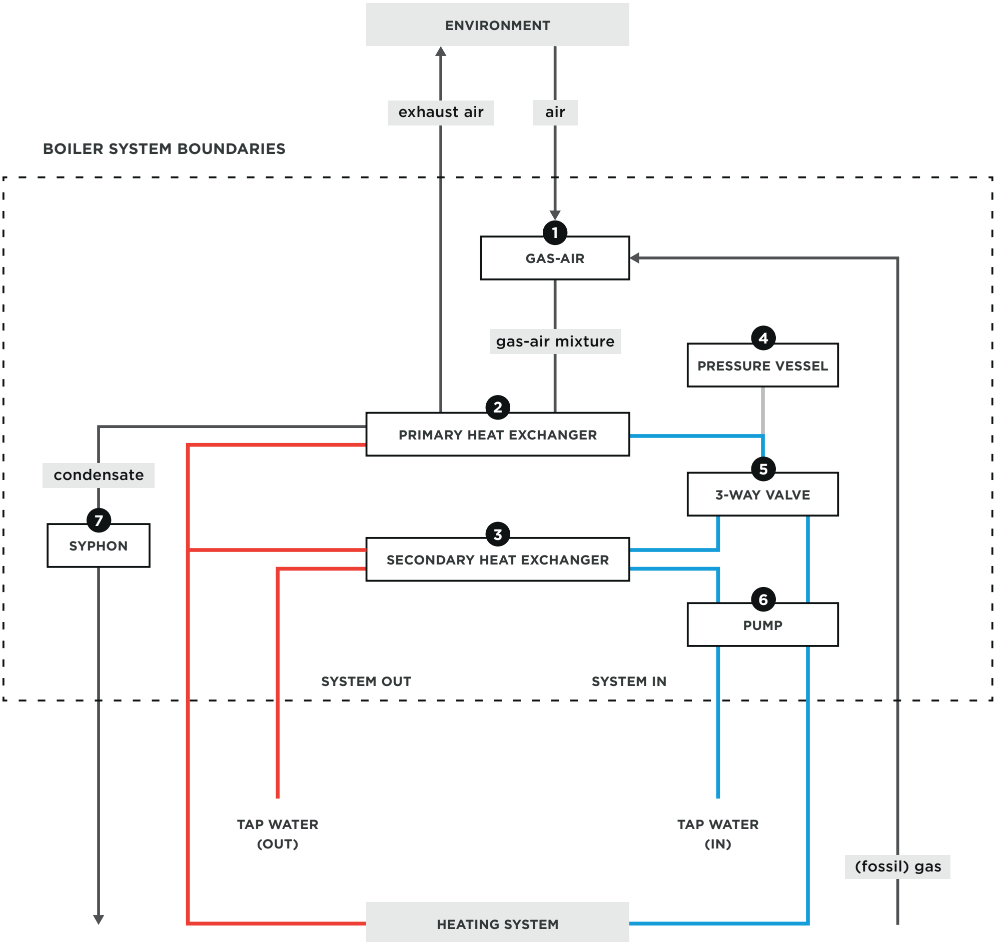


Figure E.1 Schematic overview of primary boiler components.

APPENDIX F

New Product Development (NPD) process BDR Thermea

NPD PROCESS STAGES ▶ / WORK STREAMS ▼	0 CUSTOMER NEED	1 PRODUCT DEFINITION	2 DESIGN CONCEPT	3 DESIGN ASSESSMENT
VOICE OF THE CUSTOMER	Project rationale and customer leaflet	VOC translated into high level requirements	Technical response on requirments and handschake on DPR	Customer feedback on prototypes
BUSINESS CASE	Project rationale	Business case made base on project estimations	Business case signd off by relevant MDs	Business case updated based on current insights
CONCEPT DEVELOPMENT			Physical concept is chosen and built	Product and component specifications made
PRODUCT VALIDATION			Validation plan defined	Product risk analysis (DFMEA) executed
SUPPLY CHAIN MANAGEMENT				Supplier long list made
INDUSTRIALISATION		Production location selected		Prototypes built and factory location layout defined
PREPARATION FOR LAUNCH				
PROJECT COORDINATION	Sponsor and project manager appointed	Stage Gate 2+7 dates estimated	Project team established, resources commited and targets set	Project reviewed against approved targets

Abbreviations: Voice Of the Customer (VOC), Detailed Product Requiest (DPR), Managing Directors (MDs), Enterprise Resource Planning (ERP), First Out of Tooling (FOT).

Source: BDR Thermea (2016) A practical guide to BDR Thermea's New Product Development process

4 DESIGN COMPLETION	5 INDUSTRIAL-ISATION	6 VALIDATION	7 LAUNCH PREPARATION	8 POST LAUNCH
Customer feedback on final design				Customer feedback on actual product
Business case updated based on current insights	Business case updated based on current insights	Business case updated based on current insights	Business case updated based on current insights	Post launch review executed
Specifications updated and design frozen	Specifications updated (fine tuning)	Specifications updated (final)		
Technical field trial started	Field trial started	Product approvals completed, field trial feedback evaluated	Validation plan finalised	Quality figures reviewed
Supplier selection completed	Logistics plan defined	ERP master data filled	Supply chain running according to forecast	
Prototypes built and process risk analysis (PFMEA) executed	Products built with FOT components and production process audited	Products built with finetuned components, final production BOM available	0-series built and manufac-turing process released	Series produc-tion running
Training plan and logistics phase-in/phase-out plan made	Market launch plan made	Internal training carried out	Products released for delivery	
Project reviewed against approved targets	Project reviewed against approved targets	Project reviewed against approved targets	Products releas-ed for introduc-tion and project reviewed against targets	Project reviewed against targets

APPENDIX G
Business environment Remeha

This appendix presents an elaborate analysis of Remeha's current business environment, highlighting trends and forces that could bring challenges or opportunities. These trends and forces are described in the four categories of the business environment map: key trends, market forces, macro-economic forces, and industry forces.

Key trends

- Customers prefer access over ownership
  A disruptive trend in the consumer market reveals a new generation of consumers that is willing to prefer access over ownership. This shift is demonstrated by an increase of shared cars, machinery, and daily commodities (Ellen MacArthur Foundation, 2012) and is supported by sharing platforms such as Snappcar, Airbnb, and Peerby.
- (driver) Customer needs are increasingly aimed at sustainable products as the public awareness of environmental and social responsibility is growing (Bevilacqua, Ciarapica, & Giacchetta, 2007). Remeha recognises this societal shift towards sustainable awareness and has received specific requests from clients regarding their product's sustainable character.
- Changing perception of value: include environment and social
- Internet of things: connectivity and smart domotics
- Legislation is increasingly oriented at environmental concerns (driver)
  European and Dutch governments are increasingly concerned with sustainability issues and direct their policies to address these issues. Mostly aiming at environmental aspects,
- legislation shifts focus towards product development, which increases pressure on manufacturing industries to develop sustainable products (Maxwell & Van der Vorst, 2003). Examples of relating legislative restrictions can be found in the Waste Electrical and Electronics Equipment (WEEE) and Restriction of Hazardous Substances (RoHS) directives that aim to limit environmental impacts through waste management and material use respectively. The Dutch Government aims to position the country as a circular economy hub and is developing knowledge and measures to enhance the country's resource productivity.
  On a global scale, industry is stimulated to reduce GHG emissions and even proposals for a different tax system, taxing resource consumption rather than labour, find regard in politics.
- Technological development: trace and return systems, advanced recycling, user-centred design and co-creation

Market forces

- High-efficiency condensing boiler is mostly evolved on primary functionality. Efficiencies can hardly be increased within the current product proposition; only minor gains can be achieved on domestic hot water (DHW) efficiency. Secondary product features – like usability, connectivity, and additional functionality – become more important to the end user.
- The energy market undergoes a transition from fossil fuel-based to renewable energy sources. Currently, fossil gas accounts for 95% of the energy supply to the built environment. Heat and electricity both take up 2.5% of the supply. It is expected that by 2050, fossil gas supply to the Dutch built environment is fully shut off and replaced by bio-gas (50%), heat (30%), and (green) electricity (20%). Future energy supply will be diverse (not dominated by a single energy source) and will depend on local availability.
- Current market developments show an increasing demand for solar-powered energy solutions to supply heat and electricity. Such solutions bear the potential to partly decentralise energy supply since it can be induced locally. In the future, this might allow homes or communities to become self-sustaining in terms of energy, but the need for centralised energy supply remains.
- The boiler, as it is currently developed, is a low-interest product. Customers buy the product for its functionality to supply warm water and heat their living environment. It is that functionality, rather than the product's embodiment that is of value.
- The whole heating industry develops boilers for a lifespan of 15 years. Floor-standing boilers and wall-hanging boilers are marketed for 15-20 years and 12-18 years of operational life respectively. Every boiler contains wear components that do not last the full 15-year lifespan and actual life time highly depends on the use situation.
- The primary reason for product obsolescence is diminished quality, when repair of a defect is no longer economically effective given the overall state of the product. This can be partly explained by the product's high price and low-interest nature.
- The most important criteria in a customer's buying decision is sales price. Other relevant criteria are performance and energy-efficiency. In their decision when to replace an old boiler and what new boiler to buy, end users are highly influenced by the advice from installers.
- Competing products are very similar in functionality, performance and efficiency. When new product features are introduced to the market, competitors are quick to follow suit. Typically, Remeha takes a prominent position in the market, but is rarely leading in product innovation. By responding quickly to recent market developments, they level with competition.
- As there is little functional distinction between competing products, the market is highly competitive on price and warranty conditions.

- Customer segments for Remeha's wall-hanging boilers are installers and end users. The installer professionally sells, installs and maintains boilers at the home of the end user. The end user buys a domestic heating system from installer or wholesale to benefit from warm water supply and a warm living environment.

Macro-economic forces

- Gas prices tend to fluctuate as a result of supply and demand dynamics. Demand drops as technologies become more resource-efficient, demand rises as population grows and production increases, supply drops as natural reserves of fossil gas are increasingly scarce and difficult to reach, etcetera. It is expected that gas prices will rise in the long term since natural reserves deplete. Since 2008, gas price has gradually increased for household consumers, but it has been decreasing since 2013 for industrial consumers.
- European employment rate is steadily dropping since 2013 and is currently at a rate of 8.6%.
- The European economy is growing, indicated by a GDP growth rate of 2 in 2015. The result is a slight increase in purchasing power.
- The costs of renewable energy like wind and solar are decreasing. In some countries (UAE, Australia, and Chili) the tipping point has already been reached where solar energy can be sourced cheaper than fossil fuel.
- The global middle class is expected to increase from 2 billion to 5 billion by 2030
- Urbanisation

Industry forces

- Current business model depends on the supply of raw materials for value creation. As Europe does not possess much natural resource reserves, it depends on foreign trade to import resources.
- Main competitors on the Dutch market are Nefit (Bosch group), ATAG, Intergas, Vaillant, Daalderop, and awb. Just like Remeha, they offer a diversity of heating solutions, including several variants of high-efficiency condensing boilers and smart thermostats. Products are mostly sold to the customer, thereby transferring ownership. Some competitors, including Nefit and ATAG, offer the possibility of leasing a boiler.
- The leasing contracts offered by Nefit and ATAG are similar. The duration of the contract spans 12 years, during which the end user benefits from a boiler, maintenance, 24/7 service, and safe installation. In return, the customer pays a fixed amount per month, ranging between about 25 and 45 euros, depending on the quality of the product (basic to elite).
- Some competitors mention "sustainability" at their website, but do not offer much elaboration on this terminology. It is commonly applied in relation to alternative non-gas solutions like solar installations and (hybrid) heat pumps. Vaillaint takes a more elaborate standpoint on sustainability and supports this with a strategy and targets for sustainable development. There is little known

about competitors' development on sustainability, but Daalderop is known to invest in the development of sustainable technologies, like heat pumps.

- High-efficiency condensing boilers dominate the current market for domestic heating because they are currently the cheapest and most energy-efficient solution. However, there are alternative technologies to supply heat, like heat pumps, biomass, biogas, (micro) CHP, collective heat, solar heat, all-electric, and geothermal. Currently, the availability of alternative energy sources like biogas, biomass, and collective heat is limited and technologies are expensive (CHP and solar installations) or inefficient (CHP, solar, heat pumps), which inhibits their large-scale application. As these technologies improve and the transition of the energy market progresses, they are expected to gain market shares.

APPENDIX H
Business Model Canvas product-service system

KEY PARTNERS

the network of suppliers and partners that bring in external resources and activities

- Refurbishers and recyclers
  recover value from end-of-life products and restore value to (at least) original quality
- Wholesale
  sales, distribution and finance (30-day payment terms)
- Remeha Lease BV
  organise legal and administrative lease in cooperation with e.g. Lagelande (white label lease) and Pon energy
- Waste collectors
  Collect end-of-life products from the end users
- Part suppliers
  Manufacture components and sub-assemblies according to product specifications
- Deployment agency
  Provide trained personel on a project basis
- Consultancy firm
  Advise on strategic decisions and train employees
- Design agency
  Design product parts for aesthetic properties
- Transport company
- Installer
  Install, maintain, and repair the boiler, advise customers what product or system to buy.

KEY ACTIVITIES

activities an organization needs to perform well to deliver its value proposition

- Collaborate to build closed cycles
- Product management: establish and maintain customer relations and identify market trends
- R&D: develop validated product specifications
- Procurement
- Product assembly
- Sales & marketing
- Managing resource flows

KEY RESOURCES

the assets required to offer and deliver the value proposition.

- Resources from end-of-life products
- Human resources
- Assembly facility
- Brand identity
- Storage facility
- Knowledge about the product in the use phase
- Knowledge how to organise and optimise closed-loop resource flows

COST STRUCTURE

All costs incurred to operate a business model

- Human capitcal
- Advertising and marketing
- R&D investment and testing
- Procurement parts
- Customer service
- Support costs

VALUE PROPOSITION

products and services that create value for a customer

Focus at wall-hanging and floor-standing high-efficiency boilers

Sell the performance of comfort, rather than the possession of a boiler

- Guarantee product functionality
- Eliminate fincial risks of the end-user by taking over the responsibility to maintain or repair
- Take responsibility for the cost of operation by supplying energy

- Functional and material value can be captured at high utility
- Accessibility of servicable parts

CUSTOMER RELATIONS

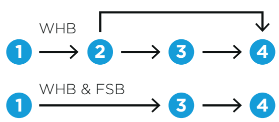
what relationship is established to acquir and retain customers

- Leasing contract
- Website
- Customer survey
- Marketing activities

CHANNELS

Channels by which a value proposition is communicated and delivered to the customer

Distribution and sales channels are B2B. Remeha (1) supplies wholesales (2) and installers (3), which deliver to the end user (4).



CUSTOMER SEGMENTS

the target groups a company aims to create value for

Installer
Sell, install, and maintain heating systems (advisory report) at non-residential buildings and housing, advise consumer

End user
Search the market to find products that fit his need and make buying decision.

Building owner
Manage the construction and maintenance of residential and non-residential real estate to be rented or sold to the end-user

Consultancy firms
Draft advisory report to propose a tailored heating system installation for building owners (primarily non-residential). This proposal includes a preferred boiler model.

REVENUE STREAMS

how an organisation captures value from delivering a value proposition to the customer

Gain periodic income through a leasing system by which customers pay for access to product performance.
Sell materials from end-of-life products to recyclers.

APPENDIX I
Customer profiles

END USER
customer profile

The end user buys their domestic heating system from installer or wholesale to benefit from warm water and a comfortable, controllable room temperature.

JOB IMPORTANCE	PAIN SEVERITY	GAIN RELEVANCE
Jobs describe what the customer is trying to get done	Pains annoy and obstruct customers before, during and after a job	Gains are the benefits the customer is trying to achieve
important	extreme	essential
control room temperature	lose money unexpectedly	safety and well-being of end-user and his family
make buying-decision	damage to domestic property	warm water and room temperature at demand
pay for product/ service	no heat supply when there is demand	reliable heating performance and service
contact installer or manufacturer for service	insufficient or fluctuating warmth	transparent cost-of-ownership
	dispose end-of-life product	positive impact on society and environment
insignificant	moderate	nice to have

INSTALLER

customer profile

The installer professionally sells, installs and maintains boilers. He is in direct contact with the end user and advises on purchase and replacement.

JOB IMPORTANCE	PAIN SEVERITY	GAIN RELEVANCE
Jobs describe what the customer is trying to get done	Pains annoy and obstruct customers before, during and after a job	Gains are the benefits the customer is trying to achieve
important	extreme	essential
install boiler, including exhaust pipe and expansion vessel	service/maintenance job is labour- and time- intensive and exceeds planning	earn profit
maintain and repair boiler	service call (requiring immediate attention) occurs unexpectedly	healthy and safe to install and maintain boilers
advise and sell to the customer	customer loses trust in the ability or reliability of the installer	deliver products that meet end user needs and expectations
configure and tune system settings (hydraulics, thermostat)	no spare parts are available to repair boiler	distinguish from competition in a visible and valued way
take back and dispose old boiler	financial risk of late or non-payment by customer	build lasting customer relations to secure continuous work
monitor energy consumption	administrative work to process invoices and payments	nice to have
insignificant	moderate	

APPENDIX J
Value maps

END USER
value map

The end user buys their domestic heating system from installer or wholesale to benefit from warm water and a comfortable, controllable room temperature.

PRODUCTS & SERVICES	PAIN RELIEVERS	GAIN CREATORS
Products and services offered to benefit the customer	Describe how products and services alleviate specific customer pains	Describe how products and services create benefit for the customer
essential	essential	essential
high-efficiency boiler	all-in monthly payment without unexpected costs	guaranteed heat supply at demand
energy supply for the boiler's operation	no upfront investment that binds to long-term commitment	convenience of full service
install boiler and assure safety of the installation	repair defects immediately	transparent contract covers all aspects of heat supply
maintenance and 24/7 repair service	relieve the responsibility and concern about maintenance or repair	short-term obligations allow to flexibly change the contract
personal advice to select the heating system that fits to needs and living conditions		use recycled and recyclable materials and components
nice to have	nice to have	nice to have

INSTALLER

value map

The installer professionally sells, installs and maintains boilers. He is in direct contact with the end user and advises on purchase and replacement.

PRODUCTS & SERVICES	PAIN RELIEVERS	GAIN CREATORS
Products and services offered to benefit the customer	Describe how products and services alleviate specific customer pains	Describe how products and services create benefit for the customer
essential	essential	essential
high-quality, reliable, high-efficiency, low-cost boilers	minimise planned maintenance	save time and effort through effective maintenance
supply service parts to repair boilers	servicable product: quick assessment and easy handling of components	distinguish and compete on the value of warmth rather than the costs
expert service support for installers to repair complex or recurring defects	standardised parts and connections that fit multiple product variants	increase demand for service contracts (from 55% to 100%)
service training for installers to inform about boiler technology and handling	reliable and quick supply of service parts for 15 years past last production date	lead generation: refer end user to installer
smart thermostat	guaranteed payment by Remeha for installation, maintenance, and service	predictable earnings
sales support		
nice to have	nice to have	nice to have

APPENDIX K
Assumptions business case

This appendix describes the assumptions behind the parameters of the business case. Table K1 shows an overview of these parameters and their values, including a reference number. This number refers to the list below, where the assumptions on each parameter are explained.

Table K.1 Business case parameters and their values.

Ref	Parameter	Value
1	Contract lease fee (excl. energy)	€25 per month
4	Contract energy fee (equal to energy costs)	€100 per month
2	Installation costs	€350 per boiler
2	Installation reimbursement	€350 per boiler
3	Average gas consumption boiler	1500 m3 per year
3	Average electricity consumption boiler	200 kWh per year
3	Energy rate gas	€0,60 / m^3
3	Energy rate electricity	€0,22 / kWh
5	Labour costs for maintenance and service	€100 per boiler per year
5	Spare parts costs for maintenance and service	€10 per boiler per year
6	Cost price Tzerra CW4 and eTwist	confidential
7	Lease period combi-comfort	15 years
8	Devaluation period combi-comfort	10 years
9	Residual value boiler	€30
10	Bad debts	3% of the revenue
11	Repayment period loan	5 years
12	Interest rate loan	2%
13	Employment costs	€120,000 per year
14	Annual number of new contracts	50; 100; 200; 400; 800; 1600; 3200; 6400; 12800; 25600; 51200

1. Monthly contract fee should compete with rental rates of competitors, which currently range from about €27,50 (CW3) to €29,00 (CW5) for a Tzerra-like boiler (source: Holland Warmte). These prices include the boiler, thermostat, installation, service, and maintenance. For a competitive position, the monthly contract fee for this business case is set at €25. This fee includes the boiler, thermostat, service, and maintenance, but does not include installation and energy costs.
2. Costs for installation of the boiler are directly passed on to the customer, either (partially) through an extra one-time payment or (partially) by factoring the costs into the monthly contract fee. A consumer research should lead to determining the structure that is most attractive to the customer. For now, the business case assumes that the costs for installation are collected through an additional one-time payment, assuming a rate of €350 per installation. Costs for replacement and removal are not yet included in the model, because it is unknown what the procedures or frequencies for replacement and removal will be.
3. A boiler consumes gas and some electricity in order to function. It is assumed that a Tzerra boiler consumers 1500 m^3 gas and 200 kWh electricity per year. The energy rates are assumed to be €0,60 / m^3 for gas and €0,22 / kWh for electricity. Energy price developments as a result of increased scarcity or market mechanisms is not included in this model.
4. The energy costs are directly passed on to the customer. Based on the assumptions described in list item 3, the monthly energy costs are set at €80,50.
5. As part of the proposition to guarantee functionality, the costs for service and maintenance are to be paid by Remeha (to the installer). Remeha effectively takes an all-in service contract with the installer for every boiler that is leased through this model. On top of that, Remeha is responsible for the costs of any service parts. The service costs are assumed at €120 per year per boiler, consisting of €10 material (service parts) and €110 labour costs.
6. As explained in section 5.3, the leasing model is organised through a financing vehicle that is legally and financially separated from Remeha. In this structure, the financing vehicle buys the boilers and thermostats from Remeha and consequently owns them. It is assumed that Remeha does not make profit on this transaction and sells their products at cost price. The specific cost prices are confidential, so they are not reported here.
7. Both the boiler and the thermostat can be leased for 15 years. This assumption is based on the 15-year lifespan for which both products are developed.
8. Since the financing vehicle Remeha Lease B.V. maintains ownership of the products, they are current assets on the balance sheet. Their value can be readily converted to cash. However, the product's value decreases over time, which is accounted for by the depreciation costs the business case. The value of the Tzerra boiler and eTwist thermostat is assumed to depreciate over a period of

10 years. The annual depreciation costs amount to value of the product (in this case equal to the cost price) divided by the depreciation period. Note that the depreciation period is not necessarily equal to the lease period.

9. At the end of the lease period, the product that is leased can still have residual value, for instance as a source of materials. The residual value of the boiler is estimated to be €30, given the current design and the current market. When boiler designs become more optimised for reverse cycles (increasing opportunities for recycling and refurbishment), the residual value will increase.
10. Bad debts account for unpredictable losses. The business case assumes the bad debts at 3% of the projected earnings from the lease and energy contract.
11. Remeha Lease B.V. needs to advance the costs for the boiler, thermostat and installation. In the proposed business case these costs are paid for through a loan (from a bank). It is assumed that the loan will be repaid over a period of 5 years.
12. The annual interest paid by Remeha Lease B.V. to the bank is assumed to be 2% of the outstanding loan.
13. Founding and running a leasing organisation like Remeha Lease B.V. requires human resources. In the first years, there is only a small number of contracts to be maintained, but more effort is required to organise the business model. In later years, activities become more routine, but a higher number of contracts means more maintenance work. It is assumed that, in average, it requires 2 FTE (full time employment) to organise and maintain processes.
14. The aim is to expand the leasing model steadily over a number of years. It is assumed that the number of contracts will double every year, starting with 50 in year 1 and growing to 51200 in year 10.

APPENDIX L
Design strategy ideation

Design strategy	Circular economy principle				
	Organise reverse cycles	Be resource effective	Think in systems	Prioritise the future	Create mutual benefit
Create value from circulated resources		●			
Separate biological from technical materials	●				
Dematerialise/virtualise		●			
Improve energy efficiency		●			
Design for maintenance and repair Predictive maintenance	●	●			
Influence user behaviour to use energy efficiently		●			
Design lifecycles/holistic approach			●		
Design value transition scenarios	●	●	●		●
Adaptable product functionality		●			
Configure/personalise product features		●			●
Design for attachment and trust Create new relations between customers and products		●			
Upgradable product		●			
Multiple consecutive use cycles		●			
Product life extension		●			
Design for durability		●			
Design for reliability/reduce chance of failure		●			
Design for pure resource flows Use non-toxic materials Use mono-materials	●				
Align the lifespan of components	●	●			
Reduce harmful emissions Carbon management		●			
Minimise materials for function		●			
Substitute technical with biological materials		●			
Use energy from renewable resources		●			

Design strategy	Circular economy principle				
	Organise reverse cycles	Be resource effective	Think in systems	Prioritise the future	Create mutual benefit
Modular product structure Distinguish short- and long-lifespan parts	●				
Standardise features	●	●			
Limit material variety in portfolio	●	●			
Design for disassembly Flexible mounting techniques Easy disconnection of joints	●	●			
Align economic and ecologic lifespan of components		●	●		
Structure sharing		●			
Integrate components		●			
Maintain resource integrity	●				

influence user behaviour
maintenance and repair
multiple consecutive use cycles
standardised features
minimise materials for function
design for durability
energy efficiency
multi-functional
upgradable product
modular product structure
product life extention
virtualise
dematerialise
design lifecycles
adaptable product
design for disassembly
design for reliability
non-toxic materials
holistic approach
create value from circulated resources
eliminate waste by design
feedback loops
attachment and trust
advanced materials
mono-materials
source locally
comply with treatment systems
monitor product in lifecycle
apply new technology
carbon management
predictive maintenance
transfer knowledge
choose new product or service
extract biochemicals from organic waste
digest anaerobically

APPENDIX M
Reverse cycle processes

Figure M.1, M.2, and M.3 explain the processes of reuse, refurbishment, and recycling respectively, by means of a simplified process flow. These flows represent a generalised view; processes of specific treatment facilities may differ in the exact process that are applied and their sequence.

REUSE PROCESS

Assess the component's condition to determine options for re-processing.

Components that cannot be refurbished are input for the recycling process.

Disassemble products or modules into separate components.

Remove dirt from the component's surfaces and cavities.

Test component and product performance to verify compliance with quality standard.

From storage, reusable components are used for product manufacturing and repair. Reusable products are distributed.

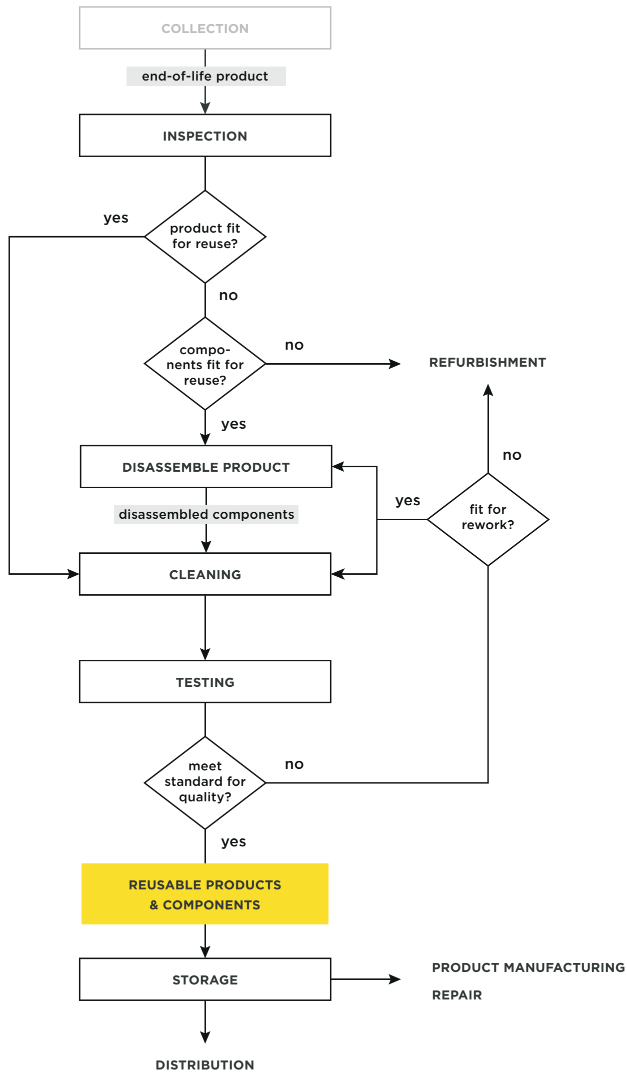


Figure M.1 Flow chart of the reuse process.

REFURBISHMENT PROCESS

Disassemble products or modules into separate components.

Assess the component's condition to determine options for re-processing.

Components that cannot be refurbished are input for the recycling process.

Remove dirt from the component's surfaces and cavities.

Components are processed to restore their condition. Proces methods vary for different components.

Test component performance to verify if it meets the standards of at least 'as new' condition.

From storage, refurbished components are used to build new products or as service part to repair existing products.

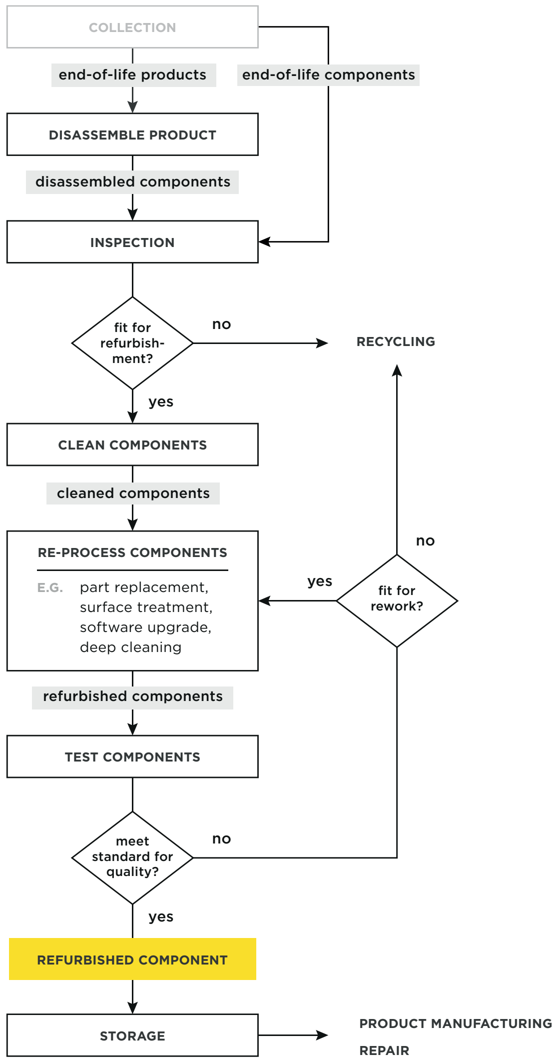


Figure M.2 Flow chart of the refurbishment process.

RECYCLING PROCESS

Disassemble products and sort components into different batches based their materials.

Compress batches into bales that are transported to processing facilities.

Recyclables are processed to retrieve the raw materials. Proces methods vary for different types of material.

Materials that cannot be recovered, are processed to retrieve embedded energy or chemical feedstock.

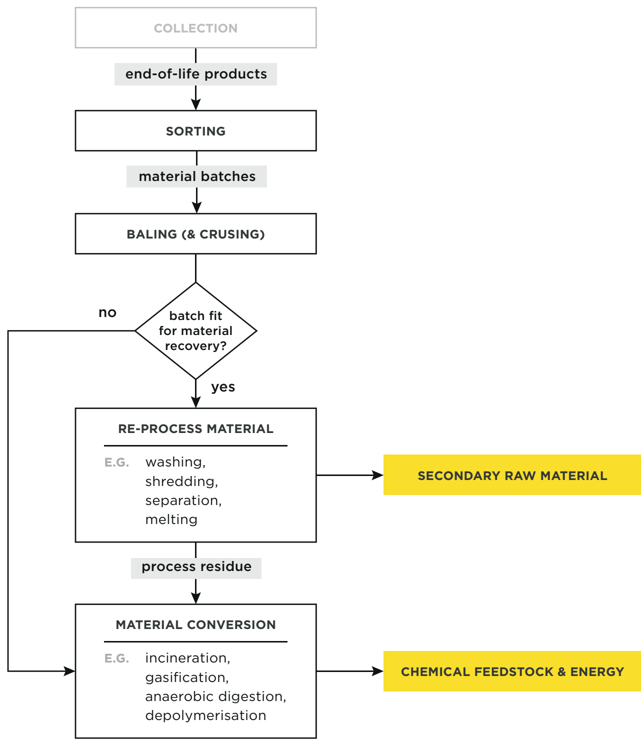


Figure M.3 Flow chart of the recycling process.

APPENDIX N
Results brainstorm Design for Disassembly

Participants: Remeha (4), Van Gerrevink (1), HR Recycling/Premium Parts (1)

This appendix describes the key insights from the brainstorm on Design for Disassembly. They purpose of the brainstorm was to formulate design guidelines that can support the development of boilers in compliance with end-of-life processes, like reuse, refurbishment, and recycling. This brainstorm session is organised in response to a collaborative project with MVO Nederland, aimed at development circular climate installations.

Design for disassembly is relevant to the circular economy because it contributes, from the development process, to establishing circular resource flows. By designing product such that components and materials can be separated at high quality, resources can circulate in pure cycles. In this way, design for disassembly contributes to maintenance, reuse, refurbishment, and recycling. An easier process of disassembly, is less cost- and labour-intensive and depends less on the expertise of specialists.

The brainstorm session is structured according to three discussion points:

- How should a boiler-assembly be designed for easy disassembly?
- How should a boiler-component be designed for closed-loop resource flows?
- How can circularity be measured and quantified?

The first two discussion points have been addressed from a focus on the product design and less with regard for the organisation of the supply chain.

Topic 1: How should a boiler-assembly be designed for easy disassembly?

- The connections between components should be easily detachable. Snap fits or screw joints are preferred over adhesives. Moreover, detaching connections should be quick and easy, for instance by allowing detachment by hand or with a few standard tools.
- Knowledge transfer could play an important role in disassembly. For instance, as disassembly instructions and the identification of the type of product and components.
- Contains standardised parts and connections that can be broadly applied. For instance, a water pump that can be used for multiple boiler types, but might also be compatible with a fridge or a dish washer.

Topic 2: How should a boiler-component be designed for closed-loop resource flows?

- Components must be made from materials that can be separated for recycling. The physical properties of materials should be compatible and if they are connected they should be separable (no composites). Exact recommendations on this aspect depend on material properties and process capabilities of treatments like recycling.
- Materials contain no toxic substances that contaminate material streams.
- Use high-quality materials that preserve their quality over consecutive use cycles, like metals.
- When material quality cannot be preserved or restored, their energy value could be utilised through incineration. In this case, it is beneficial if a material has a high caloric value.
- Use materials that can be broadly applied within the supply chain or in another supply chain. For instance, the aluminium of a heat exchanger could be used for manufacturing a car chassis.
- Distinguish parts with a short and long lifespan and adjust maintenance and reuse protocols accordingly.
- For refurbishment and reuse it is useful when a component's condition can be easily identified and its structure has a low complexity so it can be easily processed.

Topic 3: How can circularity be measured and quantified?

- Within the recycling sector, the percentage of recyclability is used as a measure of performance. This score could be used to express (part of) the performance of a circular system.
- For indicating reuse, a weight ratio could express a quantity of reused products or components.
- A Life Cycle Assessment (LCA) could be applied to quantify the environmental effects of a supply chain. Life Cycle Sustainability Assessment (LCSA) could be used in a similar way to express the impact on social and economic domains.

APPENDIX O
Guideline inventory

Table O.1 Literature research guideline inventory.

Index	Guideline	Reference
1	Minimise the total number of individual components	Telenko, Seepersad, and Webber (2008) W. Ijomah, C. McMahon, G. Hammond, and S. Newman (2007) Lowe and Bogue (2007) Van den Berg and Bakker (2015) Mital, Desai, Subramanian, and Mital (2014)
2	Minimise the number and variety of joining elements/fasteners	Telenko et al. (2008) W. Ijomah et al. (2007) Luttropp and Lagerstedt (2006) Lowe and Bogue (2007) Boothroyd and Alting (1992) Mital et al. (2014) Van den Berg and Bakker (2015)
3	Eliminate redundant parts	W. Ijomah et al. (2007) Mital et al. (2014)
4	Limit the number of different materials (per product/part)	W. Ijomah et al. (2007) Lowe and Bogue (2007) Boothroyd and Alting (1992) Mital et al. (2014) Luttropp and Lagerstedt (2006) Van den Berg and Bakker (2015)
5	Integrate components (could become conflict)	Mital et al. (2014) Boothroyd and Alting (1992)
6	Eliminate toxic or hazardous materials in part design	Lowe and Bogue (2007) Luttropp and Lagerstedt (2006) Desai and Mital (2003) Brainstorm DfD (appendix N)
7	Concentrate toxic elements in closed units	Telenko et al. (2008) Boothroyd and Alting (1992) Mital et al. (2014)
8	Allow the easy identification of a component's condition	Telenko et al. (2008) W. Ijomah et al. (2007) W. L. Ijomah, C. A. McMahon, G. P. Hammond, and S. T. Newman (2007) Brainstorm DfD (appendix N)

Index	Guideline	Reference
9	Provide permanent identification of product specifications that influence end-of-life processes and reutilisation opportunities	W. Ijomah et al. (2007) Mital et al. (2014) Telenko et al. (2008) Crowther (1999) Brainstorm DfD (appendix N)
10	Make the location and handling of fasteners and disassembly points easily identifiable	Lowe and Bogue (2007) W. Ijomah et al. (2007) Telenko et al. (2008) Desai and Mital (2003) Boothroyd and Alting (1992) Balkenende 2011
11	Identify similarities to support segmentation	W. Ijomah et al. (2007)
12	Standardise assembly groups, interfaces, components, materials and fasteners	W. Ijomah et al. (2007) Crowther (1999) Lowe and Bogue (2007) Boothroyd and Alting (1992) Mital et al. (2014) Brainstorm DfD (appendix N)
13	Ensure visibility and open access to separation joints and fasteners	Telenko et al. (2008) W. Ijomah et al. (2007) Boothroyd and Alting (1992) Crowther (1999)
14	Ensure easy access to modules and components, prioritising parts that are serviceable (cleaning or repair), reusable, and harmful.	Telenko et al. (2008) Lowe and Bogue (2007) W. Ijomah et al. (2007) Mital et al. (2014) Crowther (1999)
15	Components should be easy to clean for maintenance, reuse, and refurbishment, without damaging integrity	W. L. Ijomah et al. (2007) Telenko et al. (2008)
16	Apply smooth surfaces	W. L. Ijomah et al. (2007) W. Ijomah et al. (2007)
17	Implement reusable/swappable platforms, modules and components	Telenko et al. (2008)
18	Make component interfaces simple and reversibly separable	Telenko et al. (2008)
19	Combine similar elements in a group	Mital et al. (2014)
20	Organise a product or system into hierarchical modules by repair and end-of-life (reuse and refurbishment) protocol	Telenko et al. (2008) Van den Berg and Bakker (2015)
21	Combine components that have a similar physical life	Hata, Kato, and Kimura (2001) Brainstorm DfD (appendix N)

Index	Guideline	Reference
22	Combine components that have the same maintenance intervals	Hata et al. (2001)
23	Concentrate compatible material groups in separate subassemblies of a product	Hata et al. (2001)
24	Reduce component weight	Luttropp and Lagerstedt (2006) Lowe and Bogue (2007)
25	Specify renewable and abundantly available resources	Telenko et al. (2008)
26	Specify recyclable and recycled materials that can be (broadly) applied within the company or for which a market exists or can be stimulated	Telenko et al. (2008) Lowe and Bogue (2007) Luttropp and Lagerstedt (2006) Brainstorm DfD (appendix N)
27	Layer recycled and virgin material where virgin material is necessary	Telenko et al. (2008)
28	Specify pure materials (non-composite, non-blended, no alloys)	Telenko et al. (2008) Luttropp and Lagerstedt (2006) Brainstorm DfD (appendix N)
29	Increase the use of common materials	Van den Berg and Bakker (2015) Brainstorm DfD (appendix N)
30	Employ common and remanufactured components across models	Telenko et al. (2008) Brainstorm DfD (appendix N)
31	Reduce the product's structural complexity	W. L. Ijomah et al. (2007) W. Ijomah et al. (2007) Desai and Mital (2003) Brainstorm DfD (appendix N)
32	Avoid aging and corrosive material combinations	Mital et al. (2014) W. L. Ijomah et al. (2007) Boothroyd and Alting (1992)
33	Avoid secondary coating processes (like painting)	Mital et al. (2014) Lowe and Bogue (2007) Van den Berg and Bakker (2015)
34	Avoid non-rigid and fragile parts	Mital et al. (2014) Boothroyd and Alting (1992) Lowe and Bogue (2007)
35	Consider material compatibilities	Van den Berg and Bakker (2015) Brainstorm DfD (appendix N)
36	Specify all joints to be separable by hand or by using a few simple and standardised tools	Telenko et al. (2008) Desai and Mital (2003) Lowe and Bogue (2007) Van den Berg and Bakker (2015) Brainstorm DfD (appendix N)

Index	Guideline	Reference
37	Design connections between components to be easily detachable; avoid fixed connections	Brainstorm DfD (appendix N)
38	Use mechanical connections (fasteners) rather than chemical ones (adhesives)	Crowther (1999) Lowe and Bogue (2007) Brainstorm DfD (appendix N)
39	Minimise the number and length of (dis) assembly operation	Telenko et al. (2008) Desai and Mital (2003)
40	Make component suitable for manual handling during disassembly	Crowther (1999)
41	Allow for parallel (sequence-independent) disassembly of components	Crowther (1999) Boothroyd and Alting (1992) Van den Berg and Bakker (2015)
42	Apply non-destructive disassembly techniques prioritising connections, structures and components that are fit for reuse, refurbishment, and recycling	W. Ijomah et al. (2007)
43	Apply a linear and consistent (dis) assembly direction without the need for reorientation	Boothroyd and Alting (1992) Telenko et al. (2008)
44	Use the largest, most rigid part of the assembly as a base or fixture	Mital et al. (2014) Telenko et al. (2008)
45	Use material for fasteners that is compatible with the host component	Telenko et al. (2008) W. Ijomah et al. (2007)
46	Disassemble process circuit board (PCB) in one piece	Van den Berg and Bakker (2015)
47	Use surface-mounted device (SMD) components	Mital et al. (2014) Lowe and Bogue (2007)
48	Ensure products can be stacked	Van den Berg and Bakker (2015)
49	Ensure end-of-life products can be safely transported	Van den Berg and Bakker (2015)
50	Allow for spare part harvesting	Van den Berg and Bakker (2015)
51	Use high-quality materials that preserve their quality over consecutive use cycles	Brainstorm DfD (appendix N)

APPENDIX P
Design guide draft

Product architecture

1	Reduce the product’s structural complexity
2	Minimise the total number of individual components
3	Eliminate redundant parts
4	Integrate components (could become conflict)
5	Provide permanent identification of product specifications that influence end-of-life processes and reutilisation opportunities
6	Identify similarities to support segmentation e.g. similar materials, fasteners, tools, cleaning procedures
7	Identify component position and orientation in the product assembly
8	Ensure easy access to modules and components, prioritising parts that are serviceable (cleaning or repair), reusable, and harmful.
9	Ensure accessibility and separability of cables and connectors In case of malfunction, these should be replaceable separately
10	Use the largest, most rigid part of the assembly as a base or fixture
11	Apply non-destructive disassembly techniques prioritising connections and components that are fit for reuse, refurbishment, and recycling
12	Apply a linear and consistent (dis)assembly direction without the need for reorientation
13	Allow for parallel (sequence-independent) disassembly of components

Product module

1	Implement reusable/swappable platforms, modules and components
2	Make component interfaces simple and reversibly separable
3	Combine similar elements in a group
4	Organise a product or system into hierarchical modules by repair and end-of-life (reuse and refurbishment) protocol
5	Combine components that have a similar physical life
6	Combine components that have the same maintenance intervals
7	Concentrate compatible material groups in separate subassemblies of a product
8	Standardise assembly groups and interfaces

Product component

Uniquely identifiable parts and sub-assemblies that are designed to fulfil a specific and necessary function of the boiler. The definition of components influences the possibilities for their reutilisation.

1	Reduce component weight e.g. by using high quality materials
2	Employ common/standardised and remanufactured components across models
3	Avoid non-rigid and fragile parts
4	Concentrate toxic elements in closed units for easy removal and treatment
5	Allow the easy identification of a component's condition to determine end-of-life options for reutilisation and detect wear
6	Components should be easy to clean for maintenance, reuse, and refurbishment, without damaging integrity
7	Apply smooth surfaces
8	Make component suitable for manual handling during disassembly
9	Make sure the product is or can be protected (repacked) during transport during use life e.g. integrate packaging and casing/insolation or store packaging at product.
10	Ensure products can be stacked
11	Shape of the parts should permit the use of jigs and fixtures for reconditioning

Component connection

Connections that attach components and modules for a fixated position in the sub-assembly or product assembly. Fasteners influence the process of (dis)assembly and determine possibilities for re-attachment and reutilisation of components.

1	Minimise the number and variety of joining elements/fasteners such that a minimum variety of tools, skills, and working postures is needed for disassembly
2	Make the location and handling of fasteners (and disassembly points) easily identifiable
3	Ensure visibility and open access to separation joints and fasteners
4	Avoid fixed connections
5	Simplify and standardise component fits
6	Standardise fasteners to reduce the complexity of disassembly and increase compatibility with other systems
7	Specify all joints to be separable by hand or by using a few simple and standardised tools
8	Use mechanical connections (fasteners) rather than chemical ones (adhesives)

9	Do not use metal inserts (in combination with machine screws) for joining plastics Metal inserts cannot be properly separated from the host (plastic) material, which contaminates recycled material batches.

Material

The materials used for constructing components. Selection of materials influences options for refurbishment and recycling.

1	Consider substituting technical with renewable biological materials Prioritise the substitution of materials that cannot be recycled
2	Design with recycled materials In theory, designing with recycled materials follows the same principles as designing with virgin materials. However, the properties and behaviour of recycled material have a greater uncertainty factor, which should be accounted for by design. Some considerations are: • Prioritise standard grade recyclates. • When substituting virgin with the same recycled material, process parameters should be reconsidered and material behaviour in components should be tested. • The degree of shrinkage after injection moulding can be higher for recycled materials.
3	Apply pure (mono) materials Product parts that are made from mono-materials can potentially be recycled at high grade. • Do not apply composites composed of different materials Once a composite is formed, the different materials it consists of can no longer be separated, nor can the composed material be re-shaped into a new component. Layering recycled with virgin material of the same type is allowed. • Do not blend different polymers and additives Blending virgin with recycled material of the same type is allowed. • Prevent the use of uncommon metal alloys <IF NOT THEN> Ensure that “contaminated” plastics have a density that is different from recyclable mono-plastics (ABS, PE, PP, and PS). During the recycling process, different types of plastic are separated based on density properties. When a composite or blended plastic falls within the same density range as an applied mono-plastic, the output stream will be contaminated.
4	Increase the use of commonly applied materials Use common plastics like ABS, PE, PP, and PS since there are dedicated recycling streams for these plastics. Other plastics, like PC, PA, PHB, PMMA, and PET(?) are currently not separated in the recycling process but are incinerated.
5	Avoid secondary coating processes (like painting)

6 Ensure the compatibility of different materials for recycling

When a product is constructed from multiple materials, it is essential to choose material combinations that are compatible for recycling. Compatible materials can be separated during the recycling process when combined in a waste stream. Incompatible materials cannot and need to be physically separated before recycling. Even the smallest contamination can cause significant deterioration of material quality.

- Use material for fasteners that is compatible with the host component fasteners are recycled together with the host component

7 Ensure that suppliers meet legislative requirements on hazardous substances, specified by RoSH and REACH. Consider also compliance with the SVHCs and CARACAL list to anticipate future substance restrictions.

8 Limit the number of different materials (per product/part)

to predict disassembly procedures

9 Limit the use of additive masterbatch in plastics to modify properties

Masterbatch is used as an additive to plastics to adjust aesthetic or physical properties, for instance flame retardant, UV-absorbers, or (thermal) stabilisers.

- if an additive is necessary, apply an additive which changes the material's density so it can be separated from uncontaminated materials during recycling.
- limit the use of colourants
  Coloured plastic cannot be uncoloured in the recycling process. This colour limits opportunities for reutilising the recycled material.
- Do not apply black-coloured plastics
  Black cannot be detected by infrared sensor technology used for plastics separation, thus black components cannot be separated and recycled.

10 Provide permanent identification of the material type

The primary purpose of material identification is to promote the correct treatment of the material in reverse cycle processes. For instance, to support segregation during manual disassembly processes. Remeha's department procedure for characterisation of tooled (AP734-014) parts requires a "recycling character".

- For plastics, it is advised to use the International Resin Identification Coding System (RIC) to identify material type as this is a widely recognised standard.

APPENDIX Q

Results evaluation design guide draft

Because of the interview's rather open structure, feedback and responses from engineers address different aspects of the guideline proposal. Noteworthy remarks are listed below and are structured per participant. The names are fictional and serve as a personification of the research results and as an easy reference. Feedback on specific guidelines, e.g. referring to clarity or relevance, has been excluded from the results presented here. This specific feedback has been used to further improve the guidelines, but referring to each adjustment in this interactive process would be too elaborate.

Andy

Experience with sustainable development

Eliminate toxic or harmful substances such as PVC or PTFE or develop packaging from just cardboard. These represent occasional considerations, but no experience with dedicated and structural optimisation for sustainability.

Handout guidelines

- Our choice for materials is initially determined by its intended function in the product.
- When applying the guidelines, they need to be translated to a familiar design situation.
- Some guidelines are not relevant for certain situations, but that is ok.
- Now that we are unfamiliar with designing for closed loops, it is useful to mention background information on the guidelines (like the materials category). It clarifies and makes them more vivid. I want to know about the thought and purpose behind the guideline.
- In time, when we are more experienced, the relevance of the background information possibly decreases.
- Suggestion to clarify that the elaboration serves a specific purpose to help engineers understand and apply them, not as a thoughtless overload. Also it might be good to mention that the guidelines are time-dependent.
- The term 'guidelines' could invoke some aversion, because the term is more commonly used for strict design rule that needs to be followed.
- Andy mentioned a specific guideline to be a "too extreme measure to be mentioned first", which indicates he expects the order of the guideline list to represent a certain hierarchy of relevance/priority/applicability.

Demonstration digital tool

- Before demonstrating the digital tool, Andy was talking about bundling the guidelines into some booklet that he could use as a reference book or background information. Upon viewing the digital tool, he immediately recognised the advantage of digitised information and was enthusiastic about

this proposal. He did consider the possibility of a digital tool before.
- The layout and interaction of the demo tool are accessible and clear.
- Preferred additions to the proposal are to support the guidelines with visualisations and to offer examples with the guidelines.
- Supporting tools like the Material Compatibility Matrix are useful

Brian

Handout guidelines

- We are used to working with guidelines and people actively look for them for support;
- Remeha is working on streamlining their use and development of internal guidelines, which is currently rather unstructured.
- Just writing guidelines possibly has a limited effect on their adoption. The application could be stimulated by:
  - Establishing a basis of support and a broad awareness
  - A good presentation of the guidelines
  - Referring to guidelines in other processes or tools (like the NPD process or the Alternative Solutions Table (AST)
- Limit guidelines to the essence; too much or irrelevant information is likely not to be used.

(during this session, there was no time to demonstrate the digital design tool)

Charlie

Experience with sustainable development

Consider sustainability from the perspective of legislative requirements, for instance on labelling and recycle logo's. Aim to develop packaging from just cardboard material.

Handout guidelines

- Product engineers are used to working with guidelines and our department would like to expand the application of guidelines. Partly for consistency and as a means of recording and transferring knowledge.
- Personally, I like to work with guidelines because it gives support in my work.
- Since guidelines should be applicable to all our products, we as product engineers should translate them to our specific situation or design challenge.
- Charlie recognises there is no order of priority or importance in the list of guidelines, but suggests it would be helpful to mention more relevant guidelines up the list, because people are likely to pay most considerate attention to the top of the list.
- Certain formulations raise some confusion on the meaning and intention of the guideline. These are mostly expressed for the "connections" category, which contains unedited guidelines, formulated as they are mentioned in literature. These same guidelines were easily misinterpreted and some appear to overlap.

- Charlie thinks that the showed guidelines (connections and materials) are applicable to his engineering work on a boiler.
- Elaboration on the guidelines, like provided by the "materials" category, is experienced by Charlie as useful and supportive for his decisions.
- It would be useful to offer additional inspiration or examples with the guidelines. Also applying imagery would further support the interpretation and application of the guidelines.

Demonstration digital tool

- Looks like a good and pleasant way to work with the guidelines.
- This digital tool has my personal preference over a printed version. Possibly the older engineers like working with printed instructions better, but they can always print this.
- "I had actually hoped your research would result in something like this" This we can actually use and it makes this concrete.

Donald

Handout guidelines

- Writing the guidelines in English might hinder their usability for some engineers.
- The categories are clear, only the distinction between component and module is vague. Especially at the start of developing a new product, the difference between components and modules is not yet clearly defined.
- Donald is tempted to interpret the categories (material, connection, component, module, and architecture) as a preferred (chronological) sequence in which they should be applied. He recognises that it is not possible to assign such an order that is relevant to all design cases.
- In the guidelines, some terms are used that do not have an unambiguous meaning and might be interpreted differently by different engineers. Examples of such terms are: platform, element, sub-assembly, module, and assembly group.
- The sequence of the guidelines could be determined to place the guidelines on top that are easily applied, for instance when they do not require very impactful changes.
- Donald suggests to mark the key words in the guidelines so they can be distinguished and interpreted more easily. This could be further supported by images or icons.
- The materials category focuses predominantly at the use of plastics, but we also use a lot of metals. It might be useful to include these more explicitly in the guidelines.
- For material selection an internal list with preferred materials would be useful.
- In general, the guidelines and explanations are described in a quite complex way. Donald suggests to use some more accessible language in describing the guidelines.
- Guidelines are a good way to make product engineers aware of the circular economy.

Demonstration digital tool

- Donald believes that a digital tool is a good way to communicate the guidelines, better than a written document.
- It is suggested to connect the digital tool to some physical object to stimulate the use of the tool. The physical object can serve as a reminder of the availability of the tool.

Eugene

Experience with sustainable development

No considerable experience, once did an assignment on a LIDS wheel at school.

Handout guidelines

- At Remeha, guidelines are usually interpreted as requirements that must be followed.
- Eugene thinks guidelines are a pleasant way to use extra information for engineering work.
- The guideline categories are a logical structure for accessing the guidelines. It feels like a logical (chronological) sequence to move from architecture to material, but it is acknowledged that guidelines do not have to be used in one specific sequence. It can depend on the design case that needs to be addressed.
- In general, the presented overview of guidelines (component and material) is experienced by Eugene as accessible, clean, and not overly exhaustive. Some component guidelines need more explanation for a good understanding.
- The guidelines are seen as aspects that can be discussed in collaboration and that leave way for personal input from the product engineers.
- While reading through the (material) guidelines, Eugene indicates that they really get him thinking about the consequences for Remeha's products.
- The explanations provided with the material guidelines are experienced as useful and not too extensive, but it makes the guidelines less accessible compared to the component guidelines that contain no explanations. Eugene would prefer the explanations to be available with the guidelines, but maybe only revealing them upon clicking a guideline.

Demonstration digital tool

- Accessing guidelines digitally would be fine.
- Eugene likes the interactive element that reveals more information upon clicking (this is exactly what he envisioned for the guidelines before seeing the demo).

Fred

Experience with sustainable development

No considerable experience, once did an assignment on Cradle to Cradle in school.

Handout guidelines

- Fred believes guidelines are the best way to support engineers in designing for reverse cycles. In using the guidelines, the knowledge will eventually be adopted by the engineers.
- The guideline categories are a logical way to structure the guidelines
- The guidelines are concrete and usable. Some might already be considered intuitively (like design for disassembly), but others do trigger more awareness and new ideas.
- It would be helpful to have a list of materials that can or cannot be applied.
- When the guidelines are numbered, I feel like number 1 is the most important or that I should use the guidelines in a fixed sequence.
- While reading the guidelines (material and connection) Fred noted some terms the were unclear, like 'renewable bio-materials', 'component fit', and 'additive master batch'
- The connections guidelines (without explanations) is more accessible and pleasant to work with. However, the explanations from the material guidelines are useful for their understanding and application. I would prefer an overview that allows me to click on a guideline to reveal more information.

Demonstration digital tool

- Clicking the guidelines is pleasant. The tool brings the information more alive and is distinct from the numerable knowledge documents. The interactive nature allows to engage and inspire the user.
- Fred would like to use the list of guidelines as some sort of checklist to mark his progress and possible some additional notes.
- A nice addition would be to incorporate some sort of news feed that shows the results from using the tool: some examples of successfully designed circular products.

APPENDIX R
Guideline proposal

Architecture

arc 01 Specify the **space claims to allow easy access** to components

The accessibility of components in the assembly is influenced by the empty space around them. Sufficient space can support visual inspection, the placement of testing equipment, and the positioning of tools without the need for (extensive) disassembly.

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arc 02 Organise components into a **modular structure**

Components are grouped in modules for a specific purpose. Some Remeha products, like the Tzerra, already have a modular structure, but this is currently more aimed at ease of assembly than at for instance reusability or recyclability. The right modular structure can support easy dis- and re-assembly for reverse cycle processes.

arc 02.1 Combine components with **similar end-of-life options**

When all components that should be refurbished are combined in one module, product disassembly in reverse cycles is improved. It reduces the number of disassembly operations to harvest parts for a specific reverse cycle process. The same can be done for other end-of-life options like recycling or reuse.

arc 02.2 **Standardise the interfaces** between modules

When interfaces are standardised, modules can be applied to various boilers from different generations or families.

arc 02.3 **Concentrate PCBs in a module** to make hem easily removable

PCBs are valuable components for recycling and are processed through a dedicated waste stream. When they can be taken out in one module, separation for recycling becomes easier and requires less time.

---

arc 03 Position modules and components to **make parallel disassembly possible**

Ideally, it would be possible to have access to any component in the assembly, without needing to detach another component first. Then, the ability to disassemble is independent of any sequence, which is referred to as parallel disassembly. When this is realised, disassembly (by example for repair) becomes more time-efficient.

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arc 04 When disassembly cannot be parallel, **indicate the preferred sequence**

When certain components need to be removed before other components can be reached, this should be made clear to the operator. Indicating the preferred sequence of disassembly saves time and makes processes more predictable.

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arc 05 Position components and interfaces for an **intuitive (dis)assembly direction**

When components can be positioned and removed in one straight direction, the process of (dis)assembly will be simplified and more intuitive. For instance, releasing all cable connectors by pulling the cable harness in one direction. Try to eliminate the need complex movements that require components to be reoriented.

arc 06	**Mark** components that have **similar end-of-life protocols** Marking supports an operator to quickly and accurately identify for what processes a component is suited to restore value. This knowledge helps to segregate disconnected parts and to choose the right way of handling and processing them.
arc 07	Mark the boiler with **information about its performance** characteristics This information is useful for reverse logistics or for refurbishment partners, for instance to determine the value of components and how to process them. Relevant information is: comfort class, capacity (l/min), nominal power (kW)

Component

com 01	**Integrate multiple functions** into a single component When boiler components perform multiple functions, like insulate heat and enclose technology, less individual components are needed to fulfil the combined product functionality.
com 02	Seek to **apply or iterate upon existing components** Before designing a new component, consider if an existing component meets the required functional specification or can be used as a basis. When iterating upon an existing component, try to make the changed component compatible with the products that it is already used in.
com 03	Design new components to **fit boilers from different generations or families** The opportunities for reuse and refurbishment increase when certain components can be applied in different boilers. This involves considerations on aspects like space claim, connections to other components, and functional specification. It could be useful to already anticipate future developments in the Product Roadmap.
com 04	Design to **identify the functional condition** of a component Knowing what the condition of a component is, helps to determine if and how it should be processed to restore value. The condition could be measured by use of testing equipment, but it might also be possible to integrate a (visual) indicator in the product.
	com 04.1 Indicate the **malfunction** of parts When malfunctioning parts can be easily identified, this helps to determine the state of a component and how it could be processed in reverse cycles. An obvious defect can help to select treatments for repair and refurbishment, while indicating no flaws could qualify a component for reuse.
	com 04.2 Indicate the **degree of wear** of a part Some boiler components are susceptible to wear, which influences their lifespan. Knowing the degree of wear helps to estimate the lifetime potential that a used component still has for reuse. This information further helps to determine options for application or required treatment, but also supports to set a market value.
	com 04.3 **Monitor** the product during its lifecycle Information about the products behaviour in its lifecycle (especially the use phase) can be valuable for optimising processes or predicting the product's condition upon return. An example is Remeha's Predictive Maintenance programme.

com 05 **Mark components** with information about their characteristics

Information about a component benefits processes like reuse, refurbishment, but also repair by identifying what a component is, what it can do, and what it can be used for. This information should be linked to the component, because in reverse cycles components are separated from the product assemblies.

com 05.1 Inform about **end-of-life protocols**

Components should be designed for a specific lifecycle scenario, in which they go through multiple processes and cycles. Information about the intended scenario, makes people aware of how components should be handled or processed.

com 05.2 Inform about **performance and features**

Reuse and refurbishment focus at a component's functionality: finding a new application for it or improving its condition. Information about functional characteristics supports these processes by providing a benchmark for testing and restoring conditions and matching a component to product requirements.

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com 06 Design surfaces and geometry to **prevent the collection of filth**

Filth could harm the performance of a component during use and it decreases the component's value as a secondary resource. Processes like recycling, maintenance, and especially refurbishment involve cleaning operations to restore value.

com 06.1 Design components with **smooth surfaces**

When the roughness of a surface texture is low, dirt is less likely to stick to the surface. Even when dirt attaches, it is easier to clean.

com 06.2 **Design out crevices** that are difficult to reach for cleaning

Filth is likely to gather in crevices and there it is difficult to remove during the cleaning process. Internal crevices (like in flow channels) and external crevices (like on a casing) should both be avoided. When crevices are required for functionality, make sure they are accessible after disassembling the component.

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com 07 Shape parts so that they can be **mounted in a fixture** for testing or processing

For detailed disassembly steps or certain treatments, it might be necessary to apply controlled force to a boiler component. This is especially relevant for components that qualify for refurbishment. Fixation to stabilise the component during such processes benefits from part geometry that fits standard mounting tools.

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com 08 **Reduce wear** to individually separable components

Limit wear to a small number of components that can be easily accessed and exchanged in the boiler assembly, like the three-way valve or ignition electrode.

Connection

con 01 Specify connections that can be **detached and re-attached, repetitively**

When boiler parts can be disconnected, operations like repair, refurbishment and recycling can be carried out more easily and effectively. After a part is disconnected, it must be possible to re-assemble it, preferably using the same connections.

When applying this guideline, prioritise (economically) valuable components that are fit for reuse, refurbishment, or maintenance.

con 01.1 Ensure the possibility to easily **detach PCBs in one piece**

PCBs are valuable components for recycling and are processed through a dedicated waste stream.

con 01.2 **Use mechanical fasteners** rather than adhesives

Mechanical fasteners, like screws, snap-fits, or press-fit, can potentially be disconnected without damaging the connection or component. An adhesive bonding is broken when it is disconnected and often damages the joined surfaces as well.

con 01.3 **Prefer separable snap-fit joints** for plastic components

Snap-fit joints are quick and easy to assemble and can be designed to allow disconnection. Another advantage when applied to plastics is that the connecting elements can be integrated in the geometry of the connecting parts and made from the same material.

con 01.4 **Prevent moulding different types of plastic** together

Specific injection moulding processes (like 2K) make it possible to connect different parts (made from different materials) during the moulding process. For instance, for applying a rubber gripping surface to a moulded tool handle, or applying a foam core to save weight.

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con 02 When permanent connections are necessary, **guide destructive action**

When connections or components absolutely need to be broken in order to be detached, offer guidance on how this should be done. This will prevent causing harm to the operator or excessive damage to the product.

con 02.1 Provide **markers** that indicate **where to apply force**

Indicating where (and possibly how) to apply force, helps the operator to disassemble components efficiently and in the right way. It also prevents reusable or refurbishable parts to be damaged unnecessarily.

con 02.2 Include **breaking lines** to control the breaking points

When applying destructive force, breaking lines can ensure that damage occurs in a controlled way that separates the right parts in the right places. This could preserve certain parts and prevent fragmentation into a lot of pieces.

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con 03 Make it easy to **identify the position and handling** of connections

Boiler parts are manually attached and detached for assembly, repair, refurbishment, etcetera. Knowing where connections are located and how to handle them, helps the operator to separate parts and components in the right way and to save time.

con 04	Ensure **open access to (detachable) connections** in the boiler assembly Place connections in a position that can be easily accessed by hand or tool, allowing to work around other components. This should match the assembly sequence, but should also be designed to limit the number of disassembly steps that is needed to detach a boiler component.
con 05	**Use common connections** that are widely applied in industry Using standardised connections reduces the complexity of (dis)assembly procedures and increases a component's compatibility with other products (e.g. for reuse). When using application-specific connections, like clips for connecting flow pipes in the Calenta, aim to use them for other boilers too.
con 06	Enable the **replacement and repair of connections** When connections are integrated in the part (like clickers in the control box) the whole part becomes obsolete when connections wear out or break. When connections can be replaced, this would prevent early obsolescence.
con 07	Design connections to allow **(dis)assembly by hand or with standard tools** Installers and waste processing facilities (like refurbishment plants) operate on various products from different brands. They can work more easily and time-efficiently when parts can be disconnected using standard tools that fit multiple products.
con 08	**Minimise the number** of connecting elements in the boiler The amount of connections highly influences the time to (dis)assemble. Using a limited number of connections requires less operations, which saves time.
con 09	**Limit the variety** of connections within the boiler Different connections generally require different operations and tools. The variety of connections should be limited such that the need to switch tools or working postures is limited to save time.
con 10	**Prevent** the use of **permanent magnets** in boiler components During the recycling process, waste streams are divided with magnetic separation. Permanent magnets from the waste stream get stuck to the separation magnet and are difficult to remove.
con 11	Do not mould metal **threaded inserts** in plastic parts Metal inserts cannot be properly separated from the plastic material when they are attached in the moulding process. As a result, inserts cannot be replaced for repair and when the part is shredded for recycling, fragments of metal will remain attached to the plastic.

Material

mat 01	Increase the use of **common materials**

mat 01 Increase the use of **common materials**

Standardised materials are widely applied in industry and they appear in regular and high quantities in waste streams. Recycling systems are generally specialised in processing these materials so they can be recovered at high quality. Also, there exists an established market to reuse common materials as a secondary resource.

Common plastics are: PET, ABS, PE, PP, and PS

Common metals are: steel (stainless/carbon), aluminium (wrought/cast), iron (wrought/cast), copper, zinc, and brass

mat 02 Design with **recycled materials**

In a circular economy, it is important that the materials in a boiler can be recycled, but it is just as important that these recycled materials are used again. One way to do this is by designing boilers to be made from recycled materials.

mat 02.1 Prefer **standard grade recyclates** that are offered by the supplier

Standard grades are more commonly applied, so their properties are extensively tested. This makes their application more reliable and easier to implement.

mat 02.2 **Reconsider tooling equipment** when replacing virgin with recycled material

Recycled materials can behave different from virgin materials, due to occasional impurities. This could require adjustments to tooling or process parameters.

mat 02.3 Apply a (higher than normal) **safety factor** to select recycled material

The properties and behaviour of recycled material are less predictable, due to occasional impurities in the material. This uncertainty can be accounted for by the safety factor.

mat 03 Design parts to be made from **mono-materials**

An important question to consider when selecting materials is “can the material be recycled and re-used at high quality?” Using mono-materials makes it easier to separate materials from a waste stream and allows to recycle materials at high quality.

mat 03.1 **Prevent using composites** that consist of different materials

A composite, like a fibre reinforced plastics, is a combined material that consists of a base component (the matrix) and a filler. Once a composite is formed, the different materials it consists of can no longer be fully separated. This highly limits the possibilities for recycling composites at high quality.

mat 03.2 **Prevent blending plastics** with additives or other types of plastic

A blended material is a mixture of multiple components that form one homogeneous material with improved properties. However, blended material components are difficult, and in some cases impossible, to separate once they are mixed. This limits the possibilities for their recycling.

Some examples of widely applied additives are: flame retardants, plasticisers, UV absorbers, colourants, and fillers.

mat 03.3 **Limit** the use of **colourants** in plastics

Colourant additives cannot be removed from plastic material, which limits the material's application as secondary raw material. Specifically, **black colourants** should be used with care. Most automated recycling processes use optical sorting equipment to separate different plastics, but this technology has difficulty registering black materials.

mat 03.4 **Prevent** the use of uncommon **metal alloys**

An alloy is a mixture of a metal with another type of metal or non-metal. It is comparable to a blended plastic, but based on metal elements. Just like with composites and plastic blends, the constituents of an alloy are difficult to separate and reuse as pure materials.

If an alloy is necessary, use common ones that have established recycling streams and markets, such as (stainless) steel and brass.

---

mat 04 If an additive is necessary, apply one that gives the plastic a **unique density**

During the recycling process, different types of plastic are commonly separated by their densities. When a composite or blended plastic falls within the same density range as an applied mono-plastic (like PP or PE), it contaminates the output stream.

---

mat 05 Design boiler components with a **limited number of different materials**

A small variety of materials in a boiler, limits the number of disassembly operations that is needed to pre-sort product parts into different waste streams.

---

mat 06 Ensure that different **materials are compatible** for recycling

Compatible materials can be separated during the recycling process when combined in a waste stream. Incompatible materials cannot and need to be physically separated before recycling. Ensure that at least the materials in an assembly unit are compatible.

mat 06.1 Use material for **connectors** that is **compatible with the host part**

In practice, connectors are usually recycled together with the host component. As a result, they end up in the same waste stream. For this reason, their materials should be compatible.

mat 06.2 When using metals, ensure that **ferrous metals** are magnetic and **non-ferrous metals** are non-magnetic

In the recycling process, metal scrap is separated into ferrous and non-ferrous streams by a magnetic separator. While most ferrous metals are magnetic and most non-ferrous metals are not, this does not always apply. For instance, certain types of stainless steel (ferrous) are non-magnetic. These are likely to be unintentionally separated with non-ferrous scrap and contaminate the stream.

---

mat 07 Whenever possible, **limit the use of coatings**

Once a coating is applied, it is generally difficult to separate from the component's base material. As a consequence, coatings pollute the material streams and in some cases disturb the separation of plastics when they change density.

Examples of coatings are paint, chrome plating, galvanising, and enamel (emaille) mat 08 Mark components with a permanent **identification of their material type**

Identifying a component's material supports the effective treatment of the material in reverse cycle processes. For instance, to support separation during manual disassembly processes or to estimate a component's residual value. Remeha's department procedure for characterisation of tooled parts (AP734-014) requires a "recycling character".

mat 08.1 For plastics, adopt the **ISO 11469** to indicate material type

ISO 11469 offers a standard for generic identification and marking of plastics products. The marking system is intended to help identify plastic components for decisions on handling, waste recovery or disposal. Primary characteristics to identify are the base material and (when relevant) additives.

---

mat 09 Ensure that suppliers **comply with laws** on the use of **hazardous substances**

The application of certain substances (like some plasticisers and flame retardants) is restricted or banned in the European market. Compliance with RoSH directive and REACH regulation is required. Prevent using substances on the SVHC candidate list, which are not restricted yet, but are candidates for future restriction under REACH regulation.

---

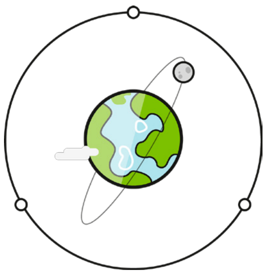
mat 10 When using plastics, **prefer thermoplastics** over thermosets and elastomers

In general, it is impossible to melt and remould thermosetting plastics, which limits their end-of-life options to reuse or down cycling. The same goes for vulcanised elastomers (like rubber). There is development in advanced processes that may increase recycling possibilities for these materials, but such processes are not yet applied on large scale.

APPENDIX S

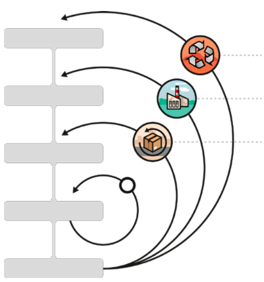
Circular economy explanation

The design tool contains an information section that explains the fundamental idea of the circular economy, how it can be influenced through product design, and how this relates to the design tool. The explanation's story line is divided into five distinct parts, which are mentioned in this appendix.



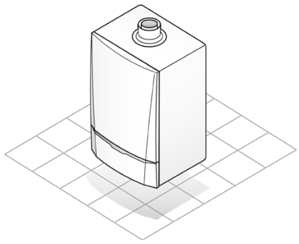
THE CIRCULAR ECONOMY

When we build our boilers, we use materials and energy resources to make components and assemble them into a functional product. Through the market, the boiler is brought to the consumer who uses it for creating warmth. The circular economy offers a new way of organising this process to use resources more productively. Instead of just disposing old or broken boilers, we will collect them and restore their value. Components could be reused for other products or materials can be recycled to make new components. Then we create a circular economy where resources are not thrown away, but continuously reused.



RESTORE VALUE SYSTEMICALLY

Restoring value means we treat used boilers so that functions and materials can be used again. This should be done by using as little energy as possible. Recycling is one way of restoring value, specifically focused at materials, but also refurbishment and reuse are important processes. Together, we call these reverse cycles. A reverse cycle starts when a boiler reaches the end of its use life. The design of a boiler highly influences the possibilities to restore value in reverse cycles. For this reason, it is relevant to consider the reverse cycles already in the product development process.

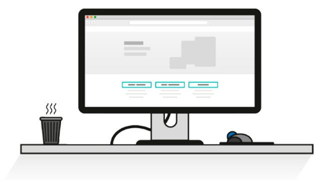


CLOSING THE LOOP BY DESIGN

When designing a product, decisions, like what material to use or how to position and connect components, influence the options for restoring value at end-of-life. By example, glued components are difficult to disassemble for reuse and composite materials are impossible to recycle. These are examples of limitations, but of course it also works the other way around. By our design choices, we can create opportunities to restore value in reverse cycles. This way, the products of today become the resources of tomorrow. But to realise this, we need a new way of thinking; focusing not only on function during life, but also on what will happen when a product is disposed.

THIS IS WHERE YOU COME IN

You, as a product engineer, have great influence on how a boiler will come to look like. You make the decisions that will make it possible to reuse boilers, refurbish components and recycle materials. By doing this, you will contribute to a future where next generations live in a healthy environment and continue to have access to resources for improving their well-being. You do all that on top of making products that benefit people with warm homes and warm water. With your expertise and creativity, you offer an essential contribution realising a circular economy, by design.



THIS TOOL WILL HELP YOU

Designing products for reuse, refurbishment, and recycling is a challenging task. It brings new considerations to your design decisions. This tool, the one you are looking at now, will help you to do this through a set of design guidelines. These guidelines are meant to create awareness and inspire you to new ways of thinking. Using this tool will guide your design decisions to create products that can be used in closed loops.

APPENDIX T
Case study brief

During the usability test, participants were asked to apply the tool to a design case. This appendix contains the instructions that were provided to the participants in the form of a design brief. In this appendix, the 'subject of study' has been described for all three design cases. The briefs that were provided to the participants during the evaluation session described only the subject of study that was assigned to that particular group.

Case study brief

You have just been introduced to the concept of the circular economy. You as a product engineer make the decisions that will make it possible to reuse boilers, refurbish components and recycle materials. To help you do this, a design tool has been developed with a set of guidelines that are meant to inform and inspire your design decisions. During this case study, you will use the design tool to generate new design solutions for a boiler component. Consequently, your experience will help to evaluate the tool's performance.

In groups of 2 or 3, you will perform the case study that is described in this document. You have 45 minutes to come up with a design solution and 10 minutes to make your results presentable. Afterwards, you will briefly explain your solution to the other groups. Be creative and enjoy your case

Case study objective
Apply the design tool to create a (re)design of a Calenta front cover that can be reused, refurbished, and recycled in a circular economy.

Subject of study: Heat exchanger
(This description has been generalised for reasons of confidentiality)
Recently a new heat exchanger component has been developed that integrates several functions into an efficient and cost-effective component. In short time, a development project will start in which a new boiler is designed around this component. This project will reconsider the product's architecture and components relating to the heat exchanger, like the gas-air unit. **The subject of your case study will be the heat exchanger**. The information about the project is meant to provide some context to your case study, but for this workshop you are not bound to any restrictions or requirements that might apply to the on-going project.

Within the scope of the bi-thermal heat exchanger, you are free to choose a more specific focus on a particular part, like the casing. If you want to choose a focus, do this within the first ten minutes of your case study, so you can spend enough time to generate ideas.

Subject of study: Gas-air

(This description has been generalised for reasons of confidentiality)
A commercial wall-hanging boiler will be redesigned to increase its efficiency. This involves changes to, amongst others, the gas-air unit. **The subject of your case study will be the gas-air unit including the gas pipe.** The information about the project is meant to provide some context to your case study, but for this workshop you are not bound to any restrictions or requirements that might apply to the on-going project.

Within the scope of the case study subject, you are free to choose a more specific focus on a particular part, like the gas pipe, venturi, or inlet silencer. If you want to choose a focus, do this within the first ten minutes of your case study, so you can spend enough time to generate ideas.

Subject of study: Calenta front cover

To keep the styling of Remeha's boilers attractive and up-to-date, the front covers of wall-hanging boilers are often re-designed. **The subject of your case study will be the Calenta front cover**. Your case study is not linked to a particular ongoing project, but you can imagine it could apply to a future Calenta project, like the Calenta Update. Note that the aesthetics of the cover are not important to this case study.

Instructions

- Use the given component as a starting point for your case. It is up to you to decide what changes you make. You may make some incremental changes, but you are also free to completely re-design certain aspects of the component.
- Be aware that this case study is meant as a creative exercise to introduce you to the design tool and to evaluate its performance. When using the guidelines, **keep an open mind and look for new and creative solutions**. At this point, try not to be too restricted by considerations of cost or feasibility.
- Make sure **that every member of your group takes the opportunity to look through the tool** attentively. This will benefit the case study results and it is necessary in order for everyone to complete the survey at the end of the workshop.
- Try to **apply guidelines from at least two and preferably three different categories** (material, component, connection, or architecture).
- As you perform your case study, try to **document any positive or negative aspects** that you experience when using the tool.

Deliverables

I would like to see how using the tool will lead to new design solutions. The primary result of your case study will be a rough design proposal for a Calenta front cover that you have designed for the circular economy. Please, make sure to deliver the following results:

- **A description of the process that has led to your design proposal**
  For instance, sketches of the different ideas that you explored. Do not spend too much time documenting this, because the next two points are more important.
- **A clear sketch and description of your (conceptual) design proposal**
  Make sure to communicate especially those features that are inspired by using the tool
- **Specify your design rationale**
  Describe explicitly what makes your design suitable for a circular economy and mention the most important guidelines that have influenced your solution. If you find that features of the initial component are already in accordance with the guidelines, please indicate those too. In this case, mention specifically that those features were not designed by you, but already existing.

You may hand in your results digitally or on paper.

APPENDIX U
Questionnaire

You have just applied a design tool to (re)designing a boiler component, specifically for the circular economy. The design tool is meant to help you in this process by providing a set of design guidelines that aim to inspire and inform your design decisions. I am interested to find out your opinion about using the design tool. This will be of great help to evaluate the tool's usefulness and identify opportunities for improvement. Your answers will be processed anonymously.

General information

Some general information could help to determine if the tool is more suitable for a certain department or case study. Check the box of the answer that applies to you.

1. What R&D department do you work for?
   ☐ projects ☐ innovations & pre-development

2. What case study did you work on during the workshop?
   ☐ gas-air ☐ front cover ☐ heat exchanger

3. How would you describe your skill level when it comes to desiging products for sustainability?
   ☐ beginner ☐ intermediate ☐ experienced

Statements

Mark the response that best describes how much you agree or disagree with the following statements

		Strongly disagree	disagree	No opinion	agree	Strongly agree
4.	The information in the tool is easily accessible	☐	☐	☐	☐	☐
5.	The tool's information about the circular economy helped me to understand what I am using the guidelines for	☐	☐	☐	☐	☐
6.	I think the guidelines are clearly formulated; I understand what they mean.	☐	☐	☐	☐	☐
7.	I was able to use the guidelines during the case study to come up with new ideas	☐	☐	☐	☐	☐
8.	I found it pleasant to work with this tool	☐	☐	☐	☐	☐

9.	I would prefer to use guidelines from a written document instead of this digital tool	☐	☐	☐	☐	☐
10.	The examples helped me to understand how to apply the guideline to my case study	☐	☐	☐	☐	☐
11.	The explanations with each guideline helped me to better understand why it should be applied	☐	☐	☐	☐	☐
12.	I need more information to be able to us the guidelines	☐	☐	☐	☐	☐
13.	I believe I could use these guidelines in my regular engineering tasks	☐	☐	☐	☐	☐
14.	The tool provides me with useful insights on how I can design products for a circular economy	☐	☐	☐	☐	☐

Additional feedback

15. How did you use the tool during your case study?

....

....

16. What do you like about the tool/what do you think are positive aspects of the tool?

....

....

17. Is there anything you missed or did not like about the tool? Please, explain your answer

....

....

18. Would you be willing to use this tool for your projects?

☐ Yes

☐ Yes, if ....

☐ No

Please explain your answer:

....

....

APPENDIX V
Results questionnaire

Table V.1a results questionnaire participants 1-3

Index	Question/statement	1	2	3
1	What R&D department do you work for?	Projects	Projects	IPD
2	What case study did you work on during the workshop?	heat exchanger	heat exchanger	heat exchanger
3	How would you describe your skill level when it comes to designing products for sustainability?	intermediate	intermediate	intermediate
4	The information in the tool is easily accessible	agree	agree	agree
5	The tool's information about the circular economy helped me to understand what I am using the guidelines for	agree	agree	no opinion
6	I think the guidelines are clearly formulated; I understand what they mean	agree	strongly agree	strongly agree
7	I was able to use the guidelines during the case study to come up with new ideas	strongly agree	agree	agree
8	I found it pleasant to work with this tool	strongly agree	agree	agree
9	I would prefer to use guidelines from a written document instead of this digital tool	no opinion	no opinion	strongly disagree
10	The examples helped me to understand how to apply the guideline to my case study	agree	agree	no opinion
11	The explanations with each guidelines helped me to better understand why it should be applied	agree	strongly agree	agree
12	I need more information to be able to use the guidelines	disagree	disagree	no opinion
13	I believe I could use these guidelines in my regular engineering tasks	agree	agree	agree
14	The tool provides me with useful insights on how I can design products for a circular economy	agree	agree	strongly agree

Table V.1b results questionnaire participants 4-9

Index	4	5	6	7	8	9
1	Projects	Projects	Projects	IPD	Projects	Projects
2	gas-air	gas-air	gas-air	front cover	front cover	front cover
3	intermediate	intermediate	intemediate	experienced	beginner	intermediate
4	agree	agree	agree	agree	agree	agree
5	agree	strongly agree	agree	agree	agree	agree
6	agree	agree	agree	agree	agree	agree
7	agree	agree	agree	agree	agree	agree
8	agree	agree	strongly agree	agree	agree	agree
9	disagree	no opinion	strongly agree	no opinion	disagree	disagree
10	agree	agree	strongly agree	no opinion	no opinion	agree
11	agree	agree	agree	no opinion	agree	agree
12	disagree	disagree	no opinion	no opinion	disagree	disagree
13	agree	agree	agree	agree	agree	agree
14	agree	agree	strongly agree	strongly agree	agree	agree

15. How did you use the tool during your case study?

Participant	Response
1	Generating ideas and searching for guidelines to relate them to. It should actually be the other way around; identify points of interest based on the list of guidelines.
2	First searching through the tool, just started somewhere (given the limited time we had) and naturally ran into relevant guidelines. We should have explored the whole tool first, finding out what information is available and where it is located in the tool
3	As background information, as inspiration for new ideas, and as a basis for assessing and justifying design solutions.
4	Mostly to support the brainstorm
5	As guideline to explore the different possibilities while analysing the component.
6	Start with a wide perspective on the assembly and go into more detail from there.
7	We considered every guideline from every category and discussed each guideline to determine if it was relevant to our case study and if so, how.
8	Starting with material and moving to architecture. We read the guideline titles and used the ‘drop down menu’ for more information and options when necessary.
9	After an ‘extensive’ search, I have a preference for a reversed order of the categories: starting at architecture and converging to material as a final category.

16. What do like about the tool?

Participant	Response
1	Pleasant workflow, well readable. Very different from a normal department procedure or guideline.
2	Accessible and clear.
3	It looks very good, explanations and examples.
4	This is a good guide to consider all aspects of sustainability. Most elements are already known, but it motivates to include it all in product development.
5	It is clear and accessible.
6	Useful support to think more holistically about complex matter.
7	Accessible, practical. Actually need more time for a better assessment.
8	Digital, to the point, clear explanations for the guidelines. We did not use the examples[2], but it appears to be a good functionality in the tool (just like the ‘drop down menu’ with supplementary information).
9	Accessible, informative. Great.

2 With this group, the screen with examples and informative resources initially did not open as it was blocked by the internet browser. The group did find the option in the tool, but only pointed out its malfunction after 30 minutes into the case study. The problem was solved, but it left them with little opportunity to explore the examples in the tool.

17. Is there anything you missed or did not like about the tool?

Participant	Response
1	Not for now, this will probably come when the tool is used more intensively.
2	When exiting the screen with examples or resources by clicking the cross in the upper right corner, the tool navigates too far back, not to the previous page.
3	When navigating back from the example screen to the guidelines, the ‘drop down menu’ is collapsed again. Possibly add the explanations of each guideline to the screen that shows the example (now only the guideline title is shown). A description of the tool’s focus and with whom to discuss the design solutions that result from the tool.
4	The sequence of the categories would be more logical as: architecture (1), component (2), connection (3), material (4).
5	The process sequence architecture (1), connection (2), component (3), material (4) would be more logical.
6	Maybe add a stronger workflow to the use of the tool, providing more support about how to use it. Top-down bottom-up approach.
7	Explicitly relate the guidelines to the level of the circular economy, so to recycling, reuse, etcetera.
8	The button that refers to the examples did not function correctly. This needs to be checked. No missing options of information were found.
9	No response at the moment.

18. Would you be willing to use this tool for your projects?

Participant	Response	Explanation
1	yes	Pleasant way to expand your insights on recycling/reuse. Also supports the deliverable in the NPD process.
2	yes	-
3	yes	-
4	yes	Especially the toolbox appears to be accessible
5	yes	-
6	yes	Gives positive energy, room for discussion. Helps to keep this subject under the attention (technology and feasibility highly prioritised at Remeha).
7	yes	-
8	yes	Especially at the start of a project this tool would be a useful way to start designing. It provides options and ideas and it motivates to think.
9	yes	We already consider the integration of function and take care not to apply toxic substances.

APPENDIX W
Case study results

Heat exchanger

- Instead of gluing the aluminium seal disk to the stainless steel coil, use a sealing cord that can be detached without damage to connection or component (con 01)
- Mark the seal disk to indicate its material (mat 08)
- Design junctions from the same material as the top casing (mat 05)
- Place disassemble instructions on the outer surface of the heat exchanger assembly (con 02)
- The casing of the heat exchanger is made from an engineering plastic, seek to apply additives such that the ‘polluted’ material has a unique density (mat 04)
- Use recycled material for the yellow fly nuts (mat 02)

Gas-air unit

- Position the PCB of the fan in the control box to centralise all PCBs in one module
- Redesign the inlet silencer to remove the tyrap that is currently around the inlet opening
- Integrate the inlet silencer and the seal into one component, made from the same material
- Remove the metal inserts in the hydro block
- Apply an electronic instead of pneumatic gas valve to reduce the number of parts
- Integrate fan house with venturi house
- Connect PCB to the fan house for more easy access and exchangability

Front cover

- Use recycled material for the foam insulation in the cover (mat 02)
- Specify the same colour for plastic components (mat 03.3)
- Make the quatre locks (that lock the front cover to the frame) from plastic that is compatible with the material of the front cover (mat 05)
- Specify plastic components without a coating (mat 07)
- Integrate the gripping/branding function with the HMI cover (com 01)

Features of the front cover that have been found to already comply with the guidelines are:

- The cover consists of several parts that can be detached, mostly without tools (con 07)
- The magnets that are applied in the cover are manually removable. (con 10)

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